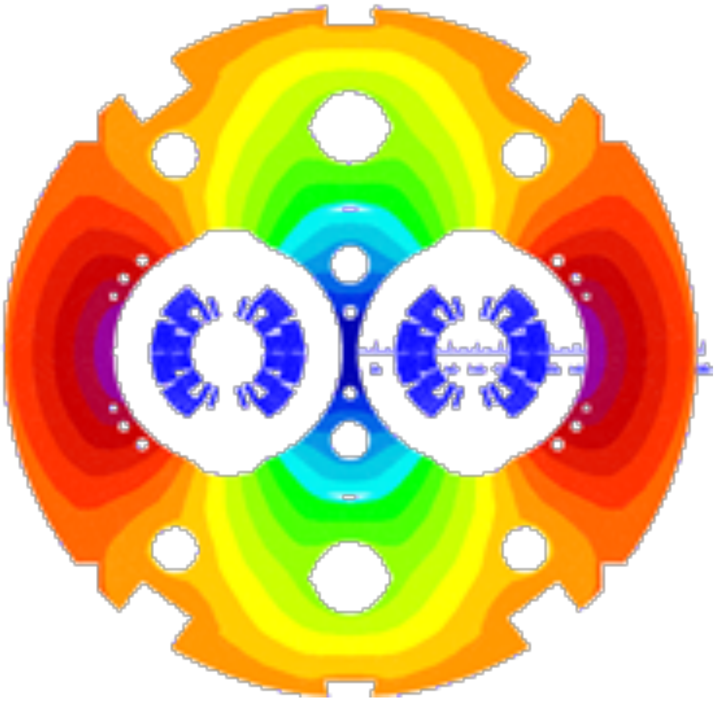

ROXIE User's Guide

Technical Documentation v4.2

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1. The Xroxie User's Interface

1.1 The Graphical User Interface

1.1.1 Overview of the Tcl/Tk widgets

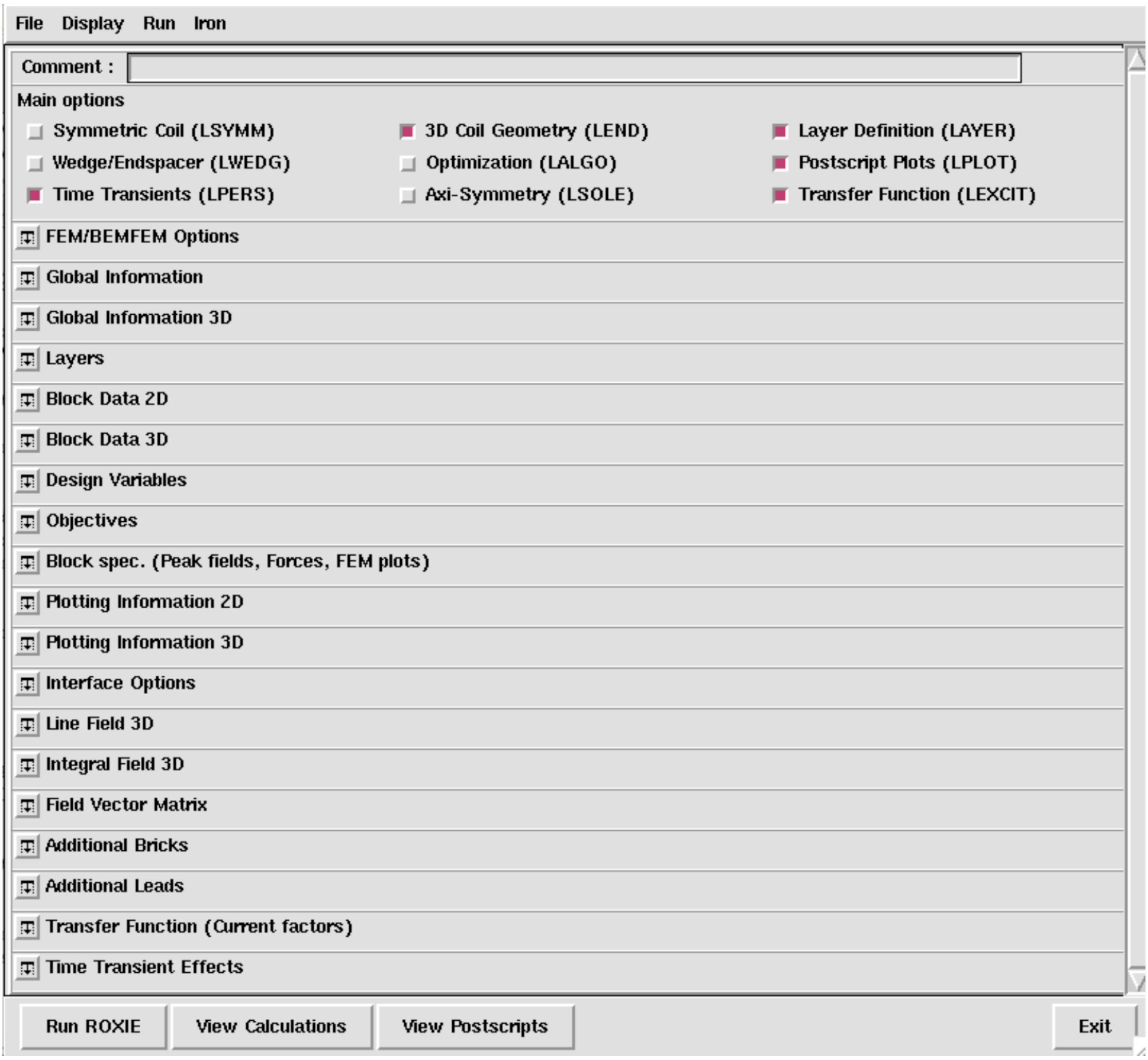
The structure of the Chapters 2-10 is imposed by the input widgets of the Tcl/Tk-based graphical user interface Xroxie. Xroxie is an X-windows program designed to supplement users of the ROXIE program with a graphical user interface (GUI). The program is intended to work with ROXIE version 5.2 and higher and aims to fulfill the following criteria: 1) To present the users of ROXIE with a single consistent interface through the complete process of creating new coil calculations. This includes creating the ROXIE input file, editing the material file, running the roxie program and viewing the results of the ROXIE calculation. 2) To assist in the editing of input files by providing the user with descriptions, hints and/or help boxes for the data required in constructing the input file.

When file is created or loaded into Xroxie, the data is presented as a form in the main Xroxie window. The layout of this form in general follows the policy of the ROXIE input data file of splitting the data into discrete sections, however the following points should be noted.

- Any sections of the form that are irrelevant for the options specified are not displayed on the form and cannot be edited by the user. For instance, the plot 3-D information is unavailable until both the LEND and LPLOT options are switched on. However, any data stored in such sections is retained until a new form is edited or Xroxie is closed down, and can be reinstated by selecting the appropriate options.
- The ROXIE data file contains a considerable amount of information, too much to display all at once in a windowing environment. As a solution to this problem a method has been devised where each section of the form can either be viewed or 'rolled up' using the push button at the left hand side of the section label. This enables space to be saved by temporarily hiding sections not being edited. In addition, the whole form can be scrolled up or down using the scroll bar at the side of the window.

The philosophy behind the form is that anywhere a blank entries exists on the form, Xroxie, and ROXIE, expect data to be supplied. However some tables allow blank entries (such as the plot 2-D 'field'). Xroxie will check for missing information in a form before it is saved or ROXIE is run. However, due to the complex interaction of the data in the input file, Xroxie cannot check the validity of this data.

In total the form defines 19 sections. These are explained in greater detail below.



View of the Xroxie Graphical User Interface. All widgets are closed

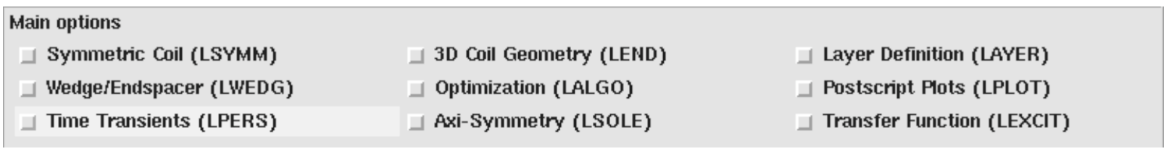
COMMENT:

Give a description (of up to 62 characters) for your model in the "Comment:"-line.

The "Comment:"-line will be plotted on top of every postscript plot.

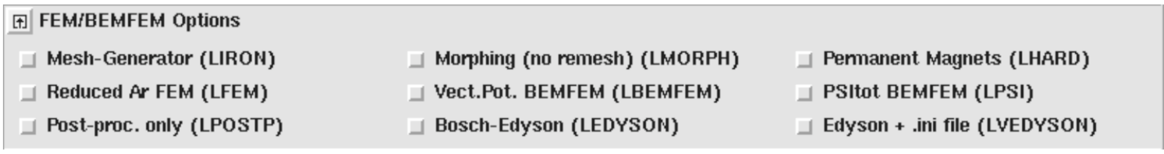
MAIN OPTIONS

This section holds the options which affect the overall operation of ROXIE. Many of them affect what data is required from the rest of the form. See the ROXIE documentation for specific information on each option.



FEM/BEMFEM OPTIONS

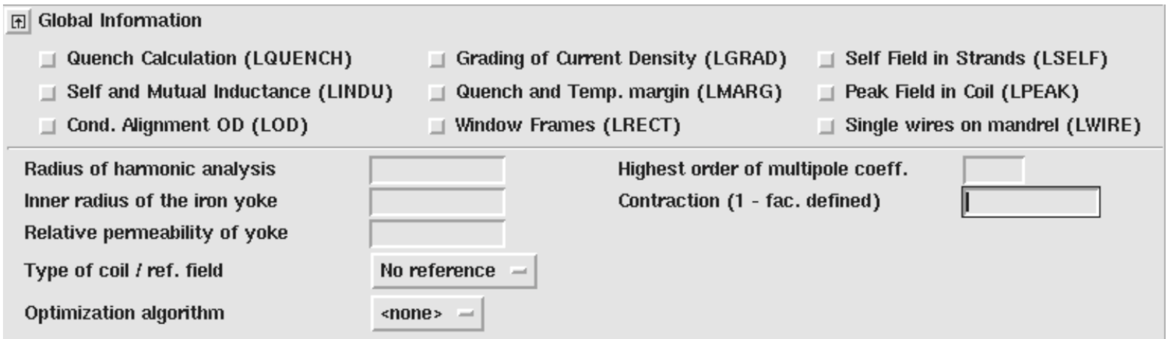
This widget has options for mesh generation and non-linear magnetic field calculation with Finite Elements or the coupling of Boundary Elements and Finite Elements.



Note that the "Bosch-Edyson"- and the "Edyson + .ini file"-options are only currently for stand-alone versions at CERN.

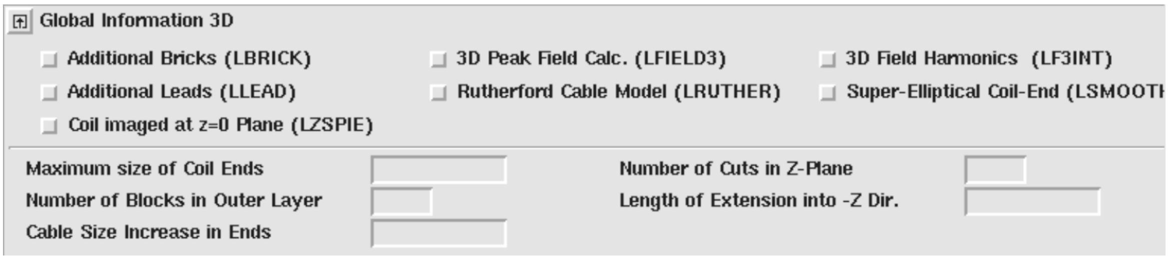
GLOBAL INFORMATION

The options part of the "Global Information"-widget yields functionalities that are generally more closely related to 2-D analytical field calculation. It also has general data about the type of magnet to be simulated, optimization algorithms, mirroring technique, etc.



3-D GLOBAL INFORMATION

This section holds the information and options required to configure ROXIE for 3-D coil end calculations. Certain options, if turned on, require additional information to be specified elsewhere on the form. This section is only available if the option 'LEND' is turned on.

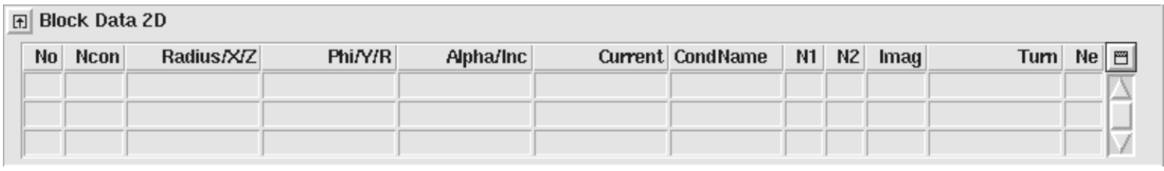


LAYERS

This table is used to define layers of coil blocks for more convenient cross-section modeling. Only available if the "Layer Definition"-option in the "Main Options" is 'on'.

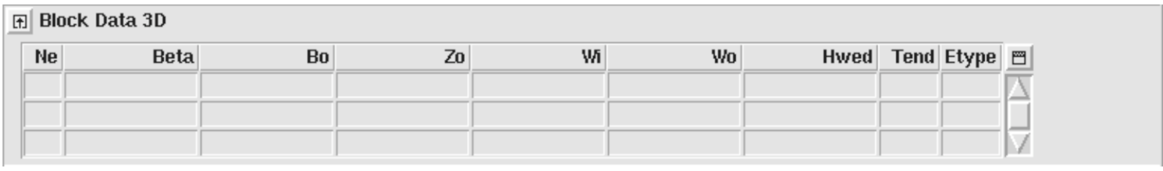
BLOCK DATA 2-D

Here the input data for the coil cross-section has to be specified. 1. The 'Imag' and 'Turn' fields are only required and available if the option LSYMM is turned off. 2. The 'Ne' field is only required and available if the option LEND is turned on. 3. The table menu holds an option to merge extra Block 2-D data from a file. This data must be in the same format as the BLOCK section of a normal output file except the BLOCK header and comment lines should be removed. The data must be compatible with the current settings of the LSYMM and LEND options in Xroxie (see points 1. and 2. above).



BLOCK DATA 3-D

As "Block Data 2-D" but for the input data of the 3-D coil ends. Only available if the "3-D Coil Geometry"-option in the "Main Options" is 'on'.



DESIGN VARIABLES

This table stores the lower and upper bounds of the design variables of an optimization run. The 'String' field in the table can take a single pre-defined symbol. This may be selected from a menu by right-clicking in the appropriate cell. The table menu holds an option to read in scan data produced by a previous run of the ROXIE program. This data is used to define starting values in the 'Xs' column. The table is also used for static geometrical transformations. Some methods and functionalities use the "Design Variables"-table to read in model parameters or other data. This might look strange at first glance, but is a means to guarantee downward compatibility of input files.

The table columns are called:

Variable	Description
No	Row number.
Xl	Lower bound.
Xu	Upper bound.
Xs	Start value.
String	Design parameter/transformation parameter.
Layer/Block/Cond./Strand	Number of blocks/layers/conductors/strands.

During an optimization run, the design parameter is varied between Xl and Xu, starting with Xs. If we want to abuse design values for transformations, i.e., if we want that they are always applied but not varied during optimization, we set Xl=Xu=Xs. It is important to note that the design variables are read at every ROXIE run and the Xs values are always applied - even if no optimization has been chosen.

- **Transformations**, i.e., Xl=Xu=Xs need to be grouped at the end of the table.
- In the "**Layer/Block/Cond./Strand**"-field we enter space-seperated integer numbers. The following format is allowed: `1 4 7-9 10` The "`n-m`"-entry is stored as "`n (n+1) (n+2) ... (m-1) m`". Note that per line no more than 20 layers, blocks, conductors or strands are stored!

OBJECTIVES

Here we define an objective function for an optimization. The table is also used to observe design variables during an optimization run or to store plot data during transient calculations. The 'String' and 'Oper' fields in the table can take a single pre-defined symbol. This may be selected from a menu by right-clicking in the appropriate cell.

With the PLOT-operand in the "Objectives"-table each objective can be plotted into a graph during optimization runs and during time-transient and transfer-function calculations.

The columns of the "Objectives"-table are described below.

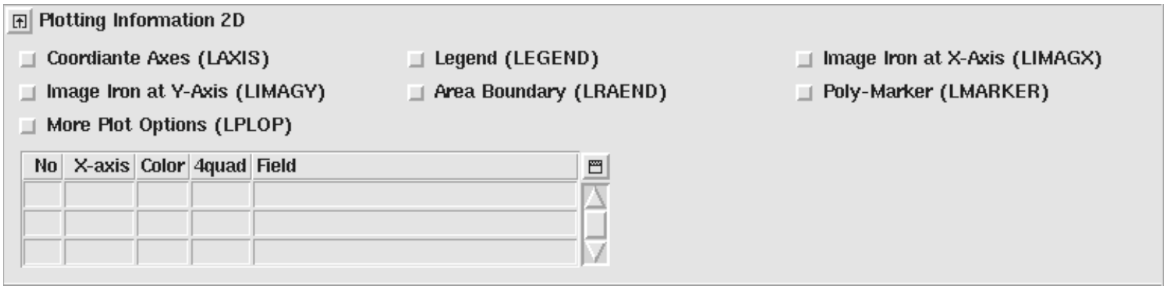
Variable	Description
Ne	Row number.
String	Right-click in a field gives a list of objectives for optimization or plotting.
Nor	Specifies the objective, e.g., gives the order of the harmonic or the number of a strand/conductor.
Oper	Operand in the objective function or PLOT-operand.
Constr./Plot	If the operand in the objective function constitutes a constraint, then the value of the constraint is put here. With the PLOT-operand, the field gives the page number onto which the plot is to be drawn.
Weight	The weighting factor for the objective. Also used with the PLOT-operand.

BLOCK SPEC.

This data line contains the numbers of those blocks in which field calculations on the strand-level are to be performed.

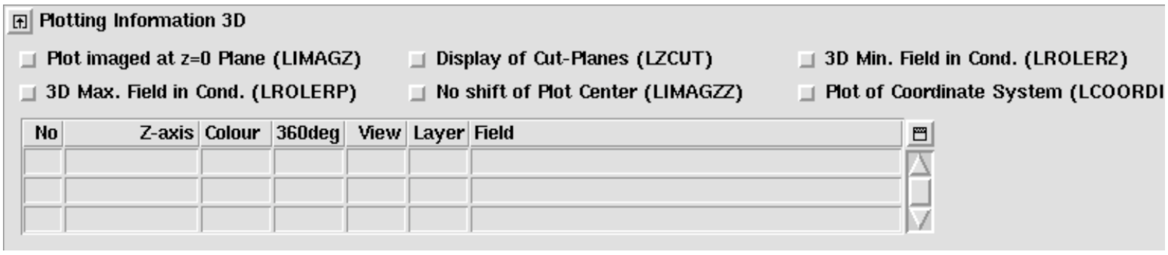
PLOTTING INFORMATION 2-D

The postscript plots produced during a ROXIE run are defined here (2-axis graphs are defined in the "Objectives"-widget). Only available if the "Postscript Plots"-option in the "Main Options" is 'on'.



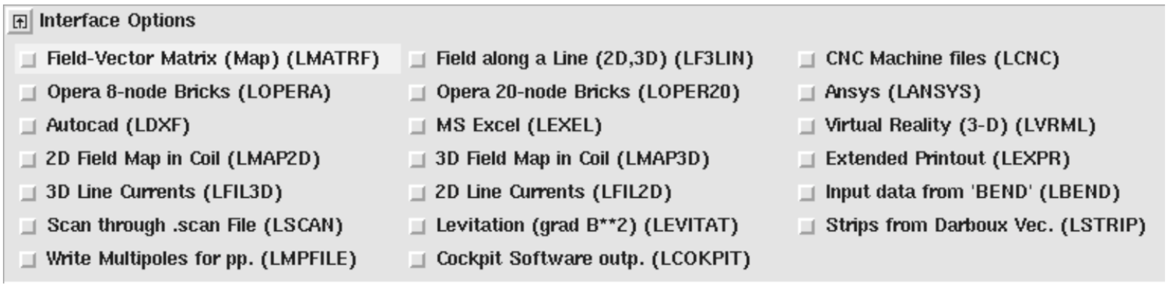
PLOTTING INFORMATION 3-D

As "Plotting Information 2-D" for 3-D plots. Only available if the "Postscript Plots"- and "3-D Coil Geometry"-options in the "Main Options" are 'on'.



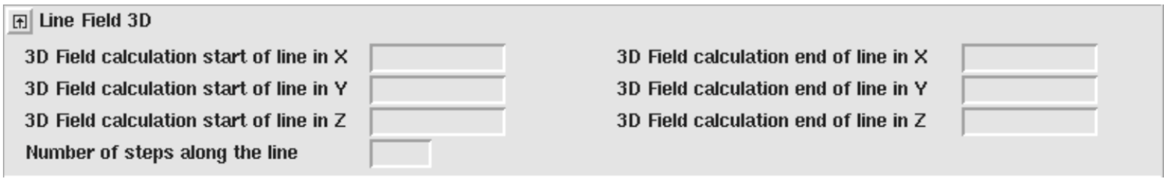
INTERFACE OPTIONS

The user can choose between different output files that act as interfaces to other programs. Also some post-processing options are hidden in this widget.



LINE FIELD 3-D

For the computation of the field in x-, y-, and z-components along a line. Only available if the "Field along a Line (2-D,3-D)"-option is switched 'on' in the "Interface Options".

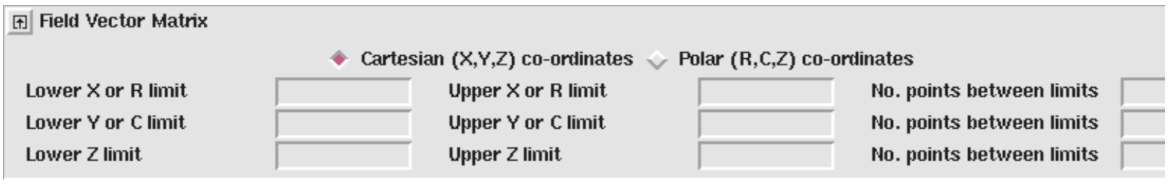


INTEGRAL FIELD 3-D

Computes the field harmonics in 3-D in a number of positions in z. Only available if the "3-D Field Harmonics"-option is switched 'on' in the "Global Information 3-D"-widget.

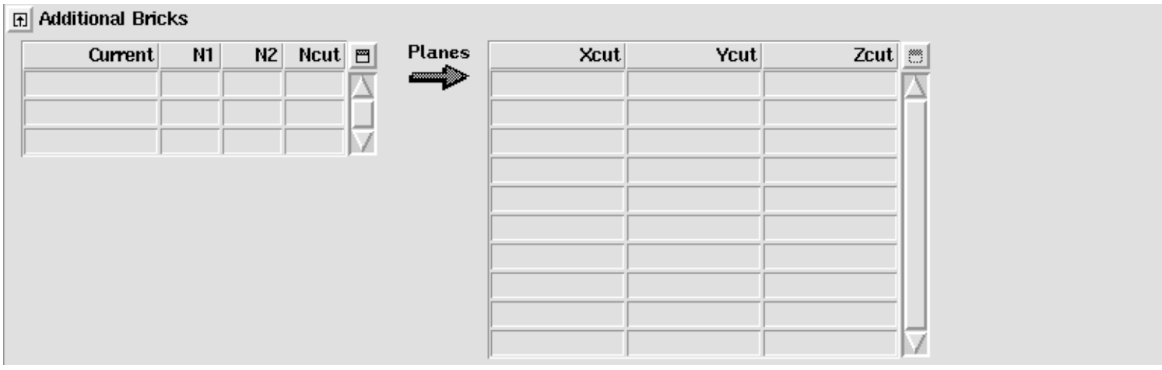
FIELD VECTOR MATRIX

Defines the matrix for a field map. Only available if the "Field-Vector Matrix (Map)"-option is switched 'on' in the "Interface Options"



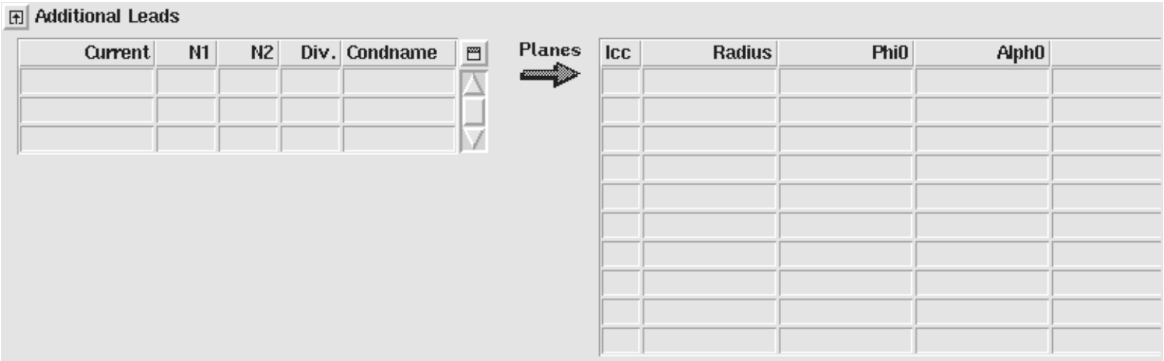
ADDITIONAL BRICKS

Additional brick elements can be defined if the "Additional Bricks"-option in the "Global Information 3-D" is 'on'.



ADDITIONAL LEADS

Additional leads can be defined if the "Additional Leads"-option in the "Global Information 3-D" is 'on'.

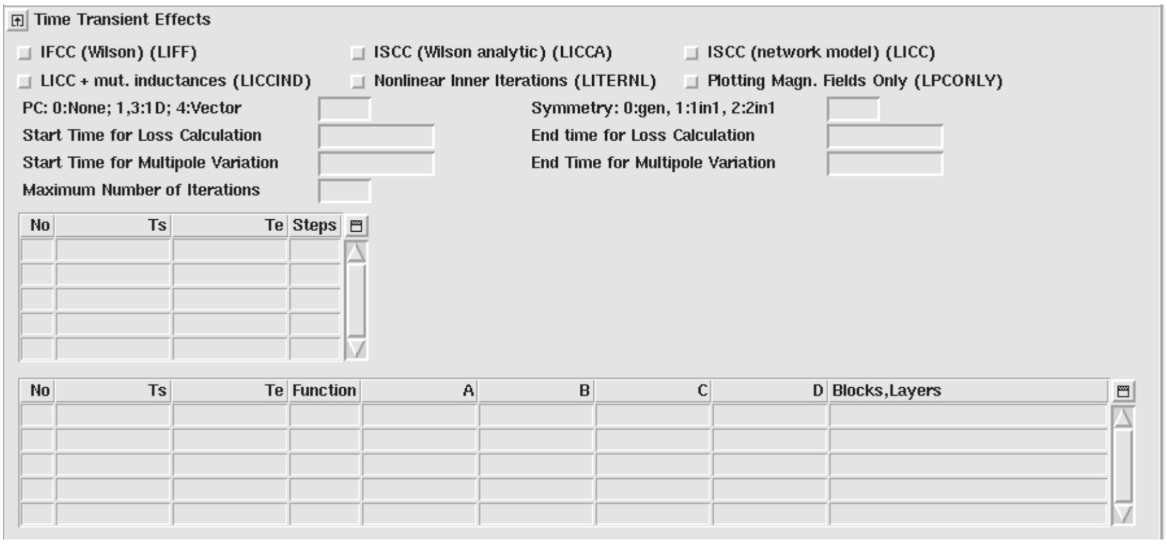


TRANSFER FUNCTION

Line of current factors each of which represents one step in a transfer function. Only available if the "Transfer Function"-option in the "Main Options" is 'on'.

TIME-TRANSIENT EFFECTS

This widget holds information on the calculation of time-transient effects in superconductive material (persistent currents, ...). Only available if the "Time Transients"-option in the "Main Options" is 'on'.



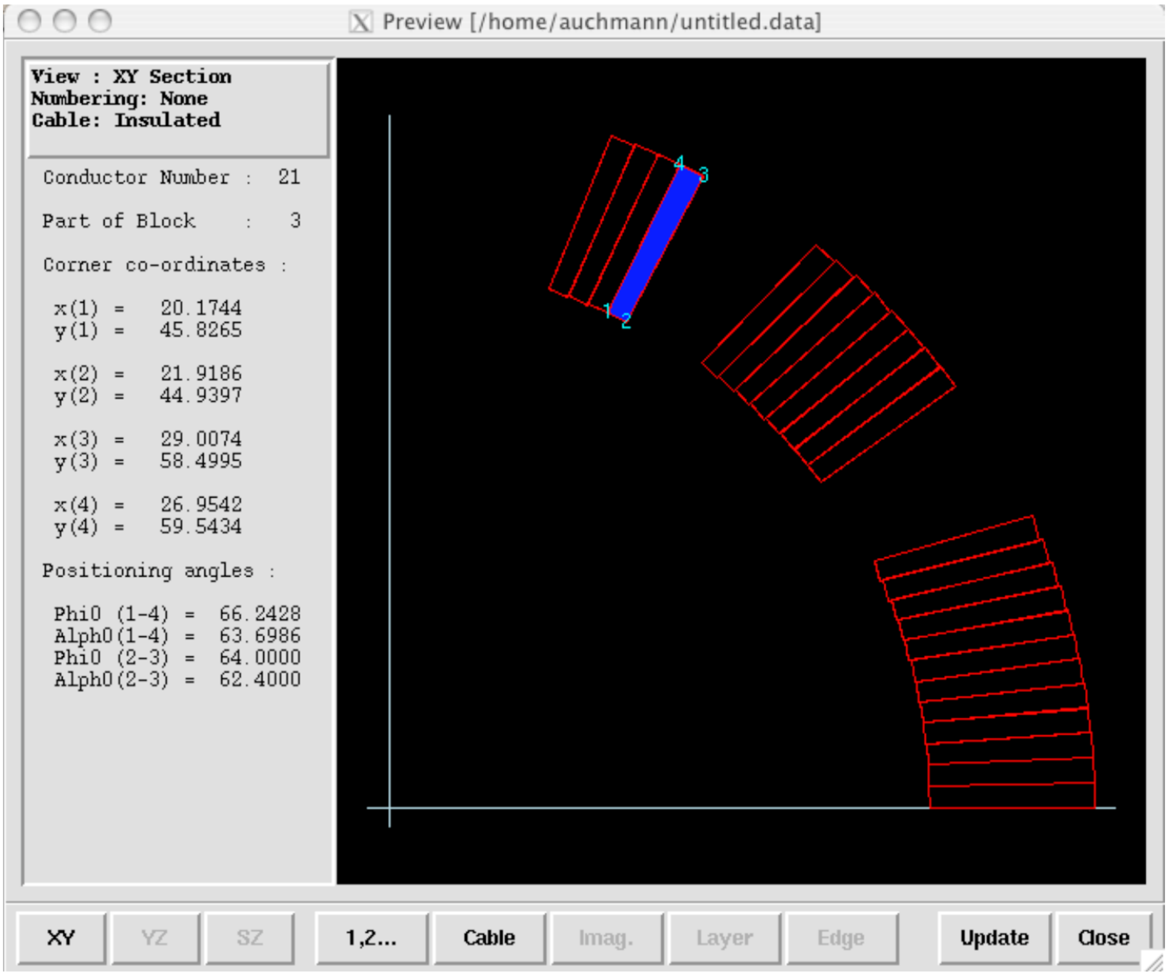
The preview window

It is possible to preview the geometry of the coil being editted in the form by selecting the menu option 'Run | Open preview window'. If there are no errors in the definition of the input file then a new window will be opened displaying a cross-sectional image of the coil as in the following screen grab. This display is controlled by the following buttons to be found at the bottom of the window:

- **XY** will display the coil's 2-D cross-sectional view in the X-Y plane.
- **YZ** will display the coil end's cross-sectional view in the Y-Z plane. This button will be unavailable if no coil end is defined (LEND is switched off).
- **SZ** will display the coil end's developed view in the S-Z plane. This button will be unavailable if no coil end is defined (LEND is switched off). The cable type will automatically revery to being 'bare' when this view is chosen.
- **1,2...** will cycle between showing no numbering, showing block numbering, and showing cable numbering on the image.
- **Cable** will toggle between displaying the cable bare or insulated.
- **Imag.** will cycle between showing all blocks, non-imaged blocks, and imaghed blocks in the YZ view. For use when two sets of image blocks are being connected at the coil ends and not available if no imaged blocks are specified.
- **Layer** will cycle through the different layers of the coil on the SZ view. For each layer the outer (34) edges will be shown in the top half of the image and the lower (12) edges will be shown in the bottom half.
- **Edge** will toggle between showing the inner (12) and outer (34) edges of the coil in the SZ view. Only of use if one layer is defined and is used when two sets of image blocks are being connected at the coil ends.
- **Update** will update the images according to the current state of the Xroxie form. This button will need to be used if the Xroxie form is modified or a new form is loaded.
- **Close** will close the preview window.

In the XY and YZ sectional views geometric information for a conductor can be obtained by moving the mouse cursor over it. The conductor will be highlighted and various geometric information will be displayed in the box to the left of the image, depending on whether the conductor is displayed as a bare or insulated cable. In addition, by dragging a rectangle over the image using the mouse it is possible to zoom in on a particular area of the coil. To re-instate the full view click on the **XY**,**YZ** or **SZ** as appropriate. It should be noted that the ROXIE program is called to perform the calculations required to create these images and this has several implications:

- The paths to the ROXIE executable and data file should be correctly set under the menu option 'Run | Set paths'.
- All relevant data required in the form to create a correct input data file must be present, even if not required to produce the geometry calculations. For instance, there should be no blank cells on the form. If ROXIE detects any errors with the form when trying to run then these errors will be reported directly to the user via a dialog window.
- If a non-zero contraction factor is specified in the "Global Information" widget, the numerical x- and y-values in the preview window will be adjusted by the factor.



The coil-geometry preview window.

1.1.2 Menu descriptions

File menu

- **Clear form** clears all data from the form, resets all options except those which are intended to be true by default, and re-titles the form as 'untitled.data'. If the existing form has been changed and not saved then the user will given the option to save the form before continuing.
- **Open form ...** displays a dialog box requesting a new data file from the user to be loaded into Xroxie. If the existing form has been changed and not saved then the user will given the option to save the form before continuing. Upon loading the new form Xroxie will perform a series of checks for invalid data. If a discrepancy is found then a dialog box will pop up describing the problem(s). The user can then choose to ignore the problem and if necessary correct the file in Xroxie, or start up a text editor and fix the file 'by hand'. This will be necessary when data is missing from the file.
- **Save form** saves the current form in place of its existing file under the same name. If data is found to be invalid or missing from the form a warning is given and the save aborted. Any old version of the file is saved under the existing filename followed by a tilde(\~) character.
- **Save form as...** displays a dialog box requesting a new filename under which to save the current form, retitles the form and saves it under the new name. If a file exists with the given name a warning is given before it is overwritten. If data is found to be invalid or missing from the form a warning is given and the save aborted.
- **Save Templates file...** saves an option sub-set to a file on disk to allow rapid setting of large sets of options on ROXIE input files.
- **Load Templates file...** overlays a new sub-set of options over the existing option set up. The template must first have been created using the `Save Templates file...` menu option.

- **Print form** prints the form out in the format of the saved data file. See menu item 'Run|Set Paths...' to choose which printer should be used.
- **Exit** closes down Xroxie. If the existing form has been changed and not saved then the user will given the option to save the form before continuing.

Display menu

- **View form as text** will withdraw the Xroxie window and display the form within the text editor specified under 'Run|Set paths...'. This facility has been provided so that existing users of ROXIE, who are used to the textual input format, may view the form using the native ROXIE format. NOTE: It has not been intended for the file to be editted using the viewer. As Xroxie and the viewer work on separate copies of the file, any editting done in the viewer will have to be saved and then re-loaded into Xroxie for the changes to be seen.
- **Maximize all sections** will expand all the roll-up sections of the form that are currently minimized, thus displaying the complete details of the form.
- **Minimize all sections** will roll up all the sections of the form that are currently maximized, thus displaying only the headers for each section.
- **Autofit all tables** will resize ALL the tables in the form, whether displayed or not, to the exact amount of rows required for the data in each table.

Run menu

- **Run ROXIE**. Runs the ROXIE program.
- **Open cable data window**. Editting the 'roxie.madata' file.
- **Open preview window**. Previewing the coil geometry.
- **View calculations**. Views the calculations file from the last ROXIE run associated with the input file being editted.
- **View postscripts**. Views the postscripts file from the last ROXIE run associated with the input file being editted.
- **Print calculations**. Prints the calculations file from the last ROXIE run associated with the input file being editted.
- **Print postscripts**. Prints the postscripts file from the last ROXIE run associated with the input file being editted.
- **Set paths...** is used to set paths to various programs and files that Xroxie needs to function correctly. When run for the first time Xroxie will create a file in the users home directory called .xroxiepath. This file retains the paths set by the user. To re-inisiate the default settings for Xroxie this file can be deleted.

1.2 How to use the tables

Various sections of the Xroxie form use tables, similar to the one pictured above, for the entry of arrays of data. The following points should be observed when using these tables:

- The tables have no maximum length and grow as entries are added. As different installations of ROXIE set varying limits on the size of arrays that can be entered, Xroxie does not check to see if these limits have been exceeded.
- When entering data into the table do not leave blank lines between lines of data. Xroxie looks for the last row containing entries to decide how many rows are specified when creating a ROXIE input file, and will interpret intermediate blank lines as missing data.

Navigating and editting tables

Below is a list of the most important editing facilities offered by the Xroxie tables. Where the mouse action refers to the 'Menu', the button at the top right of the relevant table should be clicked. This will reveal a menu from which the appropriate choice can be made.

Input method	**Keyboard**	**Mouse**	**Input form**	**Cable**
To perform action				
Move to previous cell	<Shift-Enter>		**X**	**X**
Move to next cell	<Enter>		**X**	**X**
Move to cell above	<Up Arrow>		**X**	**X**
Move to cell below	<Down Arrow>		**X**	**X**
Insert blank line into table	<Ctrl-O>		**X**	**X**
Cut row into table's clipboard	<Ctrl-W>		**X**	**X**
Copy row into table's clipboard	<Ctrl-C>		**X**	**X**
Insert table's clipboard before row	<Ctrl-Y>		**X**	**X**
Duplicate multiple lines	<Ctrl-D>	Menu		
Delete multiple lines		Menu		
Show more rows on table *	<Ctrl-Down>	Menu		
Show fewer rows on table *	<Ctrl-Up>	Menu		
Find and replace	<Ctrl-F>	Menu	**X**	**X**
Renumber first column	<Ctrl-R>	Menu	**X**	
Sort **	<Ctrl-S>	Menu	**X**	**X**
Help on column	<Shift-F1>	Click in header	**X**	**X**
Move to beginning of entry	<Ctrl-Home>		**X**	**X**
Move to end of entry	<Ctrl-End>		**X**	**X**
Delete entry	<Ctrl-/>, \<Delete>		**X**	**X**
Show geometry columns ***	<Ctrl-F1>	Menu		
Show property columns ***	<Ctrl-F2>	Menu		
Show description ***	<Ctrl-F3>	Menu		

* When using the 'Duplicate multiple lines' option the line numbers to be entered should be the logical row numbers of the table, these are NOT necessarily the same as the numbers listed in column one of the table. Choosing the renumber option will ensure that the numbering in this column and the table row numbering are the same.

** To show more or less rows for the cable table the window containing the table should be resized.

*** Sorting for tables in the input form is automatically performed on the first column of the table. However, for the cable form sorting may be done on any field. If the \<Ctrl-S> keyboard accelerator is used sorting will be done on the column that holds the input focus.

**** When paging the table for the conductor information using Ctrl-F1, F2 & F3 the keyboard focus must be in the 'Material' column.

1.3 Running the ROXIE program

Once the form has been completed, the ROXIE program can be run without leaving the Xroxie enviroment. To do this select the menu option 'Run | Run ROXIE'. Providing all the settings in the 'Run|Set Paths...' menu option are correct and the ROXIE support files are available the ROXIE program should run over the file seamlessly in a new Xroxie window. A display of execution time is shown at the bottom of the window.

To abort a run prematurely press the `Abort` button. This will cause an interuption in the ROXIE RUN. (/em Note: This should take effect immediatly but at present there is a bug which causes Xroxie to wait until the next output from ROXIE before aborting).

Once ROXIE has finished the `Abort` button will change to `CLose` and there will be a message at the bottom of the screen. If this reports an error then there was a problem:

- A) With the set up of Xroxie or the settings in the 'Run|Set paths...' m,enu option.
- B) A problem with the input file, in which case the ROXIE output will show a dragon symbol.
- C) An abnormal abortion of the ROXIE command or the runroxie script.

2. Mathematical Optimization

2.1 Optimization

The ROXIE program was developed from the onset with mathematical optimization techniques in mind. This is reflected in the structure of the input files which allows, after the definition of the nominal geometry, to address any input data as a design variable of the optimization. The data structure also allows to define basically all computed data (and the design variables) as objectives for the optimization. The program structure is also reflected in the graphical user interface with its tables for design variables and objective function definition.

After many years of development many elements have found their way into the "Design Variables" which are mere transformations or input parameters for certain algorithms. In the same way post-processing options have found their way into to the "Objectives"-table. The user will quickly get used to the concept. It has, after all, allowed ROXIE to remain almost completely downward compatible to its previous versions as additional design variable or objectives do not alter the format of the .data-file.

2.1.1 Main options

Option	Description
Optimization	Indicate that ROXIE should perform an optimization run.

2.1.2 Design variables

The "Design Variables"-table has the following columns.

Variable	Description
No	Row number.
Xl	Lower bound.
Xu	Upper bound.
Xs	Start value.
String	Design parameter/transformation parameter.
Layer/Block/Cond./Strand	Number of blocks/layers/conductors/strands.

During an optimization run, the design parameter is varied between Xl (lower) and Xu (upper), starting with Xs (start). To keep downward compatibility of the code, design variables can be "abused" for transformations or just as additional input parameters for subroutines and algorithms. In this case we set Xl=Xu=Xs. These data have to be grouped to the end of the design variable block. Design variables are parsed at every ROXIE run and the Xs values are always applied - even if no optimization has been chosen.

- **Transformations**, i.e., Xl=Xu=Xs need to be grouped at the end of the table.
- In the "**Layer/Block/Cond./Strand**" field we enter space-separated integer numbers. The following format is allowed: `1 4 7-9 10` The "`n-m`"-entry is stored as "`n (n+1) (n+2) ... (m-1) m`". Note that per line no more than 20 layers, blocks, conductors or strands are stored.

Optimization:

Three options in this menu consider the neural-networks approximator for the EXTREM-optimization algorithm, see the "Extrem with ANN Approximator"-option above. The neural network is implemented in ROXIE but fragile.

Variable	Description
STEPS	Number of steps for parametric study, compare the "Parametric Study"-option above.
NNEUR	Number of neurons for Radial Basis Function (default: 30) for Neural Network.
SSTAT	Threshold of S statistics (default: 1.3) for Neural Network.
NMLE	Threshold of NMLE (default: 0.0005) for Neural Network.

2.1.3 Global information

Optimization algorithm

Option	Description
none	Do not optimize.
Extrem	Deterministic optimization algorithm.
Quasi-Newton DFP	Quasi-Newton- or Davidon-Fletcher-Powell algorithm.
Parametric Study	Variation of design variables within bounds without optimization. The number of steps is given in the STEPS-variable from the "Optimization"-menu of the "Design Variables". The results of a sequence of ROXIE runs are written to the .output-file.
Sensitivity Analysis	Determine sensitivity of the objectives with respect to tolerances in the design variables.
Levenberg-Marquard	Compromise between Newton's Method and the Method of Steepest Descent.
Lagrange Multiplier Estimation	Determination of the Lagrange-Multipliers in the optimality condition given by the Kuhn-Tucker equations.
Mutual Inductances in Non-Linear Circuits	Determination of the non-linear (differential) mutual inductances between layers.
Blocks Individually Powered	All blocks are powered successively, while the other blocks have zero current. Method to determine the impact of one block on the field quality. Today replaced by the Bn-options in the Bn Strand Contribution of I-menu of the "Plotting Information 2-D", see Section 6.1.
Random Multipole Error	Determine the mean-value and the standard-deviation of the multipole-components due to random changes of design parameters. Evaluate the Taguchi Function.
Genetic Algorithm	Use ROXIE's genetic algorithm for optimization.
Extrem with ANN Approximator	Use a neural network to accelerate the Extrem algorithm. This option is implemented but fragile.

- The "**Genetic Algorithm**"-option does not allow to produce post-scripts during an optimization run. To take a look at the various families of designs, use the "Scan Through .scan-File"-option from the "Interface Options".

2.1.4 Objectives

The "Objectives"-table has the following columns.

Variable	Description
Ne	Row number.
String	Right-click in a field of this column gives a list of objectives for optimization or plotting.
Nor	Specifies the objective, e.g., gives the order of the harmonic or the number of a strand/conductor.
Oper	Operand in the objective function or PLOT-operand. Right-click to get a list of operands.
Constr./Plot	If the operand in the objective function constitutes a constraint, then the value of the constraint is put here. With the PLOT-operand, the field gives the page number onto which the plot is to be drawn.
Weight	The weighting factor for the objective. Also used with the PLOT-operand.

- In order to **plot graphs** with the PLOT-operand, the "Postscript Plots"-option must be switched 'on'.
- Whether or not the "Postscript Plots"-option is 'on', any optimization run produces a .post-file that contains **two plots**: The first plot shows the convergence behavior of the global objective function. The second plot gives the individual weighted objectives and their convergence.

The "Operand"-column yields a choice of operands.

Operand	Description
MIN	Minimize the objective l, min(l).
MAX	Maximize the objective l, max(l).
MIN2	Minimize the square of the objective l, $\mathrm{min}\left(l^2\right)$.
MAX2	Maximize the square of the objective l, $\mathrm{max}\left(l^2\right)$.
MINI2	Minimize the square of the inverse of the objective l, $\mathrm{min}\left(\frac{1}{l^2}\right)$.
MAXI2	Maximize the square of the inverse of the objective l, $\mathrm{max}\left(\frac{1}{l^2}\right)$.
MINABS	Minimize the modulus of the objective l, $\mathrm{min}\left(
MAXABS	Maximize the modulus of the objective l, $\mathrm{max}\left(
<	'Lower-than' constraint, $l<c$, with the upper bound c given in the "Constraint/Plot"-column.
>	'Greater-than' constraint, $l>c$, with the lower bound c given in the "Constraint/Plot"-column.
=1	'Equals' constraint, $l{!\atop =}c$, with the constraint c given in the "Constraint/Plot"-column. A linear (modulus) penalty is applied.
=2	'Equals' constraint, $l{!\atop =}c$, with the constraint c given in the "Constraint/Plot"-column. A quadratic penalty is applied.
PLOT	Plot the objective during the optimization. The page on which to plot is given in the "Constraint/Plot"-column. Multiple plotting onto one graph is possible. The weights of the "Weight"-column are applied for the plotting.

- As a general rule the quadratic operators **MIN2, MAX2, =2** yield faster convergence if the start-set of design variables is far from the optimum solution. The 'modulus'-operators **MINABS, MAXABS, =1** give better results for fine-tuning, when the start value is already a rather good design.

Global values:

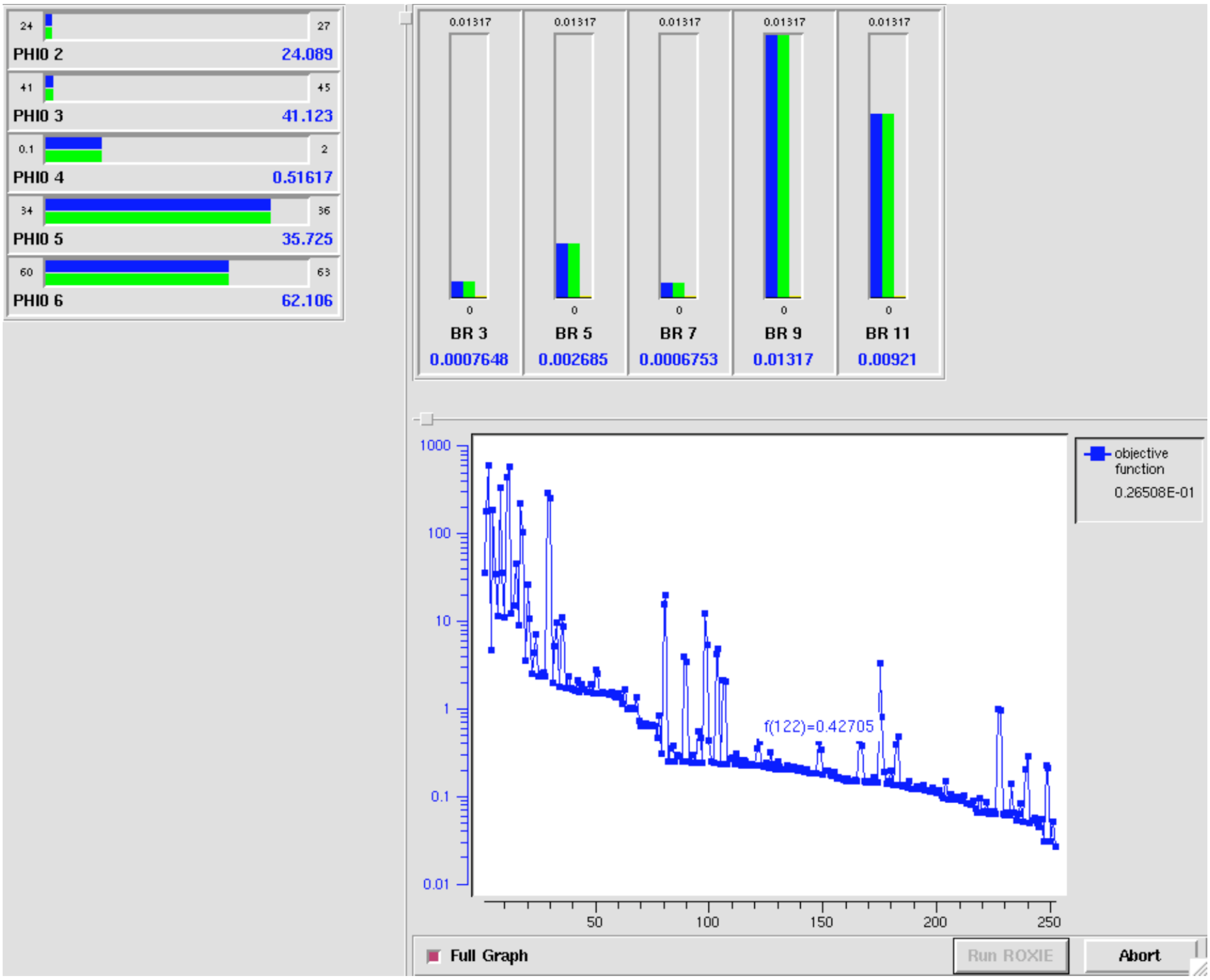
Variable	Description
NORM2X	L2-norm of the design variable vector.
NORM1X	L1-norm of the design variable vector.

2.1.5 Interface options

Option	Description
Scan Through .scan-File	The "Genetic Algorithm"-option in the "Optimization Algorithm"-variable of the "Global Information" produces a .scan-file with all design information of the different families of results. This option calls each design so it can be post-processed.
Cockpit-Software Output	Create a log-file to be read by the Tcl/Tk cockpit software for optimization, see Section The optimization cockpit

2.1.6 The optimization cockpit

The cockpit software for optimization with ROXIE is started from the "Run"-menu. It can only be started with the "Optimization"-option in the "Main Options" and the "Cockpit Software output"-option in the "Interface Options" switched 'on'. An optimization run can then be started from the cockpit window and the design variables as well as the weighted objectives can be viewed online during optimization, see Fig. below. The main graph shows the convergence of the objective function. Moving the mouse cursor above the graph shows the individual function values obtained during optimization.



The cockpit window of ROXIE during an optimization run. Upper left: Design variables between lower and upper bounds. Upper right: Objectives between the absolute maximum and minimum values obtained during the optimization run. Lower right: Convergence of the objective function.

To use the cockpit window the following Tcl/Tk environment is recommended:

Utility	Recommended Version
Tcl	8.4.9
Tk	8.4.9
BLT	2.4
BWidget	1.7

All required software can be found on the internet, e.g., on http://www.sourceforge.net. Be aware that the BLT-toolkit does not work with the more recent version of Tcl/Tk 8.4.11!

2.2 Optimization with genetic algorithms

The genetic optimization routines in ROXIE are set up to handle bit-strings with about 60 bits. In order to use the algorithm, the optimization routines have to be enabled (LALGO=.true.) and the graphics output has to be disabled. Easy adaptation of pre-defined optimization parameters is foreseen. The genetic algorithm requires the number of bits for the discretization of each design variable. This parameter has to be entered in the column Xs of the design variable block instead of a start value, which is not needed in global optimization.

Genetic algorithms also allow for integer design variables. The only integer variables accessible to the ROXIE user are NUMCBL and those defined by the user in the .iron files. NUMCBL defines the number of conductors in each coil block. It is recommended to use discretization which correspond to the range of the integer variable. For a discretization by 2 bits for instance, 2^2 different numbers of conductors can be generated. Choosing a bit string of length three, a coil block of 3, 4, 5, or 6 conductors can be chosen in the optimization. Therefore a range of 3 (Xa) to 6 (Xe) should be used in the setup. If the number of possible conductors is not dividable by the number of discretizations, the resulting non-integers are truncated in the optimization process.

2.2.1 Optimizing iron distributions

Currently the only design variable specified in the .iron file which can be addressed in the optimization is the material property. Instead of the BH-specifier (BH_air, and BHiron1 etc.) an integer variable may be used. The value 0 is equivalent to BH_air and all natural numbers are interpreted as the corresponding BHiron material. This definition allows for switching material regions from iron to air and for changes in the filling factor. For the latter case a list of material definitions has to be defined with appropriate filling factors in the roxie.bhdata file.

2.2.2 Definition of the objective function

In order to achieve good results the sensitivity of all design variables should be similar. The optimization interval should be set such that impossible or infeasible structures are avoided. Often, infeasible structures can be avoided by geometrical considerations.

2.2.3 Optimization parameters

The performance of the genetic algorithm can be influenced by an additional file named roxie.gadata. This file has to be created in the same directory as the .data file before starting the run. An example of a roxie.gadata file is given below:

```
60     ! Size of population
0.05   ! Rate of generation in percent
0.15   ! Rate of mutation in percent per iteration
6000   ! Number of iterations
```

Each number has to appear on a separate line. The comments on each line are optional. If the roxie.gadata file does not exist, default parameters are generated:

```
popsize = BIT_SIZE(child)
genrate = 0.05
mutrate = 0.0025*BIT_SIZE(child)
iterate = 100*BIT_SIZE(child)
```

2.2.4 Logging intermediate results

In order to avoid that results are lost in long genetic algorithm runs, a file roxie.gasafe is updated about every 2000 evaluations. The file has to be created before the first run, e.g., by typing 'touch roxie.gasafe'. In case of a stop, ROXIE can be re-started with the backup file. The optimization then continues from the last saved state. Each complete re-start of the genetic algorithm usually creates a new parameter set and therefore a new start population. The results of the optimization may therefore differ, since they depend on the original population. The niches found in each run, however, should be similar. A second local optimization stage may help in discriminating between distinct niches.

2.2.5 Post-processing

Evaluation of the optimization output can be done by reading the datasets from the scan-file. The scan-file contains the best 20 results of about every 2000th evaluation.

3. Graphical Output

ROXIE provides graphical output based on the CERN program library HIGZ (High level Interface to Graphics and Zebra) and thus postscript plots are produced without the use of external post-processing packages. A shortcoming of this technique is, however, that all output graphics has to be defined before the ROXIE run is launched.

3.1 General plot options

The option "Postscript Plot" in the "Main options" as well as options in the headers of the "Plotting Information 2-D/3-D"-widgets apply to a variety of different field plots. These general options are explained here, whereas the different field plots are documented in the respective chapters to follow.

3.1.1 Main options

Option	Description
Postscript Plots	Use the "Plotting Information 2-D/3-D"-widgets to generate field plots.

Note that graphs that are defined in the "Objectives"-widget are also printed to the postscript files, provided the "Postscript Plots"-option is switched 'on'.

3.1.2 Plotting information 2-D

Option	Description
Coordinate Axes	Plot coordinate axes.
Legend	Plot the Legend.
Image Iron at X-Axis	Image mesh-based plots at the x-Axis.
Image Iron at Y-Axis	Image mesh-based plots at the y-Axis.
Area Boundary Plot	Plot the boundaries of areas in the .iron-file with bold line.
Poly-Marker	Plot markers at every data point in a graph-plot that is defined in the "Objectives"-table.
More Plot Options	Extend the plotting table by more options.

The "Plot Information 2-D"-table has the following columns (including the additional options with "More Plot Options").

Variables	Description
No	Number of postscript plot.
X-Axis	Plot range in +x-direction.
Color	'Y': colour plot, 'N': Black and White.
4quad	'Y': plot all 4 quadrants, 'N': plot first quadrant only.
Fmin	Plot range of field values: min-value in the legend.
Fmax	Plot range of field values: max-value in the legend.
X-Shift	Shift the plot by this value in x-direction.
Y-Shift	Shift the plot by this value in y-direction.
Vmax	Plot only vectors up to this value (modulus). This option is used to cut off unphysical singularities in field matrix calculations.
V-scale	Scale the vectors in a field matrix plot.
Coll	Not yet documented/available.
Time	Not yet documented/available.
Field	Select a field to plot.

- Note that the **Vmax** value needs to be scaled down by the "V-scale" value: If we want to cut off all arrows larger that 4 T, and we have a "V-scale" value of 2, then the "Vmax" must be set to 2.

The fields and forces which can be displayed are documented in the respective chapters of this documentation.

3.1.3 Plotting information 3-D

As the design optimization processes of accelerator magnets is well established, it is convenient to define the plotting information before a ROXIE run, which thus avoids the launching of an external post-processor.

Option	Description
Plot Imaged at z=0 Plane	Image iron and coil at z=0.
Display of Cut-Planes	A 3-D plot is built of plane rectangles or triangles. This option highlights the edges of those elements with a thin, white line.
3-D Min Field in Conductor	See Section 3-D Analytical Field Calculation.
3-D Max Field in Conductor	See Section 3-D Analytical Field Calculation.
No Shift of Plot Center	If we use "3-D Transforms" in the "Design Variables"-table, parts of the plot in $-z$-direction might be out of the plot-range. Click this option and adjust the "Z-axis"-entry in the "Plot Information 3-D"-table to overcome the problem.
Plot of Coordinate System	Plot 3-D coordinate frame.

The "Plot Information 3-D"-table has the following columns.

Variables	Description
No	Number of postscript plot.
Z-axis	Size of plot in z-direction in mm.
Colour	'Y': colour plot, 'N': Black and White.
360deg	'Y': plot all 4 quadrants, 'N': plot first quadrant only. (Quadrants are seen in the xy-plane when looking in +z-direction.)
View	Choose between different viewpoints.
Layer	Choose between 0: all layers, 1: inner layer, and 2: outer layer.
Field	Select a field to plot.

The fields that can be plotted are documented in the respective chapters of this documentation.

- Note that ROXIE assigns the attribute of inner or outer layer by an input in the "Global Information 3-D"-widget called "**Number of Blocks in Outer Layer**" with integer input N. The first N blocks are assigned to the outer layer. This option can only be used with the "Symmetric Coil"-option in the "Main Options". The "Layer Definition"-option generally does not work due to the numbering of all blocks which is incompatible with this division in inner and outer layer.

4. Superconducting Wire and Cable Properties

In ROXIE there are two files for supderconducting wire and cable data. The older one is the roxie.madata-file. With the introduction of time-transient effects in superconductors, the cable-specific information provided in the roxie.madata-file was no longer sufficient. The roxie.cadata-file was thus introduced with a modular feature-based structure.

4.1 MADATA file

The MAterial DATA file is a database for the definition of the geometrical and superconducting properties of wires and cables. The roxie.madata-file can be edited from the Xroxie window by choosing "Open material data window (roxie.madata)" from the "Run"-menu.

The data is organized in five lines. Line one yields a "comment" in single inverted commas. Line two gives the material- (conductor-) name. Line three has geometrical data of the conductor, line four gives data of the superconducting strands in the conductor and line five yields information on the linear approximation of the critical surface around a reference working-point. A data block has the following layout:

`'COMMENT'`

`'MATERIAL'`

`HEIGHT , INNER WIDTH , OUTER WIDTH , RADIAL INS. , AZIMUTH INS.`

`NO. STRANDS , DIA OF STRAND , CU/SC RATIO , CABLING ANGLE`

`TEMP , BCREF , JC/BCREF , DJC/DB`

The data entries in lines 3-5 are not actually comma- but space-delimitted. There is a TCL/TK graphical user interface to edit the roxie.madata-file. For legacy-reasons the GUI, however, only displays data up to the DIA OF STRAND-entry. For SC-related data the user needs to edit the roxie.madata-file in an editor.

4.2 CADATA file

The CAble-DATA file stores information on different cable types, mostly but not exclusively, Rutherford-type superconducting cables. The roxie.cadata-file has been created as a replacement for the roxie.madata-file. The new file format holds more information than the roxie.madata-file in a structured way by the definition of "features". As a consequence, calculations that require additional input data, e.g., time-transient effects in SC cables, can only be performed if the conductor has an entry in the roxie.cadata-file. Double-entries in roxie.madata- and roxie.cadata-files are handled by giving priority to the roxie.cadata-entry. The roxie.cadata-file can be edited in a GUI that is opened by selecting "Open cable data window (roxie.cadata)" from the "Run" menu in Xroxie.

The roxie.cadata-file is organized in blocks. The idea behind the roxie.cadata-file is to create a modular database in which, e.g., several conductors can use the same insulation data or critical surface fit. The final definition of a conductor consists of an identification of insulation-type, cable-type, etc. by their (user-defined) names rather than by specifying all input-data for each conductor.

The roxie.cadata-file can be edited by selecting the "Open cable data window (roxie.cadata)"-item from the "Run"-menu.

Each block (INSUL, REMFIT, FILAMENT, STRAND, TRANSIENT, CABLE, CONDUCTOR) in the roxie.cadata-file starts with a new line `BLOCK_NAME X` where `X` is the a number of lines to follow. Then follows the data table, ended by a comment line where the variable (feature) names are defined.

4.2.1 INSUL block

The INSUL-block contains data on the conductor insulation. Each row contains the following data:

Variable	Type	Description
No	Integer	Row number.
Name	String	Insulation name.
Radial	Double	Radial insulation.
Azimut	Double	Azimuthal insulation.
Comment	String	Comment in single inverted commas.

4.2.2 REMFIT block

The REMFIT-block contains data on the critical surface fit for the superconductor. REM stands for 'remanent magnetization'. Each row of the table contains the following data:

Variable	Type	Description
No	Integer	Row number.
Name	String	FIT name.
Type	Integer	Type of FIT.
DJSC	Double	FIT parameter 1.
T_C0	Double	FIT parameter 2.
Alpha	Double	FIT parameter 3.
Beta	Double	FIT parameter 4.
Gamma	Double	FIT parameter 5.
C0	Double	FIT parameter 6.
BC20	Double	FIT parameter 7.
Comment	String	Comment in single inverted commas.

4.2.3 FILAMENT block

The FILAMENT-block contains data on SC filaments. Each row yields the following data:

Variable	Type	Description
No	Integer	Row number.
Name	String	Filament name.
fildiao	Double	Outer diameter of the filament [mum].
fildiai	Double	Inner diameter of the filament (e.g., fil. with copper core) [μm].
*fit		*
*fit perp *	String	Name of the critical surface fit for orthogonal direction 2.
Comment	String	Comment in single inverted commas.

- Two different fits are foreseen for **anisotropic persistent current** calculations. This is not yet implemented. For the time being both values should be the same. The fit names have to be names specified in the REMFIT block.

4.2.4 STRAND block

The STRAND-block contains data on the SC strands. Each row yields the following data:

Variable	Type	Description
No	Integer	Row number.
Name	String	Strand name.
diam.	Double	Strand diameter [mm].
cu/sc	Double	Copper to superconductor ratio.
RRR	Double	Triple-R value.
Tref	Double	Reference temperature [K].
Bref	Double	Reference B-field [T].
Jc(BrTr)	Double	Critical current density [MA/m^2].
dJc/dB	Double	Slope of critical surface with respect to B.
Comment	String	Comment in single inverted commas.

- The last four entries define a **linear approximation of the critical surface** around a working point. This data is used for the calculation of the position on the load line which is automatically performed when the "**Peak Field in Coil**"-option in the "Global Information"-widget is switched 'on'. Historically, this is an older piece of code. For the new version of quench-margin calculations the "**Quench and Temp. margin**"-option in the "Global Information"-widget must be switched 'on'. This option uses the critical surface fit defined in the REMFIT-block.
- The reference temperature of the working-point approximation is not used for the "**Quench and Temp. margin**"-option in the "Global Information"-widget. This option uses the "T_0"-entry in the CONDUCTOR block instead.

4.2.5 TRANSIENT block

The TRANSIENT-block contains data on the material properties for time-transient effects. Each row yields the following data:

Variable	Type	Description
No	Integer	Row number.
Name	String	Transient parameter-set name.
Rc	Double	Crossover resistance [Ω].
Ra	Double	Adjacent resistance [Ω].
fil.twistp.	Double	Filament twistpitch [m].
fil.R0	Double	Constant part of magneto-resistivity in filament matrix [Ωm].
fil.dR/dB	Double	Linear part of magneto-resistivity in filament matrix [Ωm/T].
strand fill.fac.	Double	Filling factor of SC-material in strand.
Comment	String	Comment in single inverted commas.

4.2.6 CABLE block

The CABLE-block contains data on the conductor geometry. Each row yields the following data:

Variable	Type	Description
No	Integer	Row number.
Name	String	Cable name.
height	Double	Conductor height [mm].
width_i	Double	Inner width [mm].
width_o	Double	Outer width [mm].
ns	Integer	Number of strands.
transp.	Double	Transposition pitch length [mm].
degrd	Double	Degradation factor. This option is not yet implemented.
Comment	String	Comment in single inverted commas.

- Height and width is not coherently defined for superconducting cables. We denote the two slightly different narrow sides as inner and outer width.

4.2.7 CONDUCTOR block

The CONDUCTOR-block contains data that define the conductor using the features defined in the previous blocks. Valid features can be included by right klicking on the mouse. Each row contains the following data:

Variable	Type	Description
No	Integer	Row number.
Name	String	Conductor name.
Type	Integer	Conductor type.
Cable	String	Cable name.
Strand	String	Strand name.
Filament	String	Filament name.
Insul	String	Insulation name.
Trans	String	Transient data name.
T_0	Double	Working temperature.
Comment	String	Comment in single inverted commas.

5. Coil Modeling

The ROXIE program includes routines for defining the geometry of coil cross-sections made of Rutherford type superconducting cables or rectangular shaped braids. The geometric position of coil-block arrangements in the cross-section of the magnets is calculated from the following input data:

- In case of cos nΘ magnets, the number of blocks, the number of conductors per block, conductor type (specified in a cable data base), radius of the winding mandrel, as well as positioning and inclination angle of the blocks. The grading of the current density is taken into account by a discretization of the cable into N1 * N2 strands, where N1 is the number of strands in the narrow direction, and N2 is the number of strands in the direction of the broad side (2*18 in case of the LHC outer layer dipole cable).
- In case of window frame magnets, the number of blocks, the number of conductors per block, conductor type, x and y position of the lower left corner of the block, and inclination angle with respect to the x-axis.
- In case of beam pipe magnets, the number of blocks, the number of conductors per block, the radius of the winding mandrel, the positioning angle of the first conductor and the increment angle for the subsequent conductors.
- In case of hollow conductors (cable in conduit), the geometry is created as in the cases above. From the cable boundary an inlaying cylindrical conductor with N1 arc segments is generated. The arc segments have an inner radius such that exactly one strand is inscribed within each segment. In the ROXIE input file the parameter N2 has to be set to zero.

5.1 2-D coil modeling

5.1.1 Main options

Option	Description
Symmetric Coil	Make use of a symmetry in the coil geometry modeling.
Layer Definition	Define layers of coil blocks, possibly each with a different symmetry.
Wedge/ Endspacer	Compute the shape of wedges and of the end-spacer in the xy-plane for the plot option WEDGE. The wedges are only calculated correctly with the "Symmetric Coil"-option.

The symmetry- and layer options are described in Section Cosine Theta Cross Section.

5.1.2 Global information

Option	Description
Cond. Alignment OD	'off': align the inner side of the conductors on the winding mandrel; 'on': align the outer side of the conductors on a radius r_\mathrm{out}=r_\mathrm{mandrel}+h_\mathrm{cond.}.
Window Frames	All blocks in the cross-section are defined as for a window frame magnet (rectangular cross-section). The entries in the "Block Data 2-D"-table are read as X/Y/Inc instead of R/\varphi/\alpha.
Single Wires on Mandrel	All blocks in cross-section define single wires on a mandrel, compare Section [Wires on the Mandrel (11_examples_coil_modelling.md#wires-on-the-mandrel).

More relevant data in the "Global Information"-widget:

Variable	Description
Type of Coil/Ref. Field	Define the symmetry type if "Symmetric Coil"-option is 'on'.
Contraction (1 - Fac. Defined)	All data in the "Block Data 2-D"-table with a phys. dimension of a length is contracted by a factor $f_{cont.} = 1 - f_{input}$, $l' = l * f_{cont.}$, thus modeling the effect of cool-down. Entry 0.01 results in a contraction by 1%.

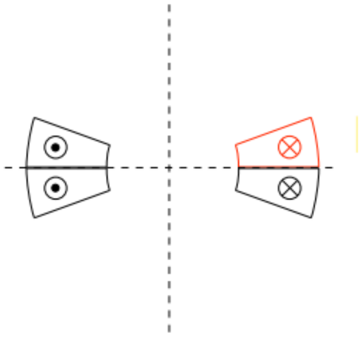
5.1.3 Layers

Only available if the "Layer Definition"-option is switched 'on' in the "Main Options". In the "Layers"-table the user assigns blocks from the "Block Data 2-D"-table to layers and defines symmetry-types of the layers.

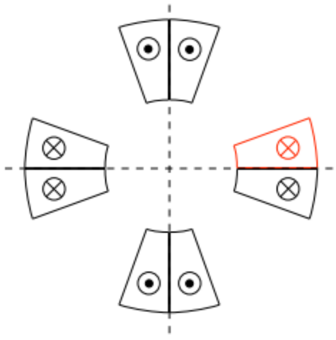
Input	Description
0	No symmetry
2	Dipole
4	Quadrupole
6	Sextupole
8	Octupole
10	Decapole
12	Dodecapole
1	One Dipole Coil
3	One Quadrupole Coil
5	One Sextupole Coil
7	One Octupole Coil
9	One Decapole Coil
11	One Dodecapole Coil
22	Dipole Connection Side
24	Quadrupole Connection Side
26	Sextupole Connection Side
28	Octupole Connection Side
30	Decapole Connection Side
32	Duodecapole Connection Side
31	Window Frame Dipole
41	Solenoid
42	Up-down symmetry (combined function magnet)
52	Dipole, Both Ends in 3-D
54	Quadrupole, Both Ends in 3-D
56	Sextupole, Both Ends in 3-D
58	Octupole, Both Ends in 3-D
60	Decapole, Both Ends in 3-D
62	Duodekapole, Both Ends in 3-D

- No more than 20 blocks can be assigned to a layer per line.

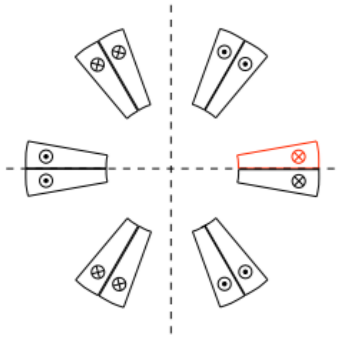
The odd numbers 1-11 define one coil only, which corresponds to one pole of the magnet. The following sketches illustrate the different options. The red block is a block entered in the "Block Data 2D"-table. The black blocks are generated by the "Layer Definition"-option.



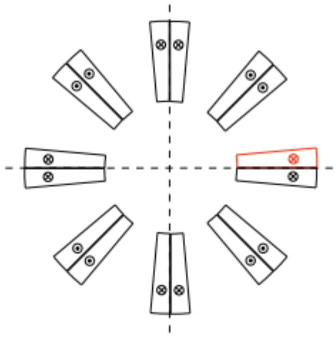
2



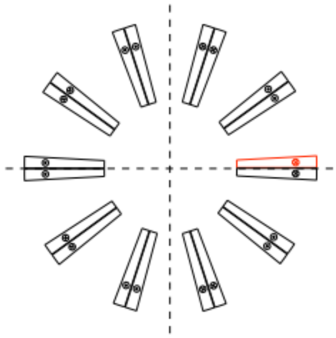
4



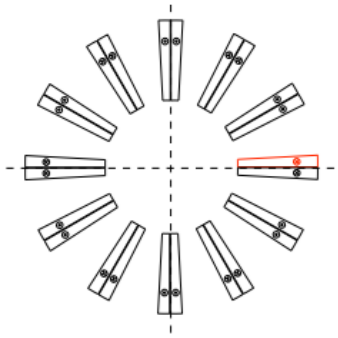
6



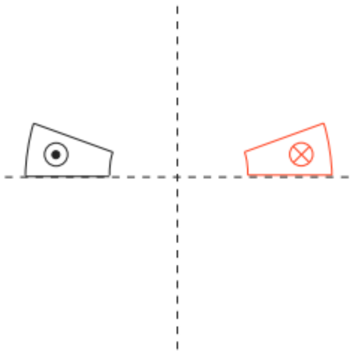
8



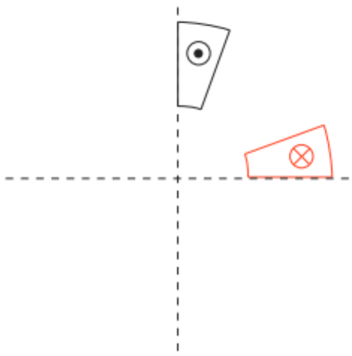
10



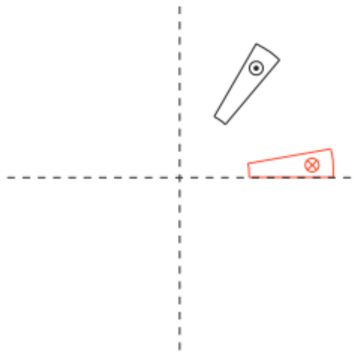
12



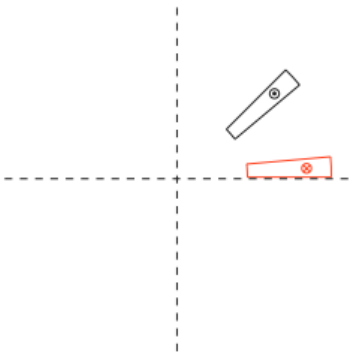
1



3



5



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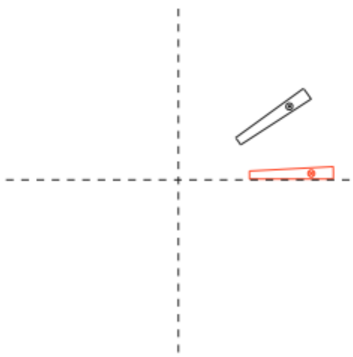

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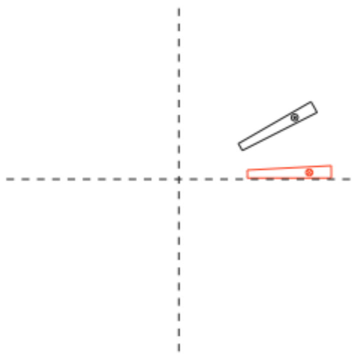

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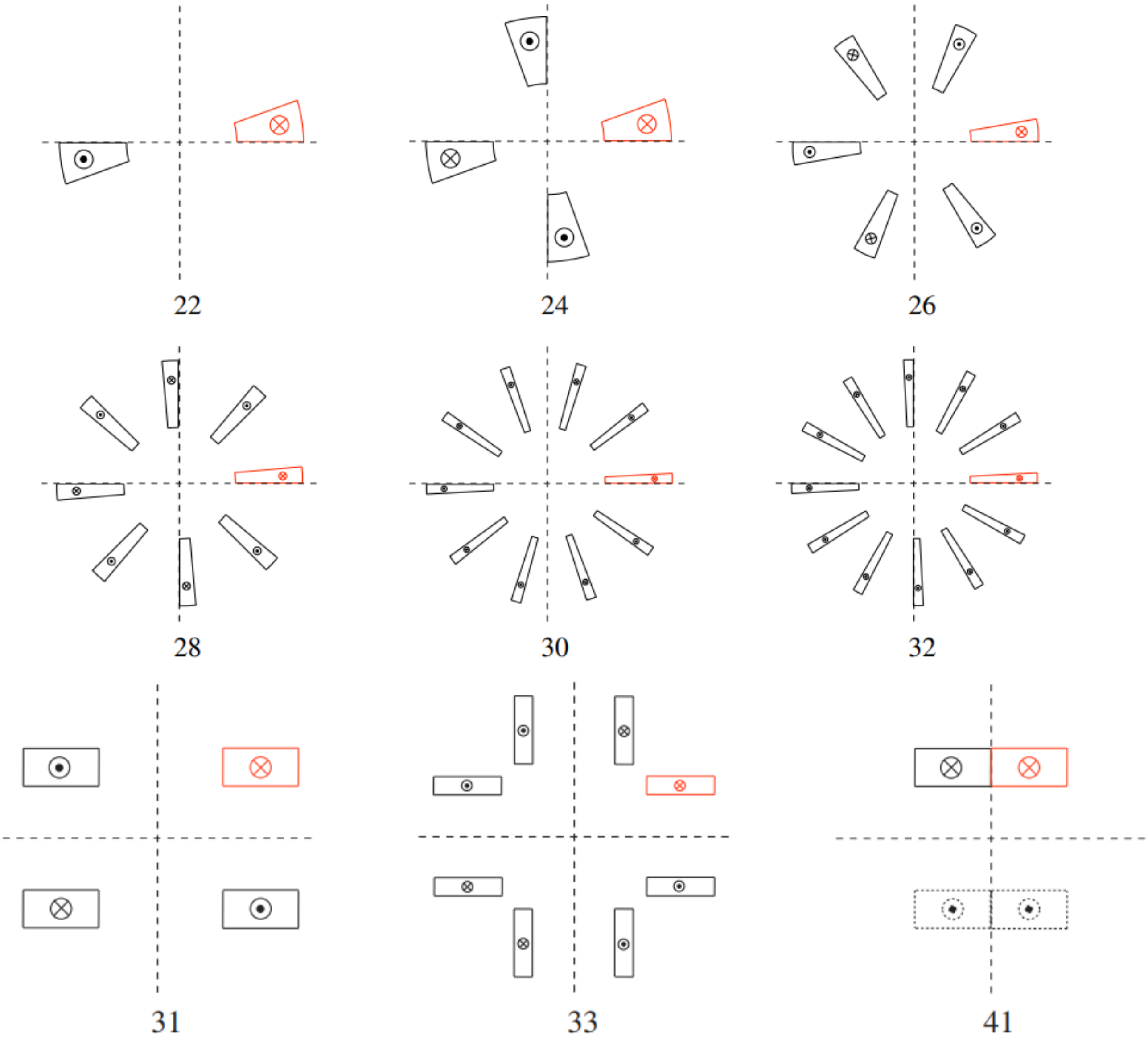
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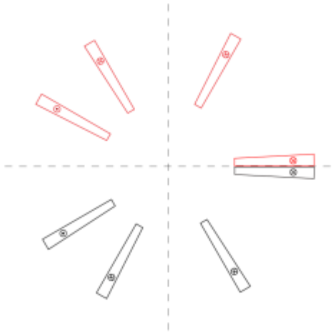
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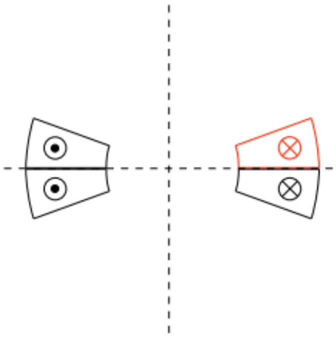
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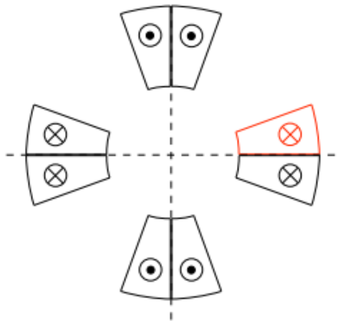
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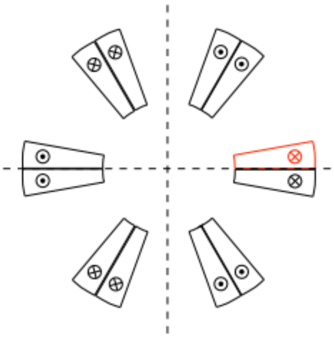
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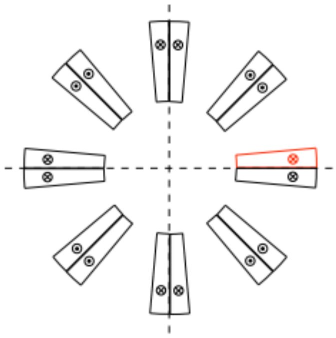
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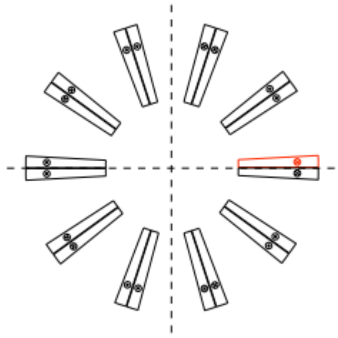
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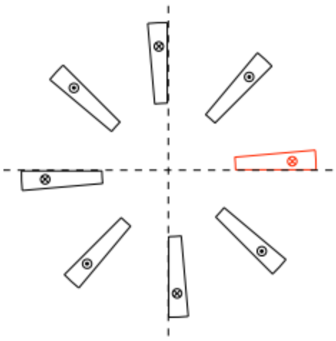

80

- The options **22-32** are intended for return-end designs, i.e., coils with an asymmetry due to the passing of conductors from one block to another during winding.
- The option **31** is intended for two-in-one window frame dipoles with the apertures atop each other. The **33**-option however, is designed for a single-aperture window frame quadrupole.
- The option **41** yields the blocks in the upper half-plane for solenoid calculations, compare Section Solenoidal Magnets
- The option **42** creates from blocks in the upper half-plane blocks in the lower half-plane with the same current direction. The option 42 is the only option which accepts that blocks be put at phi-angles larger than 90 degrees, i.e., in the second quadrant.
- In 2-D, the options **52-60** are identical to the options 2-10. In 3-D however, 52-60 will generate an entire coil made of loops of conductors, whereas 2-12 will generate only half a coil.

5.1.4 Block data 2-D

Each line in the table defines one block of conductors:

Variable	Description
No	Row number.
Ncon	Number of conductors in block.
Radius/X/Z	Radius.
Phi/Y/R	Positioning angle.
Alpha/Inc	Inclination angle.
Current	Conductor current.
CondName	Conductor Name.
N1	Radial discretization of conductor.
N2	Azimuthal discretization of conductor.
Imag	1: Block imaged at x-axis; 0: No action. (not with "Symmetric Coil" -option)
Turn	Block turned by angle. (not with "Symmetric Coil" -option)
Ne	Number of coil-end definition that applies to this block. (only with "3-D Coil Geometry"-option)

- The **N1- and N2-parameters** are explained in Section Cosine Theta Cross Section. Setting these to values for which N1xN2 is below the number of strands given in the roxie.madata- or roxie.cadata-files yields an approximation of the actual strands by a smaller number of line currents. The total current remains unchanged. This is also a way to accelerate the calculation of time-transient effects, knowing that the accuracy of the calculation will be reduced.
- The **N1- and N2-parameters** can be used to define hollow-cylinder like conductors, compare Section Cable in Conduit.
- Note that, with regard to 3-D coil end design, a **numbering scheme** should be followed. Blocks are to be ordered first by descending winding radius (outer layer before inner layer) and second by ascending positioning angle.

5.1.5 Design variables

With the geometric modeling complete, every feature (strand, cable, block, layer) can be subjected to geometric transformations such as translation, rotation, scaling, and imaging. At the same time, constraints are defined for these operations in order to avoid penetration or physically meaningless structures. Not only can the geometric properties of the magnet be changed in the optimization process, but also its material properties such as the number of strands, current density in conductors and strands, and filling factors.

Layer:

5.2 Layer:

Variable	Description
XSHIFL	X-Shift of entire layer.
YSHIFL	Y-Shift of entire layer.
NUMLBL	Number of conductors in block (put the original block number).
DRIL	Mandrel radius of block.
PHI0L	Position angle of block.
ALPH0L	Inclination angle of block.
TURNL	Turning layer by given angle.
TURNLS	Turning (but anti-clock-wise for imaged blocks).
RECTLA	Blocks in layer locally like "Window Frames"-option 'on'.
WIRELA	Blocks in layer locally like "Single Wires on Mandrel"-option 'on'.

Coil blocks (Cross-section):

Variable	Description
NUMCBL	Number of conductors.
PHI0	Positioning angle.
ALPH0	Inclination angle.
PHIR	Positioning angle (relative to Block n-1).
ALPHR	Inclination angle (relative to Block n-1).
PHIRS	As PHIR such that wedge is symmetric.
ALPHRS	Inclination angle (difference to angle giving a symmetric wedge).
PHIALP	Positioning angle and inclination angle equivalent.
GAP	Gap width of a rectangular block (relative to Block n-1).
PHIV	Azimuthal displacement of a block.
PHIVGL	Azimuthal displacement of all blocks.
RSHIFT	Radial displacement of a block.
XSHIFT	x-displacement of a block.
YSHIFT	y-displacement of a block.
ALPH0V	Increment of inclination angle.
RECTBL	Rectangular block.
WIREBL	Beam-pipe magnet block.
TILT	Tilt angle of rectangular block.
ODFAC	Conductor alignment factor (0: mandrel, 1: outer cylinder), compare the "Cond. Alignment OD"-option in the "Global Information". A number between 0 and 1 yields an alignment between somewhere between the mandrel and the outer cylinder.
INCL	Inclined buildup of rectangular block.
DFAKG	Zoom factor of cable width in all blocks.
DFAK	As DFAKG only in specified blocks.
DJFACH	Zoom factor for cable height (J=const.) in specified block.
DFACW	Zoom factor for cable width (J=const.) in specified block.

Conductors:

Variable	Description
DRI	Radius of mandrel (if "Layer Definition"-option is 'off').
DHI	Height of the conductor in block specified.
DWO	Outer width of the conductor in block specified.
DWI	Inner width of the conductor in block specified.
DRIC	Radius of conductor.
DHIC	Height of conductor.
DWOC	Outer width of conductor.
DWIC	Inner width of conductor.
DWIOC	DWIC=DWOC=DWIOC.
SHIM	Cond. is a shim (current = 0).
XSHIFC	x-shift of conductor (xy-plane).
YSHIFC	y-shift of conductor (xy-plane).
RSHIFC	r-shift of conductor (xy-plane).
XSH12	x-shift of conductor surface 1-2 (xy-plane).
XSH34	x-shift of conductor surface 3-4 (xy-plane).
YSH12	y-shift of conductor surface 1-2 (xy-plane).
YSH34	y-shift of conductor surface 3-4 (xy-plane).

2-D transform (Layers and Blocks):

Variable	Description
SHIFX	x-shift of the coil block in 2-D.
SHIFY	y-shift of the coil block in 2-D.
SHIFF	Rotation (in degrees) of coil block in 2-D.
SHIFR	r-shift of the coil block in 2-D.
SHIFLX	x-shift of the layer in 2-D.
SHIFLY	y-shift of the layer in 2-D.
SHIFLF	Rotation (in degrees) of the layer in 2-D.
SHIFLR	r-shift of the layer in 2-D.

Plotting:

Variable	Description
SCALFN	Scaling factor for numbering of conductors and blocks.

5.2.1 Objectives

Global values:

Variable	Description
DCONT	Contraction factor.
INCLM	Mean inclination angle in magnet.
INCMAX	Maximum inclination angle in magnet.

- The **inclination angle** measures the deviation of a conductor's radial axis from a radial positioning. The inclination angle is the sum over all conductors of the deviation from a radial position. Radial positioning is important in order to reduce mechanical stress to the cable in the magnet's coil end. The INCLM value is printed to the .output-file at every run of ROXIE.

Conductor data:

Variable	Description
ALLIGN	Alignment constraint.
DTWLE	Twist per unit length.
R14CO	Radial position of the insulated cable (side 1-4).
R23CO	Radial position of the insulated cable (side 2-3).
F14CO	Inclination of the insulated cable (side 1-4).
F23CO	Inclination of the insulated cable (side 2-3).
DZCON	z-position of the conductor at the apex.

Block (input) data:

Variable	Description
PHI0	Positioning angle.
ALPH0	Inclination angle versus x-axis.
CURNTB	Current, all Blocks affected (for optimization).
DRI	Radius of the conductor in Block.
DHI	Height of the conductor in Block.
DW0	Outer width of the conductor in Block.
DWI	Inner width of the conductor in Block.
DFAK	Zoom factor for width of conductor.
PHIV	Azimuthal displacement of the whole Block.
RSHIFT	Radial displacement of the whole Block.
XSHIFT	x-displacement of Blocks.
YSHIFT	y-displacement of Blocks.

Block geometry:

Variable	Description
INCLIN	Inclination angle of the last turn in bare block.
PHI1	Outer angle (inner radius) of block.
PHI2	Inner angle (inner radius) of block.
PHI3	Inner angle (outer radius) of block.
PHI4	Outer angle (outer radius) of block.
XPOS1	Position in x of corner 1 of the bare block.
XPOS2	Position in x of corner 2 of the bare block.
XPOS3	Position in x of corner 3 of the bare block.
XPOS4	Position in x of corner 4 of the bare block.
YPOS1	Position in y of corner 1 of the bare block.
YPOS2	Position in y of corner 2 of the bare block.
YPOS3	Position in y of corner 3 of the bare block.
YPOS4	Position in y of corner 4 of the bare block.
RPOS1	Radius of corner 1 of the bare block.

5.2.2 Plotting information 2-D

Geometry:

Variable	Description
NUMMC	Numbering of conductors.
NUMMB	Numbering of blocks.
NOCND	No plotting of conductors.
WEDGE	Plot the wedges between blocks and the endspacer. Only works with the "Wedge/Endspacer"-option in the "Main Options".

5.2.3 Interface options

Option	Description
Autocad	AUTOCAD-readable file to plot the cross-section.
MS Excel	Comma-delimited list of corner-coordinates of each conductor.
Extended Printout	Extended print into .output-file.
2-D Line Currents	Produces a filename.fila2-D-file which contains two tables: (1) a table with the corner points of the current-carrying areas and (2) a table with the position of the individual line currents in the model.
.iron File of Wedges	Only works with the "Wedge/Endspacer"-option in the "Main Options". Creates a file called wedges.iron.

5.3 3-D coil modeling

The input parameters for the coil-end generation are the z-position of the innermost conductor of each coil-block, its inclination angle, the length of the straight section and the size of the inter-turn spacers between the conductors. For the automatic generation of the coil-end region, three options are available:

- Coil-ends with or without inter-turn shims and conductors placed on the winding mandrel.
- Coil-ends with grouped conductors wound on end-spacers with shelves which provide for support from below and result in an alignment of the conductors at the outer radius of the end-spacers.
- Race-track coil-ends with or without additional straight sections. With this option it is possible to model solenoid and torus magnets.

Many options set in 2-D design have important consequences for 3-D modeling, e.g., type of coil: racetrack, cosine-theta, single wires. The 2-D options are not reiterated in this section.

5.3.1 Main options

Option	Description
3-D Coil Geometry	Tell ROXIE that we are doing coil ends.
Wedge/ Endspacer	Only with "3-D Coil Geometry" - tell ROXIE to do endspacer design. Not available for Window Frame magnets (Racetrack coils).

5.3.2 Global information 2-D

Option	Description
Window Frames	Racetrack-type coils.

There is an old and a new version of reacetrack coil-end generation. They are distinguished by the "Etype"-value in the "Block Data 3-D"-table. The new algorithms use end types 60 and 70, see Section 11.2.3.

5.3.3 Global information 3-D

The following options are available for in the "Global Information 3-D"-widget:

Option	Description
Additional Bricks	Add arbitrarily shaped conductors.
Additional Leads	Add conductors that can be modeled by radius/positioning angle/inclination angle.
Rutherford Cable Model	This option is currently not supported.
Super-Elliptical Coil End	Use of a hyper-ellipse as a coil-end baseline in the sz-plane.
Coil Imaged at z=0-Plane	Symmetric coil w.r.t. xy-plane. The 2nd half of the coil is not plotted in postscript plots. It is, however, taken into account in field computations. ROXIE assures the correct powering of the imaged half.
Helical Coils	Experimental option to calculate fields and forces from helical coils (tilted solenoids, double-helix, etc.).

- The **Helical Coils** option uses the "Block Data 2-D" and "Block Data 3-D" widgets for an input. The variables have a different meaning, when "Helical Coils" is switched 'on', see Section Helical Coils.

More relevant data in the "Global Information 3-D"-widget is given:

Variable	Description
Maximum Size of Coil Ends	This number is used in the automatically produced plots (yz- and sz-plane sections of coil ends. It determines also the maximum length of endspacers.
Number Of Blocks in Outer Layer	The first N blocks in the "Block Data 2-D"-table are ascribed to the outer layer.
Cable Size Increase in Ends	The cable size increases linearly over the coil end up to the apex. The option is similar to the BULGE-option in the "Coil Ends (Differential Forms)"-menu of the "Design Variables".
Number of Cuts in z-Plane	Discretization density in z-direction.
Length of Extension into -z-Direction	Coil end starts at a negative z-value.

- Generally, the "**Number Of Blocks in Outer Layer**"-option only works with the "Symmetric Coil"-option from the "Main Options" and not with the "Layer Definition". This has repercussions on the 3-D plotting of coil ends and endspacers. The option is also commonly used to design unsymmetric endspacers for connection-side coil-ends. Here, the blocks on one side are ascribed to the 'outer layer' and two independent sets of spacers can be designed.
- Don't use a none-zero "**Length of Extension into -z-Dir.**" together with the "Coil maged at z=0 Plane"-option in the "Global Information 3-D"! ROXIE won't complain but the result is not reasonable.

5.3.4 Layers

In addition to those layer symmetry-types that were introduced in 2-D, the following geometry types are available for 3-D coil end design.

Input	Description
22	Dipole Connection Side
24	Quadrupole Connection Side
26	Sextupole Connection Side
28	Octupole Connection Side
30	Dekapole Connection Side
32	Duodekapole Connection Side
31	Window Frame Dipole
41	Solenoid
42	Up-down symmetric (combined function magnet)
52	Dipole, Both Ends in 3-D
54	Quadrupole, Both Ends in 3-D
56	Sextupole, Both Ends in 3-D
58	Octupole, Both Ends in 3-D
60	Dekapole, Both Ends in 3-D
62	Duodekapole, Both Ends in 3-D

"Connection Side" means that each block is only used to give one half of a coil end. This is necessary as connection-side coil ends are generally assymmetric. Two blocks are needed to model one arc. The "Both Ends in 3-D"-option has the same functionality as the "Coil Immaged at z=0-Plane"-option in the "Global Information 3-D"-widget.

5.3.5 Block data 3-D

Variable Description

Ne Row number/number of coil-end definition. Beta Beta angle. Bo Long half-axis of ellipse on cylinder. Zo Straight Section. Wi Wedge inner width. Wo Wedge outer width. Hwed Wedge height. Tend Type of coil-end (layer definition). Etype Conductor alignment in coil-end.

5.3.6 Design variables

Layer:

Variable	Description
DBZ0L	Long half axis of the ellipse of coil end in block.
DZZ0L	Straight section of coil end in block.

Coil Ends:

Variable	Description
DBZ0	Long half axis of ellipse of coil end (if "Layer Definition" is 'off').
DZZ0	Straight section of coil end (if "Layer Definition" is 'off').
DZZR	Straight section relative to the previous block.
BETAZ	Inclination angle of block in yz-plane.
CENTER	Shifts the center of the turns.
EXTRXS	x-shift in xy-plane (saved for extrusion).
EXTRYS	y-shift in xy-plane (saved for extrusion).
EXTRPH	PHI turn in xy-plane (saved for extrusion).
DPERMF	Perimeter adjustment for conductor. Shift the lower edge of the conductor towards the magnet center.
DPERMB	Perimeter adjustment for all conductors in block. Shift the lower edge of the conductors towards the magnet center.
PERIMI	Perimeter adjustment for the inner surface of the specified spacer. Shift the lower edge of the inner surface towards the magnet center.
PERIMO	Perimeter adjustment for the outer surface of the specified spacer. Shift the lower edge of the outer surface towards the magnet center.
DYZS	y-shift of conductor in yz-plane.
DZZS	z-shift of conductor in yz-plane.
DYZSB	y-shift of block in yz-plane.
DZZSB	z-shift of block in yz-plane.
DYZSL	y-shift of layer in yz-plane.
DZZSL	z-shift of layer in yz-plane.

Coil Ends (Differential Forms):

Variable	Description
BOVERA	b/a-ratio.
HORDER	Order of ellipse.
BULGE	Bulge amplitude. Not to be confused with the BULGE-option in the "Objectives"-table which corresponds to the classical constant-perimeter coil end.
TORS1	Additional torsion (in radians).
TORS2	Additional torsion (in radians).
TORS3	Additional torsion (in radians).
TORS4	Additional torsion (in radians).

- The **differential-geometry** based 3-D **coil-end** design can now be used for field calculations and, in a limited way, for post-processing. Note that differential-geometry based coil-end design is an option for cosine-theta type magnets with the conductors aligned on the winding mandrel.
- The **BULGE**-parameter lets the user simulate the bulge effect of conductors in a coil-end block due to deformations of the cable in the coil winding process. In practice, the block are often less compacted on the lower edge than on the upper edge. The bulge amplitude releases the lower outer edge of the coil-block model.

3-D Transform:

Variable	Description
TRANSZ	z-shift of the coil-blocks in 3-D.
TRANSX	x-shift of the coil-blocks in 3-D.
TRANSY	y-shift of the coil-blocks in 3-D.
TRAIMZ	Imaging of 3-D coil-blocks at the xy-plane.
TRANSF	Turn block (in degrees) in the xy-plane to y-axis (Roll).
TRANST	Turn the block (in degrees) in zy-plane to y-axis (Tilt).
TRANSO	Turn the block (in degrees) in xz-plane to z-axis (Swing).
TRANIX	Additional straight section inserted in x-direction, compare Section Racetrack coil.
TRANLZ	z-shift of the layer in 3-D.
TRANLX	x-shift of the layer in 3-D.
TRANLY	y-shift of the layer in 3-D.
TRAILZ	Imaging of 3-D coil end at the xy-plane.
TRANLF	Turn layer (in degrees) in the xy-plane to y-axis (Roll).
TRANLT	Turn the layer (in degrees) in zy-plane to y-axis (Tilt).
TRANLO	Turn the layer (in degrees) in xz-plane to z-axis (Swing).

- Note that when using the **TRAIMZ-** or **TRAILZ-**options, the user has to ensure the correct powering of the imaged blocks/layers. In general this means an inversion of the sign of the block current with respect to the blocks/layers that are not mirrored.

Plotting:

Variable	Description
BLOCKC	Color index for blocks in 3-D - 1: blue, 2: dark blue, 3: red.
BRICKC	Color index for bricks in 3-D - 4: orange, 5: green, 0: invisible.

5.3.7 Objectives

Conductor Data:

Variable	Description
DTWLE	Twist per unit length.
CURVAT	Maximum curvature in the block. The geodesic curvature in a constant-perimeter coil end is calculated. Not to be confused with GEODE, the geodesic curvature parameter for differential-geometry coil ends.
BULGE	Bulge factor in the conductor. The bulge factor calculates the deviation from a constant perimeter coil end. Not to be confused with the BULGE-option for differential-geometry coil ends in the "Design Variables"-table.

Block (Input) Data:

Variable	Description
DBZ0	Long half axis of ellipse of coil end.
DZZ0	Straight section of coil end.
BETAZ	Inclination angle of block in yz-plane.

Coil Ends (Differential Forms):

Variable	Description
TORSIO	Maximum torsion in M^{-1}.
NORMA	Maximum normal curvature in M^{-1}.
GEODE	Maximum geodesic curvature in M^{-1}.
GEOSTR	Integral of geodesic curvature squared over the entire block. Proportional to strain energy in the block in M^{-2}.
EREG	Penalty if the edge of regression in the strip.

- The **differential-geometry** based 3-D **coil-end** design can now be used for field calculations and, in a limited way, for post-processing.

5.3.8 Plotting information 3-D

Variable	Description
CURVAT	Min/max curvature k on broad/narrow sides, R=1/k. This is not a curvature parameter calculated with the differential geometry method.
SUN	Sunshine on coil ends.
COIL	Plotting of coil-blocks.
BRICKS	Plotting of additional bricks and leads.
SPACER	Plotting of end spacers.

- **Automatic generation of plots.** With the "**3-D Coil Geometry**"-option switched 'on' in the "Main Options" a number of plots is automatically generated, whenever postscript plots are done. The first is a cut through the yz-plane. The second shows the outer layer blocks in the sz-plane in a split representation. The left half shows the lower edge of the cables, the right half shows the upper edge. The third plot gives the same split representation of all coil-blocks. Finally, the fourth automatically produced plot yields only the upper edge of all conductors in the sz-plane.
- Also the "**Wedge/Endspacer**"-option in the "Main Options" leads to an **automatic plot** of enspacer shapes in the the yz- and sz-planes.

5.3.9 Interface options

Option	Description
CNC Machine files	Endspacer Design Output.
Opera 8-node Bricks	3-D bricks of the coil end for the "Opera" field calculation program.
Opera 20-node Bricks	3-D bricks of the coil end for the "Opera" field calculation program.
Virtual Reality (3-D)	Writes a filename.wrl-file which can be opened by any VRML-browser for an interactive 3-D-view of the coils.
3-D Line Currents	Produces a filename.fila3-D-file which contains information on the positioning of line currents in the 3-D coil model.
Input Data from 'BEND'	Read-in coil end from the 'BEND' coil-end design program.
Strips from Darboux Vectors	Design differential geometry-based coil ends.

- The "**Strips from Darboux Vectors**"-option switches the coil-end design method from constant-perimeter coil ends to differential-geometry based coil ends.

5.3.10 Additional Bricks

The input for additional bricks is made in two tables. The first table describes the current in a conductor, the number of strands and the number of cuts in the conductor. The second table defines the cuts for each conductor. Choosing a conductor in the first table activates the respective second table. The table data is defined as follows:

Variable	Description
Current	Current in the additional conductor.
N1	Number of strands from corner 1 to 4 and 2 to 3.
N2	Number of strands on side 1-2 and 3-4.
Ncut	Number of cuts to define the conductor.

Variable	Description
Xcut	x-coordinate of a corner of a cutting plane.
Ycut	y-coordinate of a corner of a cutting plane.
Zcut	z-coordinate of a corner of a cutting plane.

Four lines in the second table define one cutting plane of a conductor. The number of cutting planes equals the number of bricks plus one.

5.3.11 Additional leads

The input-scheme for additional leads is similar to that of additional bricks. Two tables define a conductor and the positioning of the conductor in the cut planes. The first table defines one conductor type per lead:

Variable	Description
Current	Current in the conductor.
N1	Number of Strands in radial direction.
N2	Number of Strands in azimuthal direction.
Div.	Number of divisions in z-direction.
Condname	Name of the conductor in roxie.madata- or roxie.cadata-file.

Variable	Description
Icc	Positioning of the lead: '0': the position defined by r/\varphi is in the middle between corners 1 and 2; '1': r/\varphi define corner 1.
Radius	Positioning radius.
Phi0	Positioning angle.
alph0	Inclination angle.
Z0	z-position of cutting plane.

One line in the second table defines one cutting plane of the additional lead.

6. Analytical Field Calculation

In the coil cross-sections and 3-D coil ends the current flow is modeled by line currents in the positions of SC strands in the cables. This chapter treats the calculation of electromagnetic fields from line currents via the Biot-Savart law and the resulting electromagnetic forces on the conductors.

6.1 2-D analytical field calculation

6.1.1 Main Options

Option	Description
Axi-Symmetry	Regard (x)- and (y)-coordinates as (z)- and (r)-coordinates and solve the Maxwell Equations in cylindrical coordinates. To model axi-symmetric 3-D cases in 2-D.

- With the "**Axi-Symmetry**"-option all conductors in the cross-section must be positioned in the upper half-plane. They are then interpreted as current-loops with the x-axis as axis of rotation.
- The "**Axi-Symmetry**"-option produces a plot of the axial and radial field-components over the z-position. The fields are plotted at different radii between the center of the solenoid and the coil. These plots however do not consider fields due to iron magnetization!

6.1.2 Global information

Option	Description
Grading of Current Density	Take into account the inhomogeneous current density in keystoned cables.
Self Field in Strands	For the calculation of the fields at strand-level: take into account also the self field. We define as the self-field the maximum value of the field generated by a strand on its surface, i.e. $I_{strand}/2\pi r_{strand}$.
Self and Mutual Inductance	Calculate self- and mutual inductances between layers. The output is written into a table in the .output-file.
Quench and Temp. Margin	Calculate the distance to the critical surface in the position of every strand.
Peak Field in Coil	Calculate the field at strand-level.

- To switch the "**Grading of Current Density**"-option 'off' in keystoned cables allows for a better comparison of ROXIE results with other, FEM-based field calculation programs which would model the current by a homogeneous current density.
- The "**Quench and Temp. Margin**"-option uses the fit of the critical surface given in the roxie.cadata-file's REMFIT block. The "**Peak Field in Coil**"-option also prints a margin to load line for every block. This option uses the linear approximation of the critical surface around a working point. Note that, in order to obtain good results, both, the fit and the linear approximation must be entered in roxie.madata- or roxie.cadata-file according to measurements!

Be aware that the method used with the "**Self and Mutual Inductance**"-option is only applicable in the absence of nonlinear magnetic material. Otherwise the "Mutual Inductances in nl. Circuits"-option must be chosen in the "Optimization Algorithm"-field of the "General Information". The nonlinear self inductance is evaluated using the SINDU- and SINDUD-options in the "Global Values"-menu of the "Objectives". The latter options are used with the "Transfer Function"-option.

Switching to 'on' the "**Peak Field in Coil**"-option has many implications.

- The forces upon each conductor are calculated.
- The position of each conductor on the loadline is determined and the maximum per block is written to the .output-file. This functionality uses the linear approximation of the critical surface.
- Plots of the blocks' position on the loadline and of the forces on the conductors are automatically plotted when the "Postscript Plots"-option is switched 'on'.
- "Peak Field in Coil" is required to be switched 'on' for a number of other options, e.g., quench margins, inductances, plots of fields and currents in the coils, time-transient calculations, ...

Variable	Description
Radius of Harmonic Analysis	Radius for Fourier Decomposition of the radial component of the field.
Inner Radius of the Iron Yoke	For mirroring method.
* Relative Permeability of Yoke*	For mirroring method.
* Highest Order of Multipole Coeff.*	Calculate the coefficients of the Fourier Series up to this order.
* Type of Coil/Ref. Field*	For relative multipole coefficients in units 10^{-4}. They are related to the specified field component in

6.1.3 Design variables

Layers:

Variable	Description
CURNLH	Current in specified block.

Coil Blocks (Cross-Section):

Variable	Description
TEMPBL	Operation temperature in block.

- The **TEMPBL**-option sets the operation temperature in specified blocks, e.g., to test the impact of an inhomogeneous cooling on the margins to quench or on persistent currents. The TEMPBL-option is used with features that use the critical-current fit function and not with those that use the linear approximation thereof.

Current:

Variable	Description
CURNTB	Current, all blocks effected.
CURNTH	Current, only specified block.
CURNTC	Current, only specified conductor.
CURNTS	Current, only specified strand.
CURNTD	Short circuit current (IB1 positive, IB2 negative)???.
CURNTF	Current factor for all blocks.
CURRFH	Current factor, only specified block.
CURRBH	Current factor plus/minus one, only specified block. Binary operator to switch current in block between '+ ' and '- '. For use with genetic algorithm. Input 0,1 => factor 1, -1.

Quench, Inductance:

Variable	Description
TURNS	Number of turns per conductor (for inductance calculation). The strands in a cable are usually connected in parallel (Rutherford type cable). If they are connected in series, then the inductance increases by the number of turns per conductor.

Additional Field:

Variable	Description
ADDX	Constant induction (in tesla) in x-direction.
ADDY	Constant induction (in tesla) in y-direction.

Other:

Variable	Description
XCOIL	x-displacement of the measurement coil (harmonic analysis).
YCOIL	y-displacement of the measurement coil (harmonic analysis).
FCOIL	Turning of the measurement coil (harmonic analysis).
DELLI	Ellipticity of coil. Simulate a deformation of the coil and the mandrel.
R	Radius of iron yoke for mirroring method.
CONPHI	Constant current shell up to angle phi.
COSPHI	Cosine current shell up to angle phi.
ELLPHI	Intersecting ellipses up to angle phi. No longer supported.
IRISB3	b_3 correction for iris plot (units).
IRISB5	b_5 correction for iris plot (units).
IRISB7	b_7 correction for iris plot (units).
IRISB9	b_9 correction for iris plot (units).
IRIERR	Maximum error in plot (units). Maximum on the legend of an iris plot.
GDFZQMA	Good-field zone quality criterion (units) to calculate the radii of the good-field zone as used with the GDFZRMA, GDFZRMI, and GFZWID options in the "Objectives"-block below.
MAXW	Radius for calculation of forces with Maxwell stress tensor. Calculate the forces on objects inside a circle, centered at $x=0$, $y=0$ with this radius.

- For a comment on the "**GDFZQMA**"-option see the remark on the "GDFZRMA", "GDFZRMI", and "GFZWID" options in the "Objectives"-section below.

6.1.4 Objectives

Normal Multipoles:

Variable	Description
B	Field.
BR	Field related to the main component.
BQUEN	Field at short-sample current (quenchfield).

Skew Multipoles:

Variable	Description
A	Skew field components.
AR	Skew field related to the main component.

Global Values:

Variable	Description
NIB	$N\,I/B_\mathrm{ref.}$
GFZRMA	Good-Field Zone outer radius.
GFZRMI	Good-Field Zone inner radius.
GFZWID	Good-Field Zone width (outer radius minus inner radius).
MARGMI	Minimum margin to quench. Calculated from linear approximation of critical surface.
XCOIL	x-Displacement of the measurement coil.
YCOIL	y-Displacement of the measurement coil.
DELLI	Elliptical deformation of the coil on the mandrel, compare the DELLI-option in the "Design Variables".
SINDU	Self inductance.
SINDUD	Differential self inductance.
TORQUE	Torque from Maxwell stress tensor, compare the MAXW-option in the "Others"-menu of "Design Variables".

- The "**GDFZRMA**", "**GDFZRMI**", and "**GFZWID**" options calculate the inner and outer radii of a zone, in which the field is of good quality. The quality is defined in terms of the sum of unwanted field (other than main component field). If this unwanted field, related to the main component (in units $10^{-4})$, is below the value specified in the "Design Variables" as GDFZQMA, then this radius has 'good field'. For a dipole, only an outer radius exists, delimiting a circular zone of 'good field'. For higher-order multipolar fields the good-field zone is generally delimited by an inner and an outer radius. The inner radius is due to lower-order field errors. The good-field calculations are closely related to the iris-plots, in that the radii belong to circles that can be inscribed into the iris plot, delimiting a specified color region. The radii can be plot in the "Plotting Information 2D". For more information on the theoretical aspects of the good-field zone, contact Nikolai Schwerg (nikolai.schwerg@cern.ch).

Peak Fields:

Variable	Description
PEAK	Peakfield in the block.
LOADLI	Percentage on the load line.

Magnetization Data:

Variable	Description
AB	Skew and normal in one plot. No longer supported.

Solenoid Data:

The solenoid options are available with the "Axi-Symmetry"-option 'on' in the "Main Options".

Variable	Description
SOLBXM	$\max
SOLBYM	$\max
SOLBXD	$\Delta
SOLVOL	Total coil volume.
SOLVOB	Coil volume of specified block.

6.1.5 Block spec. (Peak fields, Forces, FEM plots)

In this data line the blocks are specified in which to do peak-field calculations, force-calculations and more. The following format is allowed:\ `1 4 7-9 10`\

6.1.6 Plotting information 2-D

Geometry:

Variable	Description
YOKE	Imaging iron yoke.
DISPLV	Displacement vectors in Blocks.

Aperture:

Variable	Description
QUAL	Field quality in aperture. Deviation from pure field is calculated in every point from Biot-Savart law.
IRIS	Like QUAL but deviation calculated from the field harmonics (faster).
GFZ	Good-field zone. For more information, see remarks on the "GDFZRMA", "GDFZRMI," and "GFZWID" options in the "Objectives" section above.
MATR	Field vectors in cross-section. Modulus represented by arrow size.
MATRC	Field vectors in cross-section. Modulus represented by color code.
MATRP	Like MATR but only field from SC-magnetization (PCs, ISCCs analytic model, IFCCs).

- Note that the **MATR**, **MATRC**- and **MATRP**-options can be operated as such or with the "Field-Vector Matrix"-option from the "Interface Options". The option lets the user define the matrix spacing and produces an output file. Furthmore, the reduced field from numerical field calculations is only taken into account if the "Field-Vector Matrix"-option is used.
- The **QUAL**-option evaluates the formula $f_{ij}=1-\frac{B(\mathbf{x}{ij})}{B}(\mathbf{x}_{ij})}$ in a matrix of 100x100 points (200x200 for 360° plots) over the plotting range. The color-scheme has one color for every 0.1 units of 10^{-4}. With the 20-color legend, the maximum field-deviation displayed is 2 units of 10^{-4}.
- The **IRIS**-option works similarly to the QUAL-option. The difference is that the field is not calculated in every matrix point from Biot-Savart law but it is generated from the Fourier-Series expansion. This method is faster. By default the legend encompasses 8 units of 10^{-4}. Each color therefore represents 0.4 units of 10^{-4}. For the IRIS-option, the upper bound of the legend can be set using the IRIERR-option in the "Other:"-menu of the "Design Variables".

Coil Fields:

For all coil fields the "Peak Field in Coil"-option must be switched 'on'.

Variable	Description
A	Vector potential.
BX	Magnetic field (x-component).
BY	Magnetic field (y-component).
*$	B
B	Magnetic field vectors.
BPERP	B perpendicular to the broad face of conductor.
BPARA	B parallel to the broad face of conductor.
MARG	Margin to quench (in %).
MARGT	Temperature margin (in K).

- The **MARG**- and **MARGT**-options are calculated from the critical current fit. Compare comment on the "Quench and Temp. Margin"-option in the "Global Information" above.

Lorentz Forces:

For all force calculations the "Peak Field in Coil"-option must be switched 'on'.

Variable	Description
FX	Electromagnetic force in x-direction.
FY	Electromagnetic force in y-direction.
*$	F
F	Force vectors.
FPERP	F perpendicular to the broad face of the conductor.
FPARA	F parallel to the broad face of the conductor.
FORC	Electromagnetic forces on blocks.
FPN	$F$$\parallel$ over $F$$\perp$.

Current Distribution:

For all current representations the "Peak Field in Coil"-option must be switched 'on'.

Variable	Description
I	Current in strand.
JELE	Current density in strand.
JCU	Copper current density in strand.
JSC	Superconductor current density in strand.
*$	I
*$	JEL
*$	JCU
*$	JSC

Bn Strand Contribution of I:

For all harmonic representations the "Peak Field in Coil"-option must be switched 'on'.

Variable	Description
B1	B_1 contribution of strand current.
B2	B_2 contribution of strand current.
B3	B_3 contribution of strand current.
B4	B_4 contribution of strand current.
B5	B_5 contribution of strand current.
B6	B_6 contribution of strand current.
B7	B_7 contribution of strand current.
B8	B_8 contribution of strand current.
B9	B_9 contribution of strand current.
B10	B_{10} contribution of strand current.
B11	B_{11} contribution of strand current.

6.1.7 Interface options

Option	Description
Field-Vector Matrix (MAP)	Define a field-vector matrix and produce a file. A widget opens in the GUI. The reduced field from numerical field calculations is taken into account, compare Section 5.1.1.
Field Along a Line (2-D,3-D)	Calculate the field in x- and y- component along a file. Output is written to a postscript file and .output-file. An extra widget opens.
2-D Field Map in Coil	Write the field at every strand to a file, compare Section 5.1.6.
2-D Line Currents	Produce a filename.fila2-D-file which contains two tables: (1) a table with the corner points of the current-carrying areas and (2) a table with the position of the individual line currents in the model, compare Section 5.1.7.
Write Multipoles for Pp.	Write the multipole components to a file for post-processing, compare Section 5.1.8.

6.2 Levitation in 2-D

To calculate the levitation force-field, the "Field-Vector Matrix"- and "Levitation (grad B^2)"-options are used. The algorithm calculates the levitation forces in every point defined with the "Field-Vector Matrix"-option, henceforth called the reference matrix. A plot is produced that shows the forces in x- and y-direction in the points of the reference matrix.

6.2.1 Objectives

Magnetic levitation:

Variable	Description
LEVDX	Variation of force (x-component) over the reference matrix.
LEVDY	Variation of force (y-component) over the reference matrix.
LEVYM	Maximum levitation force (y-component) over the reference matrix.

6.2.2 Plotting Information 2-D

Aperture:

Variable	Description
QUAL2	Levitation force error on F_y.
QUAL3	Levitation force error on F_y and F_x.

- The **QUAL2**- and **QUAL3**-options evaluate the forces in x- and y-direction in a matrix of 100x100 points (200x200 for 360° plots) over the plotting range. The deviation of the force field from the mean-value in the reference-matrix is evaluated. The color-scheme has one color for every percent of deviation. With the 20-color legend, the maximum displayed force-deviation 20 percent.

6.2.3 Interface Options

Option	Description
Levitation (grad B**2)	This option must be 'on' in order to do levitation calculations.

6.3 3-D Analytical Field Calculation

In this section we only document those options that are proper to 3-D calculations and thus not available in 2-D.

6.3.1 Global Information 3-D

Option	Description
3-D Peak Field Calc.	Calculate the field and forces on strand level.
3-D Field Harmonics	Calculate the integrated multipole components along a line. An extra widget opens in the GUI.

- For **3-D Peak field calculations** is is also imperative to have the "Peak Field in Coil"-switch 'on' in the "Global Information".
- In "**3-D Field Harmonics**"-calculations a maximum number of 8 integration points is printed separately to the .output-file. Above 8 steps, only the integral harmonics are being printed. The orders of multipoles to be plotted are specified in the "Objectives"-table. A plot is then automatically generated when the "Postscript Plots"-option is switched 'on'.

6.3.2 Design variables

Plotting:

Variable	Description
SCALIZ	3-D field cones plotted in $-z$-direction regardless of the "Plot Imaged at z=0 plane".

Additional Field:

Variable	Description
ADDZ	Constant induction (in tesla) in z-direction.

6.3.3 Other

Variable	Description
FSCAL	Main field component (absolute value) to which relative 3-D integrated harmonics should be related when the "3-D Field Harmonics"-option is switched 'on' in the "Global Information 3-D"-widget.

6.3.4 Objectives

Normal Multipoles:

Variable	Description
B3	Average field over end, calculated with the "3-D Field Harmonics"-option in the "Global Information 3-D"-widget.
B3R	B3, related to main component, calculated with the "3-D Field Harmonics"-option in the "Global Information 3-D"-widget.

Skew Multipoles

Variable	Description
A3	Average field over end, calculated with the "3-D Field Harmonics"-option in the "Global Information 3-D"-widget.
A3R	A3, related to the main component, calculated with the "3-D Field Harmonics"-option in the "Global Information 3-D"-widget.

Conductor Data

Variable	Description
PVAR	Variation of pressure on the narrow face.

Peak Fields

Variable	Description
PEAK3-D	3-D Peak field in the block.

6.3.5 Plotting information 3-D

Option	Description
3-D Min. Field in Cond.	Choose the filament with the lowest field in the peak-field conductor for the Roller-coaster plot.
3-D Max. Field in Cond.	Choose the filament with the highest field in the peak-field conductor for the Roller-coaster plot.

- The "**3-D Min. Field in Cond.**" and "**3-D Max. Field in Cond.**"-options produce so-called Roller-coaster plots. The option "3-D Peak Field Calc." must be 'on'. For each block specified in the "Block spec. (Peak fields, Forces, FEM plots)"-widget the conductor with the largest peak-field is chosen. The field and its components are plotted over the intersection number in z-direction and, in a second plot, over the z-coordinate. The data is also written into tables in the .output-file.

Variable	Description
P	Pressure due to Lorentz forces on surfaces.
FXFZ	F_z on the broad side; F_x on the narrow side.
FYFZ	F_z on the broad side; F_y on the narrow side.
FRFF	F_r on the broad side; F_φ on the narrow side.
B	B_min on the broad side; B_max on the narrow side.
BMID	Average B on the broad and narrow sides.
JZ	Current in z-direction.

- The **JZ**-option works only if the "Peak Field in Coil"-option is switched 'on' in the "Global Information".

7. Mesh Generation

While the definition of the coil geometry is driven by a user's interface based on the Tcl/Tk script language (data stored in a file named filename.data), the input data for the mesh-generator has to be written into a file named filename.iron. To combine a coil with the appropriate iron yoke, the .data- and .iron-file must have the same name. The .iron-file can be opened from the Xroxie environment from the "Iron"-menu as soon as the "Mesh-Generator"-option is 'on' in the "FEM/BEMFEM Options".

In this section the rules and commands for the creation of the .iron-file are given together with an example. The HyperLine command supports design features for the creation of parametric meshes in magnet design.

7.1 General rules

- The lines are ended by a semicolon.
- To comment a line insert a '--' in front of it. Comments can also be added at the end of lines.
- Variables can be up to 100 characters long.
- The file has to start with the command "HyperMesh;". Omitting this command allows to be compatible to an older version of the mesh-generator.

7.2 Definition of parameters

- Scalar variables cannot start by kp,ln,ar, or BH
- All arithmetic operations plus the functions like Sin, Cos, Asin, Acos, Sqrt, and Tan are allowed in scalar expressions.
- Design variables are defined with the prefix dv and its value is given by ROXIE if they are defined as design variables in the .data file as well.

7.3 Definition of keypoints

- Keypoints are represented with variables starting with kp, e.g. kp1 or kpleft.
- Possible operation with keypoints: sum, scalar multiplication, subtraction.
- Keypoints are defined from the scalar expressions with the operators [xcoor, ycoor] for Cartesian coordinates and [radius @ angle] for polar coordinates.
- It is possible to access the coordinates of a keypoint as kp1.x for the x-componet and kp1.y for the y-component of keypoint kp1.

7.4 The HyperLine command

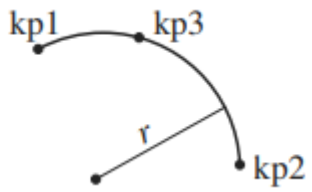
The HyperLine command was introduced to facilitate the input of complicated geometries. It is applied instead of the Line, Arc and Ellipse commands to define lines. The syntax is as follows:

```
ln1 = HyperLine(kp1,kp2,"string",arg1,arg2,arg3,arg4);
```

The "string" determines the type of the HyperLine. According to the chosen line type the arguments arg1-arg4 have different functions. Usually only some of them are user supplied, some of them can be defined optionally. The following sections summarise all different HyperLine types and explain the meanings of the parameters:

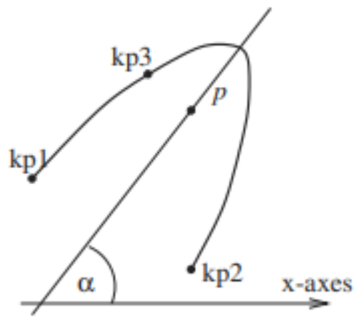
7.4.1 Curves & Arcs

Arc



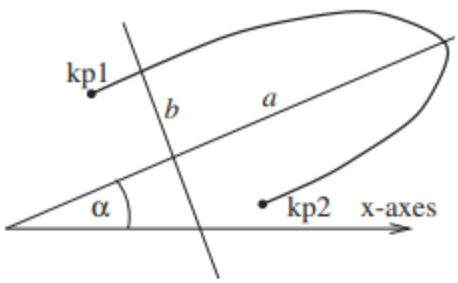
This is the keyword used for drawing a circular arc. `arg1` is either the radius r of the arc or the name of a third key-point (`kp3`). `arg2` is optional and determines the linear contraction factor of the mesh (the default value is 0.5). For positive radii always the smaller arc segment is drawn, for
negative radii the bigger one.

ParabolicArc



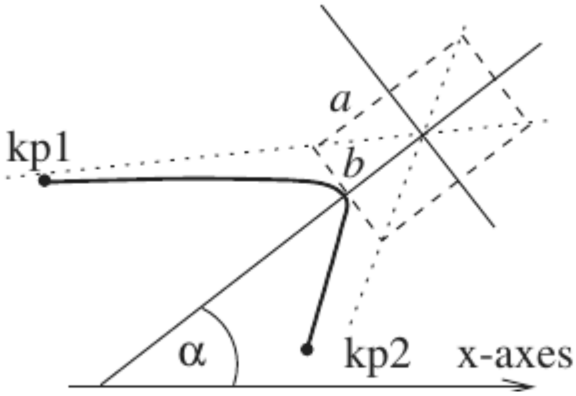
This string signifies that this line will be a parabolic arc. As first argument `arg1` the parameter p (p defines the parabola by the equation $y^2=2px$) or a third key-point `kp3` has to be supplied. `arg2` is optional and determines the linear contraction factor of the mesh (the default value is 0.5). The third parameter is the angle α. Its default value is 0.

EllipticArc



This keyword denotes an elliptic arc. The first and the second argument determine the two half axes a and b (a and b define the ellipse by $\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$), the third argument `arg3` (optional) is the linear contraction factor of the mesh (the default value is 0.5) and `arg4` (optional) is the angle α (default is 0).

HyperbolicArc

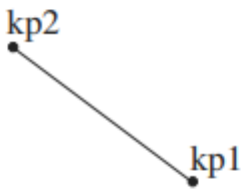


A hyperbolic arc is drawn. The first and the second argument determine the two half axes a and b, the third argument `arg3` (optional) is the linear contraction factor of the mesh (the default value is 0.5) and `arg4` (optional) is the angle α (default is 0).

Interpolation

This type is very similar to the old `Ellipse` command. The first argument `arg1` has to be a third key-point. An interpolating function, equivalent to a finite-element shape function is drawn between the three key-points. The second argument is optional and denotes the linear contraction factor of the mesh (the default value is 0.5).

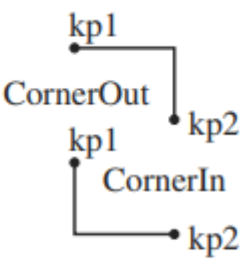
Line



This command will connect `kp1` and `kp2` with a straight line. `arg1` is optional and determines the linear contraction factor of the mesh (the default value is 0.5).

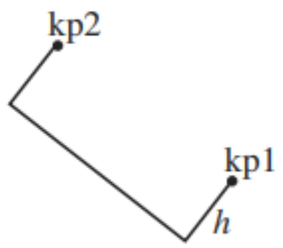
7.4.2 Element-macros of features used in magnet design

CornerIn & CornerOut



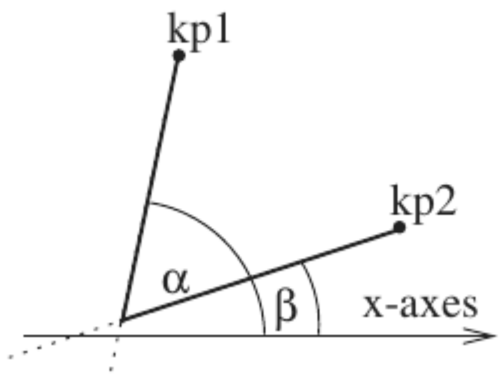
This line type creates a corner with both lines parallel to the y- and x-axes. This feature appears frequently in iron yokes of LHC magnets.

Bar



This line type creates three sides of a rectangle. The inclination and the orientation are determined by the sequence of the two key-points `kp1` and `kp2`. The first argument `arg1` (optional) is the height h of the rectangle (negative values change the orientation). The default value of the height is half of the distance between the two key-points.

Notch

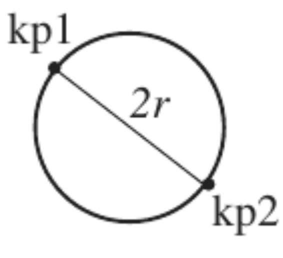


This line type creates a corner with two lines inclined by the angles α (arg1) and β (arg2). The default values are α = 0 and β = π/2.

7.4.3 Closed lines

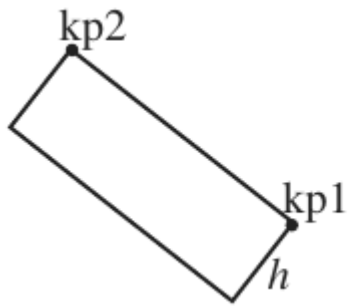
These lines border an area themselves. However, the area has to be defined afterwards using the `HyperArea` command (see Section HyperArea command).

Circle



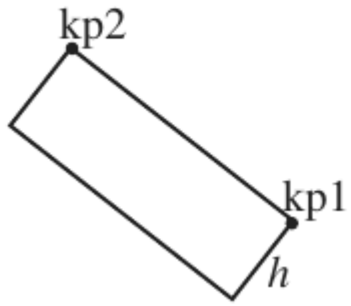
The `"Circle"` line type creates a circle with the two key-points `kp1` and `kp2` lying on a diameter.

Ellipse



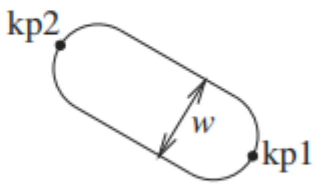
This keyword will yield an ellipse with one half axes defined by the two key-points `kp1` and `kp2`. The first argument (optional, default is $b=a$) either denotes the second half axes b of the ellipse or is the name of a third key-point lying on the ellipse (`kp3`).

Rectangle



This line type will draw a closed rectangle defined by the two key-points `kp1` and `kp2` and the first parameter ($h=$ `arg1`). If no argument is supplied then a square is drawn.

MillCut



This keyword will create a closed line as shown on the sketch. The main symmetry axes is defined by two key-points `kp1` and `kp2` . The first argument (optional, default is half of the distance between the two key-points) determines the width w of the object.

7.5 The HyperArea command

The `HyperArea` command is an extension of the old `Area` command. In contrast to the old command which needed a closed polygon consisting of four lines only, `HyperArea` can define areas that are bordered by any number N of lines. Of course the surrounding polygon has to be closed. If more than 2 lines are supplied the lines have to be **ordered in a mathematically positive sense** (anti clockwise). The exact grammar is as follows:

`ar1 = HyperArea(ln1,ln2,` ... `,ln` N `,material);`

The names of the lines have to start with the two letters `ln`, but are free otherwise. For better understanding the lines have been enumerated in our example. The last argument of `HyperArea` is regarded as the material of the area. The name of the material can be `BHiron1` -- `BHiron9` referring to one of the nine B-H curves given in the `roxie.bhdata` file or is simply `BHair` for a meshed air region (air region part of the FEM-domain) or `BH_air` for an air region without mesh (field computation via boundary elements).

7.6 The HyperHoleOf command

The `HyperHoleOf` command is necessary to define holes in areas. If for example area `ar1` lies entirely in area `ar2` (e.g. a hole in the iron yoke) the following line has to be included into the iron file after the definitions of both areas:

`HyperHoleOf(ar1,ar2);`

This signifies that `ar1` is a hole of `ar2`.

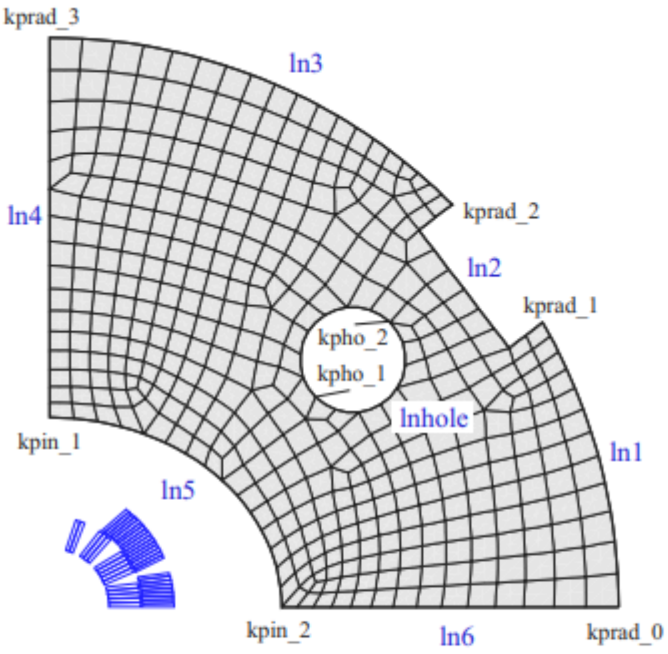
7.7 The Lmesh command

The `Lmesh` command serves for defining the mesh density in the domain.

`Lmesh(lnN,K);`

Where `lnN` is the line number `N` and `K` is the number of element edges along that line.

7.8 Example of the ".iron" file for mesh generation



This is the example input file for the above case:

```
HyperMesh;

mm=0.001;                Pi=3.14159265;
dv RADIUS=270;           radius=RADIUS*mm;
dv RAD_HO=50;            rad_ho=RAD_HO*mm;
dv ELL_A=110;            ell_a=ELL_A*mm;
dv ELL_B=90;             ell_b=ELL_B*mm;

kprad_0 = [radius @ 0];
kprad_1 = radius*[Cos(Pi/6), Sin(Pi/6)];
kprad_2 = [radius @ Pi/4];
```

```
kprad_3 = [0 , radius];
kpin_1  = [0 , ell_b];
kpin_2  = [ell_a , 0];
kpho_1  =  kprad_1 - 2*[kprad_0.x-kprad_1.x,0];
kpho_2  =  kpho_1 - [rad_ho/Sqrt(2.0), rad_ho/Sqrt(2.0)];

ln1  = HyperLine(kprad_1,kprad_0,"Arc",radius,0.4);
ln2  = HyperLine(kprad_1,kprad_2,"Bar",20*mm);
ln3  = HyperLine(kprad_3,kprad_2,"Arc",radius,0.6);
ln4  = HyperLine(kpin_1,kprad_3,"Line",0.4);
ln5  = HyperLine(kpin_1,kpin_2,"EllipticArc",ell_a,ell_b);
ln6  = HyperLine(kpin_2,kprad_0,"Line",0.4);
lnhole = HyperLine(kpho_1,kpho_2,"Circle");

aryoke = HyperArea(ln1,ln2,ln3,ln4,ln5,ln6,BHiron2);
arhole = HyperArea(lnhole, BH_air);
HyperHoleOf(arhole,aryoke);

Lmesh(ln1,12);
```

7.9 Mesh extrusion for 3-D problems

To generate a 3-D mesh from a 2-D cross-section by extrusion, a file: \<filename>.extrude is needed. HERMES first generates a 2-D .hmo-file and then it runs HMO2HMO3-D, which produces a 3-D file by "extrusion" into z-direction.

The .extrude-file has one line for every extrusion of an area defined in the .iron-file.\

Variable	**Type**	**Description**
name	String	Area name starting with ar....
start	Double	z-position of start of extrusion.
end	Double	z-position of start of extrusion.
bias	Double	Biasing of mesh spacing towards start- or end-position of extrusion.
num	Integer	Number of elements in z-direction.
mat	String	Material name.

The material name entry is optional. If no name is given, the material of the .iron-file is chosen. The input must be uniform, i.e., all entries must have a material name or no entry has it.

In the example of Chapter 7{reference-type="ref" reference="chap:hermes"}, an .extrude-file looks like this

```
aryoke -0.2 0.0 0.5 8 BHiron5
aryoke 0.0 0.2 0.5 8 BHiron2
```

The above file produces a 3-D mesh of material BHiron5 from -20 cm to 0 cm in z-direction with 8 elements. Subsequently the 2-D mesh is extruded into BHiron2 from 0 cm to 20 cm. Note that, if the 2-D cross-section contains more than one area (holes must not be extruded!), then the extrusion interval in z might be different for different areas. The author of the .extrude-file must ensure that the layers with element boundaries in z-direction match for all areas - even if the areas do not touch.

An extrude file for two areas, say `aryoke1` and `aryoke2` could look like this

```
aryoke1 0.0 0.4 0.5 3
aryoke2 0.0 0.4 0.5 3
aryoke2 0.4 0.5 0.5 1
```

Now `aryoke1` and `aryoke2` are extruded from 0.0 cm to 40.0 cm and `aryoke2` continuous from 40.0 cm to 50.0 cm. In this examples the material is assigned to the areas that is specified in the 2-D .iron-file.

8. Numerical Field Calculation

This chapter treats the calculation of electromagnetic fields in presence of non-linear magnetic material. In 2-D there are two different methods available: A reduced vector-potential formulation for a Finite Element (FEM) approach and a total vector-potential formulation for a hybrid method of boundary elements (BEM) and finite elements. Permanent magnets, non-linear (differential) inductivity, and force calculations are implemented in the BEM-FEM code. In 3-D, ROXIE offers a magnetic scalar-potential- and a magnetic vector-potential formulation for a BEM-FEM calculation. A mesh generator is available for parametric 2-D mesh generation and extrusion of 2-D meshes in z-direction.

8.1 The BHDATA file

The roxie.bhdata-file has information on the magnetization curves of ten different materials, `BHiron1 - BHiron10`. Each material has one data block in the roxie.bhdata-file. A block starts with two data lines which are followed by a data table. The first line gives the material name `BHironX` The second line is structured as follows:

Variable	Type	Description
num	Integer	Number of measurement points in the table.
fil	Double	Stacking factor of the yoke in z-direction.

The tabular data has `num` lines with entries for B [T] and H [A/m]:

Variable	Type	Description
B	Double	Magnetic induction in Tesla.
H	Double	Magnetic field in Ampère/meter.

Material names and comments are often written following the last data line in a table.

- Each table in the roxie.bhdata-file must start with the origin, i.e., B=0, H=0.
- Especially in dense 3-D calculations, the quality of the B(H)-curve determines the speed of convergence. Even **non-convergence** has been observed, leading to inaccurate results. In cases of non-convergence: check your ROXIE model for input errors; check your B(H)-curve for unphysical behavior; make the mesh coarser.
- ROXIE assumes that a material is completely saturated if a **magnetic induction B exceeds the data** given in the roxie.bhdata-file. Above the B-values in the respective data-table ROXIE calculates with the magnetic permeability of free space. This can be a nasty pitfall when you calculate with B(H)-curves of linearly permeable material. Recall, however, that no material retains a high permeability up to very large magnetic induction!

Never forget that a simulation including non-linear material can only be as accurate as the user supplied material-data.

8.2 General options for numerical field calculation

8.2.1 FEM/BEMFEM Options

Option	Description
Mesh-Generator	Produce a Finite Element mesh from an .iron-file.
Post-proc. only	For non-transient BEMFEM calculations in 2-D only. Such changes to post-processing parameters may be made which do not require recalculation of the problem.

8.3 Global information

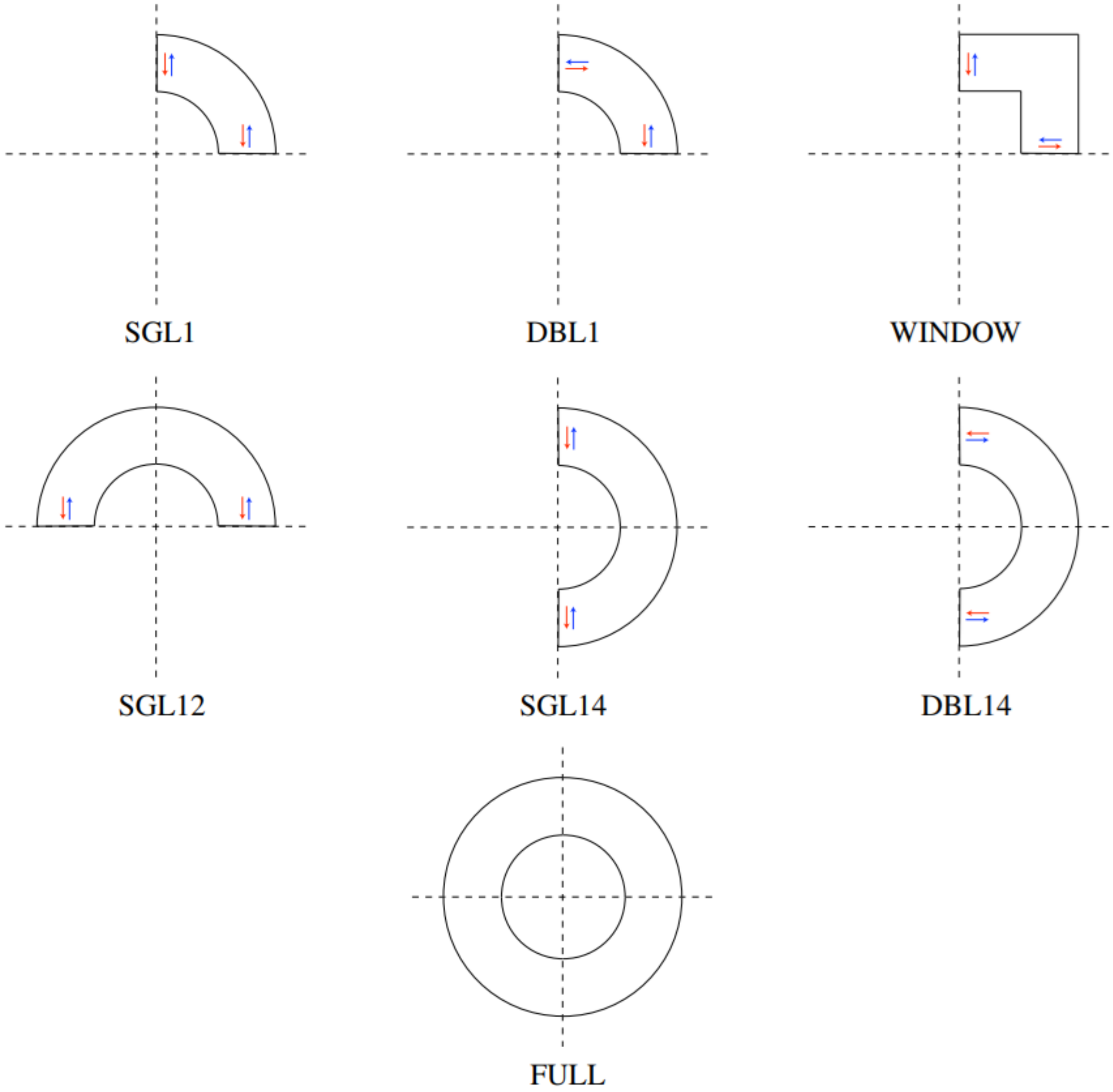
Set the "Optimization Algorithm"-variable to "Mutual Inductances in Nl. Circuits" to calculate the differential mutual inductances.

8.3.1 Design variables

Plotting:

Variable	Description
HMOMM	Dimensions in .hmo file given in mm.

- The .hmo-file has geometrical data usually given in meters. If, however, the data is to be read in millimeters, the **HMOMM**-option passes this information to ROXIE.
- The boundary conditions settings in the "FEM"-, "BEMFEM 2D"-, "BEMFEM 3D (Half)"-, and "BEMFEM 3D (Full)"-menus of the "Design Variables" apply to all 2-D (and 3-D) calculations. Parallel arrows to the symmetry planes correspond to a Dirichlet boundary condition, $B_n = 0$. Perpendicular arrows correspond to a Neumann boundary condition, H_t.



8.3.2 Objectives

The following options are available for both 2-D algorithms, FEM and BEM-FEM:

Normal Multipoles:

Variable	Description
BIR	Geometry and iron.
BIRR	Relative BIR.

Skew Multipoles:

Variable	Description
AIR	Gemetry and iron.
AIRR	Relative AIR.

Global Values:

Variable	Description
SINDU	Self inductance, see also SectionTransfer function and Section Differential inductance.
SINDUD	Differential self inductance, see also Section SectionTransfer function and Section Differential inductance.

8.3.3 Plotting Information 2-D

Aperture:

Variable	Description
MATR	Field vectors in cross-section. Modulus represented by arrow size.
MATRC	Field vectors in cross-section Modulus represented by color code.
MATRP	Like MATR but only field from SC-magnetization (PCs, ISCCs analytic model, IFCCs).

Note that the **MATR**, **MATRC**- and **MATRP**-options have to be used with the "**Field-Vector Matrix**"-option from the "Interface Options". The option lets the user define the matrix spacing and produces an output file. The reduced field from numerical field calculations is only taken into account if the "Field-Vector Matrix"-option is used.

Coil fields

Variable	Description
ARED	Reduced A.
BR	Reduced |B|.
BREDX	Reduced Bx.
BREDY	Reduced By.

8.3.4 Interface options

Option	Description
Field-Vector Matrix (Map)	Define a field-vector matrix and produce a file. A widget opens in the GUI. The reduced field from numerical field calculations is taken into account.

8.4 2-D reduced FEM

8.4.1 FEM/BEMFEM Options

Option	Description
Reduced Ar FEM	Use the 2-D reduced vector-potential solver.

- To use the **reduced vector-potential solver**, the entire problem domain needs to be meshed. The coils themselves yield a source vector-potential contribution to the solution calculated by Biot-Savart's law. The coil domain thus does not to be modeled in the mesh geometrically, although it needs to be covered by the mesh.

8.4.2 Design variables

FEM:

Compare the drawings on page .

Variable	Description
SYMMR	Maximum angle for harmonic analysis within FEM area (90/180/360). Contrary to BEM-FEM calculations a harmonic analysis outside the FEM-domain is not possible!
RIHARM	Rescaling of radius for harmonic analysis. The field harmonics are rescaled from the radius value given in the "Global Information" to this radius. A larger value in the "Global Information" might yield better accuracy, depending on the FEM mesh.
SGL1	Single aperture dipole with yoke defined in 1st quadrant.
DBL1	Double apperture dipole / single aperture quadrupole with yoke in 1st quadrant.
WINDOW	Window frame dipole with yoke in 1 quadrant.
SGL12	Single/double aperture dipole with yoke in 1st and 2nd quadrant.
SGL14	Single aperture dipole / single aperture quadrupole with yoke in 1st and 4th quadrant.
DBL14	Double aperture dipole with yoke defined in 1st and 4th quadrant.
FULL	No symmetry planes.

8.4.3 Plotting information 2-D

FEM:

Variable	Description
MESH	Finite-elemet mesh.
IRON	Iron yoke.
AR	Reduced vector potential A.
|BRED|	Reduced magnetic field $\|B_r\|$ (iron magnetization only).
|BTOT|	Total magnetic field $\|B_t\|$ (iron and coil).
|BS|	Source field $\|B_s\|$ (coil only).
MUE	Relative magnetic permeability μ_r in iron yoke.
MUEFAC	$(\mu_r-1) / (\mu_r + 1)$ in iron yoke.

8.5 2-D BEM-FEM coupling

8.5.1 FEM/BEMFEM Options

Option	Description
Vect.Pot. BEMFEM	Use the 2-D coupling method of Finite Elements (yoke iron) and Boundary elements (coils, air region).

- Contrary to the reduced vector-potential FEM, with **BEM-FEM** coupling the air- and coil regions need not be meshed.

Post-proc. only allows to re-process 2-D field plots without running the solver again. Notice that the evaluated field points must not be altered.

Pre-proc and plotting allows to display 2-D and 3-D coils and finite element meshes without running the solver. Notice that the LBEMFEM or the LEDYSON options nevertheless have to be set on true. This has to be done in order to activate the appropriate pre-processors and data transfer routines.

8.5.2 Design variables

BEMFEM 2-D:

Compare the drawings on page .

Variable	Description
SGL1	Bn(x=0)=0,\;Ht(y=0)=0 (single aperture dipole with yoke defined in 1st quadrant).
DBL1	Ht(x=0)=0,\;Ht(y=0)=0 (double aperture dipole / single aperture quadrupole with yoke in 1st quadrant).
WINDOW	Bn(x=0)=0,\;Bn(y=0)=0 (window frame dipole with yoke in 1st quadrant).
SGL12	No boundary condition at x=0, Ht(y=0)=0 (single/ double aperture dipole with yoke in 1st and 2nd quadrant).
SGL14	Bn(x=0)=0, no boundary condition at (y=0) (single aperture dipole / single aperture quadrupole with yoke in 1st and 4th quadrant).
DBL14	Ht(x=0)=0, no boundary condition at (y=0) (double aperture dipole with yoke defined in 1st and 4th quadrant).
FULL	No symmetry planes.
CURRY	Index to coil (FEM coils). Not yet documented.
FRINGR	Radius of fringe field calculation
FRINGA	Maximum angle for fringe field calculation (from x-axis).
ACCIMP	Improved accuracy of the GMRES iteration of BEMFEM (70dB instead of 55dB).
NSTEPS	Set maximum number of steps in Newton-Algorithm to 10 (instead of 50).

- The **FRINGR**- and **FRINGA**-options produce plots in the .post-files that show the magnetic field (components and total) on an arc around the coordinate centre.

8.5.3 Plotting information 2-D

BEMFEM:

Variable	Description
MESH	Finite-element mesh.
IRON	Iron yoke.
AR	Total vector potential A in FEM domain.
|BTOT|	Total magnetic field |B| in FEM domain.
MUE	Relative magnetic permeability μ_r in iron yoke.
MUEFAC	$(\mu_r\text{-}1) / (\mu_r + 1)$ in iron yoke.

- To plot the iron yoke and/or information on the iron yoke, the **IRON**-option must be specified together with the field, e.g., 'IRON AR' will plot the vector potential in the yoke, whereas only 'AR' will not have any effect.

8.6 3-D BEM-FEM coupling

With the "3-D Coil Geometry"-option 'on' in the "Main options", ROXIE expects also a 3-D mesh and uses 3-D numerical algorithms. The choice in the algorithms is between a total vector-potential BEM-FEM formulation and a total scalar-potential BEM-FEM formulation. All options (other than the choice of a formulation) in this section apply to both, the vector-potential- and the scalar-potential formulation.

8.6.1 FEM/BEMFEM Options

Option	Description
Vect.Pot. BEMFEM	3-D coupling method of Finite Elements (yoke iron) and Boundary elements (coils, air region). The problem is formulated in terms of the 3 components of the magnetic vector potential.
PSItot BEMFEM	3-D coupling method of Finite Elements (yoke iron) and Boundary elements (coils, air region). The problem is formulated in terms of the magnetic scalar potential.

- The "**Vect.Pot. BEMFEM**"-option, due to the linear, mesh-point-wise approximation of the three components of the magnetic vector potential, cannot approximate jumps in the vector potential. These jumps occur on sharp edges and corners in the presence of important jumps of the magnetic permeability at the edge/corner. These problem-types might lead to unphysical and inaccurate results.

The "**PSItot BEMFEM**"-option avoids the above problem. It is available, however, only for single-aperture magnets, i.e., if the coil is centered at the origin.

8.6.2 Design variables

BEMFEM 3-D (half):

The "half"-versions of boundary conditions assume that the iron yoke is mirror-symmetric with respect to the (z=0)-plane. Compare the drawings on page .

Variable	Description
SGLH1	Bn(x=0)=0,\;Ht(y=0)=0 (single aperture dipole with yoke defined in 1st quadrant).
DBLH1	Ht(x=0)=0,\;Ht(y=0)=0 (double aperture dipole / single aperture quadrupole with yoke in 1st quadrant).
WINDOH	Bn(x=0)=0,\;Bn(y=0)=0 (window frame dipole with yoke in 1st quadrant).
SGLH12	No boundary condition at x=0, Ht(y=0)=0 (single- / double aperture dipole with yoke in 1st and 2nd quadrant).
SGLH14	Bn(x=0)=0, no boundary condition at (y=0) (single aperture dipole / single aperture quadrupole with yoke in 1st and 4th quadrant).
DBLH14	Ht(x=0)=0, no boundary condition at (y=0) (double aperture dipole with yoke defined in 1st and 4th quadrant).
FULLH	No symmetry planes.

BEMFEM 3-D (full):

The "full"-versions of boundary conditions assume that the iron yoke has no symmetries in z-direction.

Variable	Description
SGLF1	Bn(x=0)=0,\;Ht(y=0)=0 (single aperture dipole with yoke defined in 1st quadrant).
DBLF1	Ht(x=0)=0,\;Ht(y=0)=0 (double aperture dipole / single aperture quadrupole with yoke in 1st quadrant).
WINDOF	Bn(x=0)=0,\;Bn(y=0)=0 (window frame dipole with yoke in 1st quadrant).
SGLF12	No boundary condition at x=0, Ht(y=0)=0 (single- / double aperture dipole with yoke in 1st and 2nd quadrant).
SGLF14	Bn(x=0)=0, no boundary condition at (y=0) (single aperture dipole / single aperture quadrupole with yoke in 1st and 4th quadrant).
DBLF14	Ht(x=0)=0, no boundary condition at (y=0) (double aperture dipole with yoke defined in 1st and 4th quadrant).
FULLF	No symmetry planes.

8.6.3 Objectives

Peak Fields:

Variable	Description
STRFEL	Field along strand (with LEND and line-field option).

Peak field calculations in 3-D with iron are computationally extremely costly and therefore not implemented in ROXIE. The 'STRFEL' option allows to calculate the field along a single strand in 3-D, including source- and iron field. To use 'STRFEL' you have to specify the strand number in the "Nor" column, "PLOT" in the "Oper" column and 1 and 1 for the remaining columns. Furthermore you have to switch "on" the "Field along a Line (2-D,3-D)" option in the "Interface Options" and supply dummy values. ROXIE then uses its algorithms for a field along a line. The points along the line are located in the line-current segments which constitute a strand. For an example see Section 3D Peak Field Calculation.

8.6.4 Plotting information 3-D

In 3-D plots, the iron yoke is always represented when the respective "FEM/BEMFEM Options"-options are 'on'. Unless the 'SUN'-option is chosen, the magnetic induction is displayed on the surface elements of the iron yoke.

8.7 Transfer functions

8.7.1 Main options

Option	Description
Transfer Function	Calculate field at different levels of excitation.

- The "**Transfer Function**"-option triggers a series of successive calculations. It is not a time-stepping. No time-transient effects are taken into account. The "Transfer Function"-option is primarily used to determine the influence of yoke saturation on the field quality.

8.7.2 Objectives

Global values:

Variable	Description
NIB	N I / Bref
BOVERI	Transfer function Bref/I (in T/kA).
SINDU	Self inductance, see Section Differential Inductance.
SINDUD	Differential self inductance, see also Section Differential Inductance.

- With the "Self and Mutual Inductance"-option switched 'on' in the "Global Information", the **SINDU**- and **SINDUD**-options let you evaluate the linear and differential inductance of the magnetic circuit during a transfer function. A plot is produced if the "Postscript Plots"-option is 'on' that shows L and L_\mathrm{d} as a function of excitation.

Normal multipoles (vers. excit.):

Variable	Description
BIRI	Normal multipoles (injection field level).
BIRRI	Relative BIRI.
BIRN	Normal multipoles (nominal field level).
BIRRN	Relative BIRN.
BIRD	Normal multipoles (variation).
BIRRD	Relative BIRD.

Skew multipoles (vers. excit.):

Variable	Description
AIRI	Skew multipoles (injection field level).
AIRRI	Relative AIRI.
AIRN	Skew multipoles (nominal field level).
AIRRN	Relative AIRN.
AIRD	Skew multipoles (variation).
AIRRD	Relative AIRD.

- For the **BIRI**- and **AIRI**-options the injection field level is assumed to be the first level in the "Transfer Function"-widget.
- For the **BIRN**- and **AIRN**-options the nominal field level is assumed to be the last level in the "Transfer Function"-widget.

8.7.3 Transfer function

The input in the line of the "Transfer Function"-widget is a space-delimitted enumeration of excitation factors. The currents given in the "Block Data 2-D"-widget are scaled by each of the given values successively.

8.8 Permanent magnets in 2-D

8.8.1 FEM/BEMFEM options

Option	Description
Permanent Magnets	Read in magnetization data from .VEFI-file and assign to areas in .iron-file according to design variables (see below).

8.8.2 Design variables

BEMFEM 2-D:

Variable	Description
HARD	Index to magnetization vector field compare Section Permanent magnets in 2d.

- For the **HARD**-option, the value in the "Xl, Xu, Xs"-columns of the table is of integer type. It points to a vector field defined in the so-called .VEFI-file, see SectionVefi file. The number in the right column of the design variables points to an area in the .iron-file. In fact, it rather points to a material name. A number 2 in the right table corresponds to the second material name in the first block of the .hmo-file, see Section HMO file. You therefore need to check the .hmo-file in a first run before you can assign vector fields. The magnetic characteristic of the permanent magnet is given in the roxie.bhdata-file under the respective material name. For an example see Section Permanent magnets in 2d.

8.8.3 The VEFI file

The .VEFI-file defines vector fields for the calculation of (hard) permanent magnets in 2-D. The .VEFI-file is used in connection with an .iron-file and a .data-file that uses the option 'HARD' in the "Design variables"-table. For an example see Section Permanent magnets in 2d.The first line of the .VEFI-file has two parameters:

Variable	Type	Description
NFIELD	Integer	Number of vector fields to be defined.
TBLOCK	Integer	Total number of building blocks.

Then follows the definition of each vector field that consists of a header record and a sequence of pairs of records specifying the building blocks. The header record has three parameters:

Variable	Type	Description
IFIELD	Integer	Consecutive number of vector field.
NBLOCK	Integer	Number of building blocks for the vector field.
FACT	Double	Scaling factor for the vector field.

The first line of the building block data yields the following parameters:\

Variable	Type	Description
IBLOCK	Integer	Consecutive number of building block.
PCOSY	Integer	Pointer to the frame of reference.
ITYP	Integer	Type of coordinate system (1: Cartesian, 2: cylindrical).
IDIR	INTEGER	Direction of the vector field (+/-1: first, +/-2: second, +-3: third basis vector).
ILIMIT(3)	Integer	Flags specifying the type of inequality for the range of each coordinate (see below).

The second line has the limit parameters:\

Variable	Type	Description
XYZLO(3)	Double	Lower limits for the range of each coordinate.
XYZHI(3)	Double	Upper limits for the range of each coordinate.

The ILIMIT flags have the following meaning, e.g. for the x-coordinate:

ILIMIT=0 $-\infty \le x \le \infty$

ILIMIT=1 $-\infty \le x \le x_{high}$

ILIMIT=2 $x_{low}. \le x \le \infty$

ILIMIT=3 $x_{low}. \le x \le x_{high}$

9. SC-Related Time-Transient Effects

This chapter introduces ROXIE features to simulate superconductor magnetization, the persistent currents (PCs), as well as Eddy-Current effects on the strand level, the interfilament coupling currents (IFCCs) and on the conductor level, the interstrand coupling currents (ISCCs) in Rutherford-type cables. The PC models have been developed at CERN whereas the analytical models for IFCCs and ISCCs are based on models by M. Wilson. A network model for more accurate modeling of ISCCs is equally available.

All models in this chapter have in common that they should be used with the "Layer Definition"-option in the "Main Options". For the use of semi-analytical models, the "Symmetry: 0: Gen., 1: in1, 2: 2in1"-option in the "Time Transient Effects"-widges allows to make use of coil symmetries nevertheless.

The term 'SC magnetization' is used for all quantities in ROXIE's semi-analytical models, also for Eddy-Current effects such as IFCCs and ISCCs. These effects are modeled as magnetizations on the strand/cable level.

9.1 Semi-analytical models for SC magnetization

The main material parameters for the SC magnetization models are found in the roxie.cadata-file which is editable via the "Open cable data window (.cadata)"-entry in the "Run"-menu. Main input parameters are found in the "Time Transient Effects"-widget.

The analytical formula to compute the strand-magnetization from PCs is given by:

$$M = \sum_{i=1}^{n} M_i = \sum_{i=1}^{n} \int_{q_i}^{q_{i+1}} m_i(q)\,\mathrm{d}q.$$

$$\begin{aligned} M_i &= \frac{4r\xi}{\pi} \int_{q_i}^{q_{i+1}} J_\mathrm{c}(B(q))(1-q)^2\,\mathrm{d}q \\ &= \frac{4r\xi\mathcal{F}}{\mu_0\pi} \int_{q_i}^{q_{i+1}} \frac{(1-q)^2}{\sqrt{B(q)}}\,\mathrm{d}q, \end{aligned}$$

$$M_i = \frac{4rB(q)}{5\pi\mathcal{F}^2\mu_0^2\mathcal{H}^3}\left[B_\mathrm{ext}^3 + \xi\mathcal{H}\mathcal{F}\mu_0\left(\left(5-4q+\frac{5}{4}q^2\right)\xi\mathcal{H}\mathcal{F}\mu_0 - (q-4)B_\mathrm{ext}^{3/2}\right)\right]\Bigg|_{q=q_i}^{q=q_{i+1}}$$

The IFCCs are evaluated from:

$$M_\mathrm{f} = \lambda_\mathrm{w}\,\partial_t B\,\frac{l_\mathrm{w}}{2\pi}\underbrace{\frac{1}{\rho_0+\rho_1 B}}_{\rho_\mathrm{eff.}}.$$

The user is required to provide the wire filling-factor λw, the wire twist-pitch lw and the effective resistivity ρeff which consists of a constant part ρ0 and a coefficient due to magneto resistance ρ1.

ISCCs are calculated as the sum of the following components:

$$
\begin{aligned}
M_{\mathrm{c}}^{\perp} &= \frac{1}{120}\,\frac{\partial_t B^{\perp}}{R_{\mathrm{c}}}\,l_{\mathrm{c}}\,N(N-1)\,\frac{c}{b},\\
M_{\mathrm{a}}^{\perp} &= \frac{1}{3}\,\frac{\partial_t B^{\perp}}{R_{\mathrm{a}}}\,l_{\mathrm{c}}\,\frac{c}{b},\\
M_{\mathrm{a}}^{\parallel} &= \frac{1}{8}\,\frac{\partial_t B^{\parallel}}{R_{\mathrm{a}}}\,l_{\mathrm{c}}\,\frac{b}{c}.
\end{aligned}
$$

The user provides the cable twist-pitch lc, the contact- and adjacent resistances, Rc, Ra and the cable dimensions b (narrow side - the mean value is taken for keystoned cables) and c (broad side).

9.1.1 Main options

Option	**Description**
Time Transient	Perform a time-stepping, evaluate superconductor magnetization.

9.1.2 Design variables

Layers:

Variable	**Description**
FILDIL	Filament Diameter in layer (in \mum).

Coil Blocks (Cross-Section):

Variable	**Description**
FILDIA	Filament Diameter in block (in \mum).
TEMPBL	Operation temperature in block.

- The **TEMPBL**-option sets the operation temperature in specified blocks, e.g., to test the impact of an inhomogeneous cooling on the margins to quench or on persistent currents. The TEMPBL-option is used with features that use the critical-current fit function and not with those that use the linear approximation thereof.

Magnetization:

Variable	**Description**
STRPRI	Print info of specified strand(s).
ABSCIS	Field harmonic versus excitation- (B_n versus I) plot (see objectives): take I of specified block number (default is block 1).

9.1.3 Objectives

Magnetization data:

Variable	Description
MSTR	Magnetization in filament.
BSTR	Magnetic induction in filament.
MSTRT	Magnetization modulus.
BSTRT	Magnetic modulus.
MSTRF	Angle of magnetization.
BSTRF	Angle of magnetic induction.
AB	Skew and normal harmonics in one plot. Currently not supported.
DTRF	Current factor of block as function of time.

- The **MSTR***- and **BSTR***- and **DTRF**-options plot excitation, field and resulting strand magnetization. The x-axis data varies between the chosen analytical model: IFCCs and PCs-option 1 and 3 yield plots over the excitation current (of the first block); ISCCs and PCs-option 4 plot over the time. For the latter two options, the **MSTRF**- and **BSTRF**-options yield the angular information of the respective strand's magnetization and excitation.

9.1.4 Plotting Information 2-D

Coil fields:

Variable	Description
MX	SC magnetization (x-component).
MY	SC magnetization (y-component).
|M|	SC magnetization (modulus*sign).
MMOD	SC magnetization (modulus).
M	SC magnetization vectors.
P	Losses per strand in W/m. The losses due to filament/strand/cable-magnetization is computed as \frac{\mathrm{d}\mathbf{M}\cdot \mathbf{B}}{\mathrm{d}t}. For the ISCC magnetization model this yields the Ohm's losses.
PINT	The integral \int \mathbf{M}\cdot\mathrm{d}\mathbf{B} is calculated and updated at every time step. The result is the integrated magnetization losses for PCs, IFCCs and the ISCC magnetization model in J/m.
BPERP	B perpendicular to broad face of the conductor.
BPARA	B parallel to broad face of the conductor.

Bn strand contr. of M:

Variable	Description
M1	B_1 contribution of SC magnetization.
M2	B_2 contribution of SC magnetization.
M3	B_3 contribution of SC magnetization.
M4	B_4 contribution of SC magnetization.
M5	B_5 contribution of SC magnetization.
M6	B_6 contribution of SC magnetization.
M7	B_7 contribution of SC magnetization.
M8	B_8 contribution of SC magnetization.
M9	B_9 contribution of SC magnetization.
M10	B_{10} contribution of SC magnetization.
M11	B_{11} contribution of SC magnetization.

9.1.5 Time Transient Effects

Options

Option	Description
IFCC (Wilson)	Interfilament Coupling Currents - analytical model by M. Wilson.
ISCC (Wilson Analytic)	Interstrand Coupling Currents - analytical model by M. Wilson.
Nonlinear Inner Iterations	Only with BEMFEM calculations of a nonlinear iron yoke are 'on'. This option makes ROXIE recalculate the contribution of the iron yoke at every step of the inner magnetization iteration. If 'off' the nonlinear iron yoke is only calculated before the first and after the last step of the inner iteration.
Plotting Magn. Fields Only	The harmonic analysis is done only from the fields due to SC magnetization. The perturbation of the field quality due to SC magnetization is calculated.

- The "**IFCC (Wilson)**"-option uses a formula to evaluate the total strand magnetization which does not take into account those Eddy-Current loops that close in the outer copper coating of the strand, i.e., it assumes a highly resistive barrier between the filaments and the outer coating.
- The "**ISCC (Wilson Analytic)**"-option a homogeneous magnetization in each conductor. The nature of ISCCs is better represented in a network model, see Section 9.2{reference-type="ref" reference="sec:transientnetwork"}.

Parameters

Variable	Description
PC: 0:None; 1,3:1D; 4:Vector	Persistent Current (PC) calculations. '0': no PC calculation; '1','3': two implementations of the same 1D persistent current model; '4': vector hysteresis model for field-changes in modulus and direction.
Symmetry: 0: Gen., 1: 1in1, 2: 2in1	To use time-transient effects, you should use the layer-option which generates the full coils. If there is a symmetry, then you may specify only the blocks first quadrant (in the right aperture) in the "Block spec. (Peak fields, Forces, FEM plots)"-widget. SC-magnetization is then only evaluated in these blocks. The contribution of the other blocks in the layer is considered automatically.
Start Time for Loss Calculation	Start time for loss calculation (in seconds).
End Time for Loss Calculation	End time for loss calculation (in seconds).
Start Time for Multipole Variation	The BIRD- and BIRRD-options in the "Objectives"-table calculate the multipole variation during a transfer function or during a transient calculation. For the latter, the time-frame for the variation can be given.
Start Time for Multipole Variation	The BIRD- and BIRRD-options in the "Objectives"-table calculate the multipole variation during a transfer function or during a transient calculation. For the latter, the time-frame for the variation can be given.
Maximum Number of Iterations	Maxim number of iterations in the determination of the SC magnetization.

Time-Grid definition

The table for the definition of a stepping time-grid has the following columns.

Variable	Description
No	Number of interval.
Ts	Start time of interval (seconds).
Te	End time of interval (seconds).
Steps	Number of time steps in interval.

Excitation function definition

The table for the definition of excitation functions for each block of conductors has the following columns. Each block can be assigned a number of successive excitation functions over time intervals that need not be the same as the stepping intervals in the table above. At every step of the stepping table each block must be assigned one (and only one) excitation function.

Variable	**Description**
No	Number of excitation function definition.
Ts	Start of excitation interval.
Te	End of excitation interval.
Function	Predefined excitation functions.
1: Linear ramp, from A(T_\mathrm{s}) to B(T_\mathrm{e}),	
2: A+B\cos(C t + D),	
3: Parabolic from A(T_\mathrm{s}) to B(T_\mathrm{e}) with acceleration C, \frac{C}{2}t^2 + \beta t + \gamma, where \beta and \gamma are calculated to match A and B at T_\mathrm{s} and T_\mathrm{e}.	
4: Exponential from A(T_\mathrm{s}) with derivative B,	
5: Quadratic from A(T_\mathrm{s}) with maximum slope C and linear slope increase during B\,\Delta T, compare Fig. 9.1. Parameter D is '1': ramp up, '2': ram up and down, '3': ramp down.	
A	Function parameter A.
B	Function parameter B.
C	Function parameter C.
D	Function parameter D.
Blocks,Layers	With the "Symmetric Coil"-option blocks are assigned the excitation function in the specified time interval. With the "Layer Definition"-option, individual layers are assigned excitation functions.

- **Function** number 5 with D=2: In this case the \Delta T in Fig. 9.1{reference-type="ref" reference="fig:gsiexcitationfunction"} is set to (T_\mathrm{e}-T_\mathrm{s})/2.

Quadratic excitation function as used in fast-ramping magnets.

9.2 Network model of Interstrand Coupling Currents

For the simulation of interstrand coupling currents an electrical-network model is implemented in ROXIE. In this model, interstrand coupling currents are not treated as an additional magnetization of the SC conductors (as in the above analytical model) but as additional (positive and negative) line currents in the position of each strand.

The network model of ISCCs cannot be used with nonlinear iron.

9.2.1 Plotting Information 2-D

Current distribution:

Variable	Description
ICC	Interstrand coupling currents.

9.2.2 Time transient effects

Options:

All analytical SC magnetization models must be 'off'.

Option	Description
ISCC (Network Model)	Network model (without inductance matrix for interstrand coupling current determination.
LICC + Mut. Inductances	Compute and use the inductance matrix in the network model.
Plotting Magn. Fields Only The harmonic analysis is done only from the fields due to ISCCs. The perturbation of the field quality due to ISCCs is calculated.	

Parameters:

The "Symmetry"-parameter should be set to zero and all blocks be specified in the "Block spec. (Peak fields, Forces, FEM plots)"-widget.

Time-grid definition:

The same time-grid definition is used as for the analytical models.

Excitation Function Definition:

The excitation function is defined in the same way as for the analytical models.

9.3 Quench Calculation

ROXIE features a new quench simulation tool. The tool is currently under development. A first version is available in ROXIE 9.3. This version corresponds to the IEEE paper [@Schwerg:2007lr] by Nikolai Schwerg. It is highly recommended to read this paper before using the algorithm.

To do quench simulation, the following options need to be set

- "Quench Calculation" in "Global Information".
- "Self and Mutual Inductance" in "Global Information".
- "Quench and Temperature Margin" in "Global Information".
- "Peak Field in Coil" in "Global Information".
- "Time Transients" in "Main Options". For a description of the "Time Transients"-widget in the context of quench, see Section 4.3{reference-type="ref" reference="sec:quench_ex"}.
- "Layer Definition" in "Main Options".
- All conductors must be specified in the "Block spec." widget.
- A winding scheme needs to be specified, see Section 4.3{reference-type="ref" reference="sec:quench_ex"}.

Quench calculation with ROXIE automatically produces a number of files for post-processing with gnuplot:

- The roxie.dat file contains about 30 quantities over time, one row per time-step. The description is found in the last line of the file.

roxie.QUENCH is an event-history of the quench simulator.

- .xdat-files contain relevant data per conductor and time-step.
- .xsp-files are overwritten in each time step. By calling

gnuplot load "filename.xsp"

you can plot cross-section data.

- .gnu-files are gnuplot macros to display .xdat and files and the roxie.dat file. They are loaded by

gnuplot load "filename.gnu"

The files can also be viewed during a simulation run. Update a view by typing the gnuplot command "e".

- Overview.gnu shows the characteristic quantities (voltages, current, resistances, and temperature).
- Powers.gnu shows the dissipated power over the coil cross-section.
- Xsections.gnu shows cross-section data (temperature margin, field, resistances, and temperature).
- Voltages.gnu shows voltages versus time (terminal voltage, induced voltage, ohmic voltage, dump resistor voltage, diode voltage).

The following gnuplot macros produce postscript files

- Report.gnu reports the most characteristic quanities over time and in the cross-section.
- roxie.dat.gnu Illustrates the roxie.dat file (see above).

Note that all the output files can take several hundreds of megabytes of disc space!

9.3.1 Global information

Option	Description
Quench Calculation	Perform a quench simulation.
Winding Scheme Input	Change the conductor numbering in the preview window according to winding scheme.

- For the quench algorithm the user is required to supply the winding scheme of the magnet's coils. The **"Winding Scheme Input"**-option serves to debug the winding-scheme input.
- The winding-scheme input is documented in an example in Section 4.3{reference-type="ref" reference="sec:quench_ex"}.

9.3.2 Design variables

Quench, Inductance:

Variable	Description
QUENCH	Conductor number in which quench originates. Use the conductor number from the preview window with the "Winding Scheme Input"-option 'off'.
QLOSST	Time constant of interstrand coupling currents.
HEATTT	Heat transfer coefficient from turn to turn per unit length.
HEATER	Heater delay (in seconds) for specified conductor (covered by the heater). Use the conductor number from the preview window with the "Winding Scheme Input"-option 'off'.
HEATP0	Power per conductor per length (either exponentially decaying or constant).
HEATTA	Time constant (in seconds) for exponential heater power (needs HEATP0 to be set).
DUMPR	Dump resistor (ohm).
DUMPT	Delay (in seconds) for switching-in of the dump resistor.
QDIOD	Diode threshold voltage (V).
QDIODR	Diode forward resistance (ohm).
QUTH	Quench detection threshold voltage (V) (on the terminal of the magnet).
QMI	Maximum number of time-steps.
QCD	Number of discretization steps for field re-calculation (based on magnetic energy change) (default = 50).
QIMF	Lower threshold (in terms of a fraction of the initial current) to stop quench calculation (default = 0.001).
RUNGES	Minimum time step size (seconds) for adaptive Runge-Kutta (default = 0.0001).
RUNGEM	Maximum time step size (seconds) for adaptive Runge-Kutta (default = 0.1).
RRR	RRR for conductors in layer.

- **"HEATTT"** is the heat conductance per unit length between adjacent conductors (in $\mathrm{W}\mathrm{m}^{-1}\mathrm{K}^{-1}$).

If the **"HEATER"** variable is not specified for a conductor (or set to zero), then the conductor is not covered by a heater.

A conductor covered by a quench heater will quench after the heater delay if "HEATP0" and "HEATTA" are not set. If "HEATP0" and "HEATTA" are set, then the conductor quenches when the heaters have supplied enough energy to increase the conductor temperature above the critical value.

If **"HEATP0"** is set, then a constant heating power is transferred to a conductor covered by a quench heater.

If, in addition to "HEATP0", **"HEATTA"** is specified, then the heating power decays exponentially with "HEATTA" as a time constant.

If **"QUTH"** is not set, then the quench is assumed to be detected immediately. Otherwise, heater- and dump-resistor delays ("HEATER" and "DUMPT") are counted from the time, when the quench detection voltage is reached at the magnet terminals.

If the **"QDIOD"** value is not specified or set to zero, then the magnet is immediately short-circuited. The "QUTH" value is then obsolete and the quench is immediately detected.

The magnetic field is not calculated in every time-step of the quench calculation, but only at **"QCD"** excitation levels. The value must be sufficiently high to resolve the nonlinear iron-yoke response, but sufficiently small to allow for a reasonably fast simulation.

The **"RUNGES"** and **"RUNGEM"** values determine the bounds for the adaptive time-step algorithm. If both are set to the same value, the time-stepping is no longer adaptive.

Note that for plotting graphs from the "Objectives" widget, no more than 200 points can be considered. If you want to plot, e.g., the terminal voltage over time from the "Objectives"-table, **"QMI"** must not have a value above 199. Note however that alternative post-processing based on gnuplot exists (see above) that does not suffer this limitation.

9.3.3 Objectives

Quench:

Variable	Description
T	Temperature in specified conductor (0 = peak temperature).
I	Overall current.
R	Total effective resistivity of the magnet (including dump resistor).
MIITS	MIITS $\int I^2\,\mathrm{d}t$ in units $10^6\,\mathrm{A}^2\mathrm{s}$.
V	Potential difference between the specified conductor and input terminal, which is connected to ground (NOR = 0 yields the terminal voltage).
VMAX	Peak voltage between any conductor and ground.
VDUMP	Voltage on the dump resistor.

- Note that for plotting graphs from the "Objectives" widget, no more than 200 points can be considered. If you want to plot, e.g., the terminal voltage over time from the "Objectives"-table, **"QMI"** must not have a value above 199. Note however that alternative post-processing based on gnuplot exists (see above) that does not suffer this limitation.

9.3.4 Plotting Information 2-D

Coil Fields:

Variable	Description
T	Conductor temperature.
V	Conductor potential to ground.

10. Interfaces

For examples of the interface-files see Chapter 5.

Option	Description
Field-Vector Matrix (Map)	Write a file filename.matrf
CNC Machine files	Endspacer machining file. With "3-D Coil Geometry"-option in "Main options".
Opera 8-node Bricks	3-D bricks of the coil end for the "Opera" field calculation program.
Opera 20-node Bricks	3-D bricks of the coil end for the "Opera" field calculation program.
Autocad	Autocad (.dxf) file of coil cross-section.
MS Excel	Produce a text-file, importable in MS Excel, of coil cross-section geometry.
Virtual Reality (3-D)	Writes a filename.wrl-file which can be opened by any VRML-browser for an interactive 3-D-view of the coils.
2-D Line Currents	Produces a filename.fila2-D-file which contains two tables: (1) a table with the corner points of the current-carrying areas and (2) a table with the position of the individual line currents in the model.
.iron File of Wedges	Only works with the "Wedge/Endspacer"-option in the "Main Options". Creates a file called wedges.iron.
Coilmesh File	Produces a coilmesh.iron-file with one area for each conductor.

Option	Description
3-D Line Currents	Produces a filename.fila3-D-file which contains information on the positioning of line currents in the 3-D coil model.
Extended Printout	Add mostly geometrical information to the .output-file.
2-D Field Map in Coil	Write the magnetic induction in the position of every strand to a file.
3-D Field Map in Coil	Write the magnetic induction in the position of every strand in every intersection in z-direction to a file.
Input data from 'BEND'	Read in coil end geometry from 'BEND' output file.
Write Multipoles for Pp.	Write multipoles into text file (one line/time step) for post-precessing, e.g., in MS Excel.

- In 2-D, the "**Field-Vector Matrix (Map)**"-option only produces a file if a matrix-option (MATR, MATRC or MATRP from the "Aperture"-menu) is chosen in the "Plotting Information 2-D"-widget.
- The "**Write Multipoles for Pp.**"-option will only yield relative multipoles. If the "no reference"-item is chosen in the "Type of Coil/Ref. Field"-field of the "Global Information" no output is written.
- Without the "3-D Peak Field Calc."-option in the "Global Information 3-D", the "**3-D Field Map in Coil**"-option produces a file with only the geometrical information of strands in the coil end.

11. Examples of ROXIE Applications

11.1 Coil Modeling 2-D

We start with the cosine-theta coil geometry as this is the option that ROXIE was initially conceived for.

11.1.1 Cosine-Theta cross-section

The "Block Data 2-D"-table is the basic input instrument to create a 2-D coil model. A coil is made of blocks which are formed by a number of conductors - usually Rutherford-type or ribbon-type conductors, rectangular in shape. The conductors are placed in the cross-section such that they approximate a cosine-n-theta current-density distribution in a circular shell around the magnet's aperture.

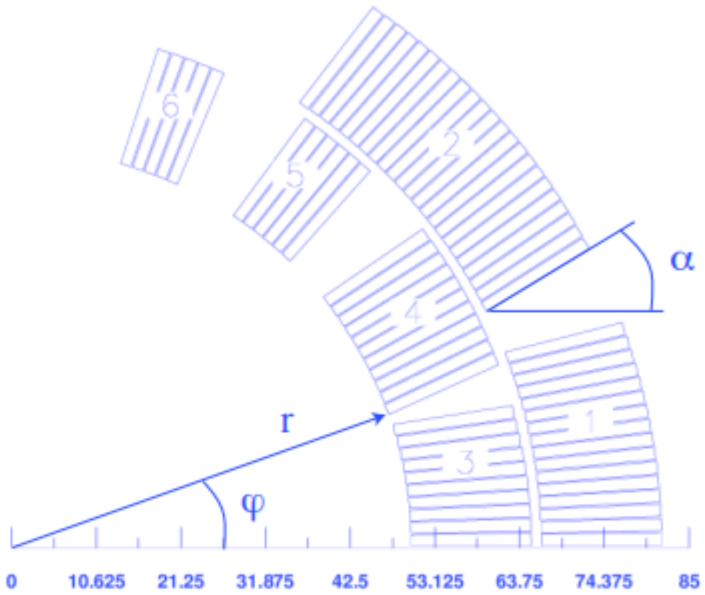


Fig 11.1: The parameters r (radius), φ (positioning angle) and
(inclination angle) used in the definition of a block of conductors.

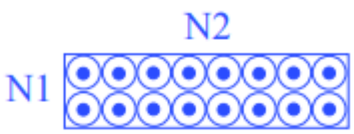


Fig 11.2: The parameters N1 and N2.

The parameters r (radius), φ (positioning angle) and α (inclination angle) are shown in the Fig. 11.1. The conductor name must be defined in the roxie.cadata-file. The variables N1 and N2 give the discretization in radial and azimuthal direction of the conductors, see Fig. 11.2. This is not equivalent to the number of strands which is given in the input file roxie.data-file under Block Data 2D widget. The three blocks in Fig. 11.3 (left) are defined by the following input table.

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	12	50	0.01	0.0	1000	YELLOWIN	2	18	0	0
2	8	50	37.0	35.3	1000	YELLOWIN	2	18	0	0
3	4	50	64.0	62.4	1000	YELLOWIN	2	18	0	0

The effect of the turn and image data is illustrated in Fig. 11.3 (right). The input is given below.

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	12	50	0.01	0.0	1000	YELLOWIN	2	18	0	20
2	8	50	37.0	35.3	1000	YELLOWIN	2	18	1	0
3	4	50	64.0	62.4	1000	YELLOWIN	2	18	0	0

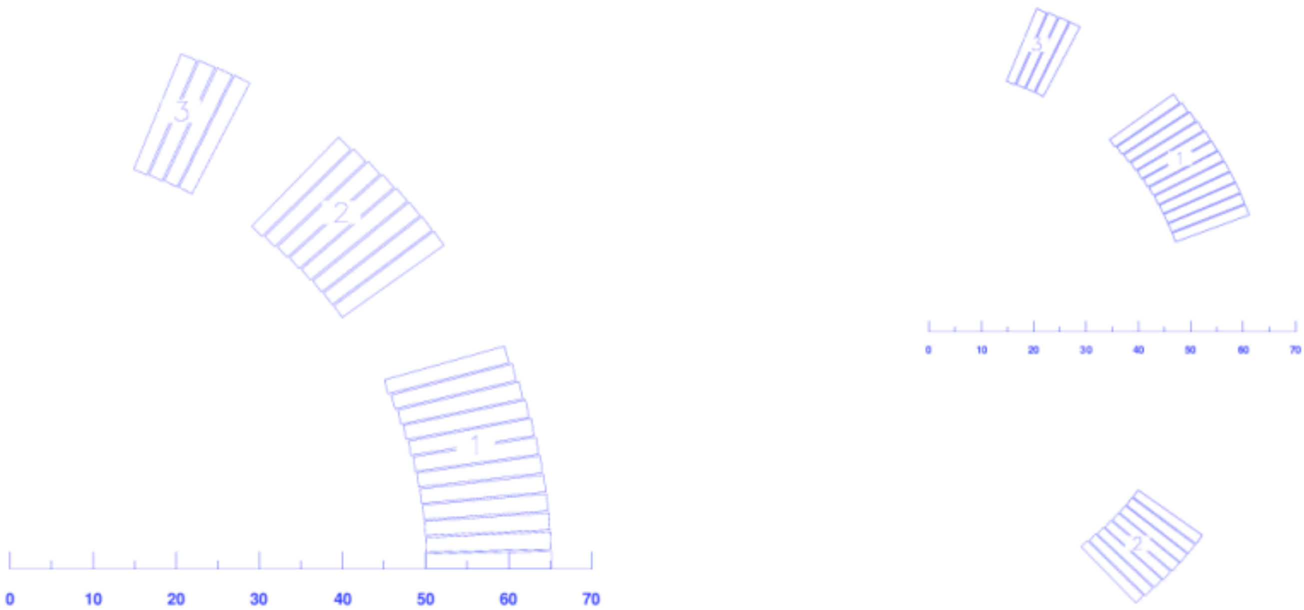


Fig. 11.3: Left: 1st quadrant of a dipole design. Right:Use of image and turn data in the "Block Data 2-D"-table.

11.1.2 The Symmetry option

To make use of symmetries in coil designs the "Symmetric Coil"-option was included in the "Main Options". The cross-section is defined for one pole only and only in the first quadrant. ROXIE does not actually generate the entire coil-geometry - no block- or conductor numbers are given. The "Type of coil/ref. field"-value in the "Global Information"-widget tells ROXIE what kind of magnet symmetry is to be used. The implicitly defined conductors and the sign of the current in each of them are taken into account during field calculation.

At a later stage of development, the layer option was introduced, see Section 11.1.3, which is now standard for many features such as non-linear iron calculations with BEM-FEM coupling or persistent current calculations. The reason for this is that the layer-option generates the entire coil geometry with all conductors. The advantage of the symmetry- over the layer option is that, in order to do a transformation (e.g., during an optimization run) only those blocks (of the first pole) that lie in the first quadrant need to be addressed and all implicitly defined blocks and conductors are transformed accordingly.

With "Dipole" defined in the "Global information"-widget and the "Symmetric coil"-option checked in the "Main Options", the geometry of Fig. 11.3 looks like Fig. 11.4.

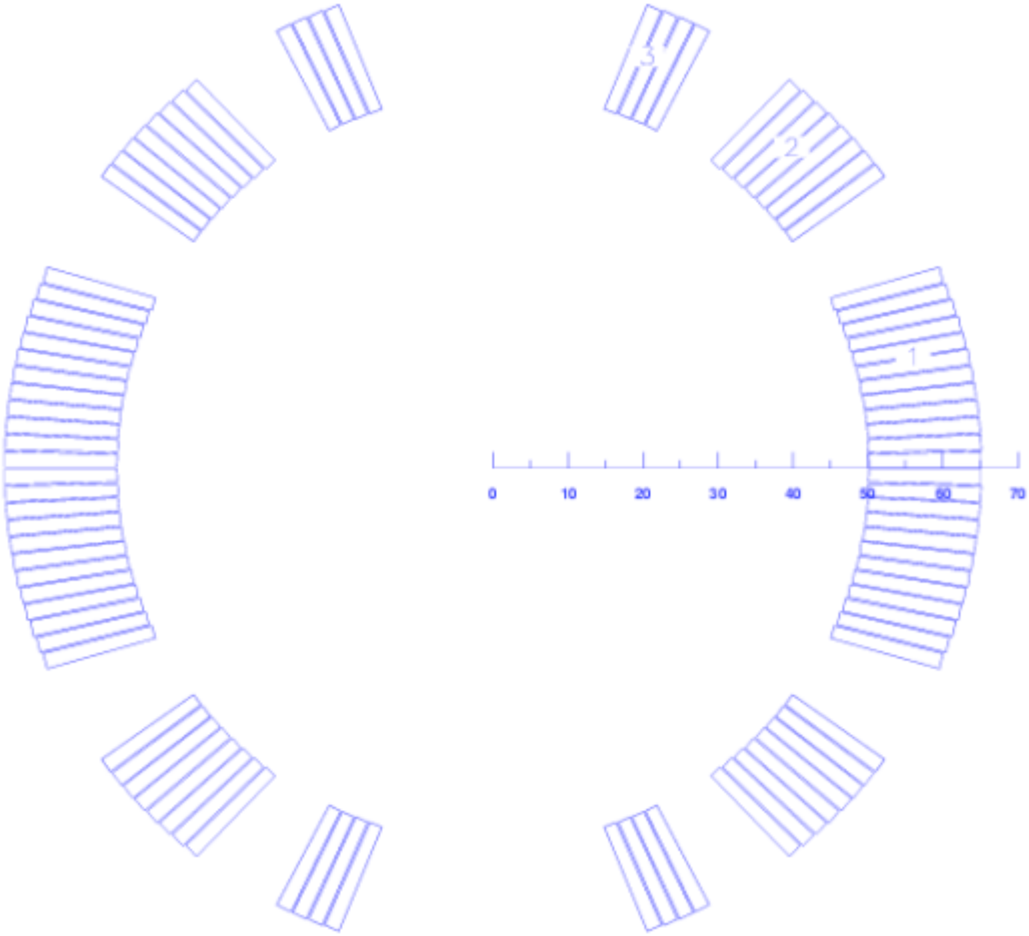


Fig. 11.4: Geometry of Fig. 11.3 with symmetry option. Note that ROXIE does not give block- (or conductor-) numbers to the implicitly defined entities.

11.1.3 The Layer option

As mentioned above, the layer option, contrary to the symmetry option, generates additional blocks of conductors from the ones that are specified in the "Block Data 2-D"-table. It also allows to assign different geometry types to different layers in the cross-section. To this purpose the "Layer"-widget appears that allows to assign blocks to layers and to specify the respective geometry type. The following input produces the geometry in Fig. 11.5.

Layers

No	Symm	Blocks
1	2	1-3
2	4	4

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	12	50	0.01	0.0	1000	YELLOWIN	2	18	0	01
2	8	50	37.0	35.3	1000	YELLOWIN	2	18	0	0
3	4	50	64.0	62.4	1000	YELLOWIN	2	18	0	0
4	16	68	0.01	0.0	1000	YELLOWOU	2	18	0	0

With the layer option switched 'on', the "Type of coil/ref. field"-value in the "Global Information"-widget does not define the coil geometry but only the reference field for harmonic field analysis, see Chapter 6.1. Many transformations in the "Design Variables"-widget apply to individual conductors, blocks or entire layers. A transformation applied to a block in the "Block Data 2-D"-table applies to this block alone and not to the ones generated by the layer option. Therefore it is important to understand the numbering scheme of the generated blocks:\ The first numbers are given to the blocks defined in the "Block Data 2-D"-table. Then the algorithm works layer by layer and block by block, i.e., it will start with block number one in layer one and generate and number the mirrored and turned new blocks before passing on to block 2 in layer 1. Then comes layer 2 and so forth, compare Fig. 11.5. The block numbering can always be checked either in the "Preview Window"-or by printing block numbers in a postscript plots.

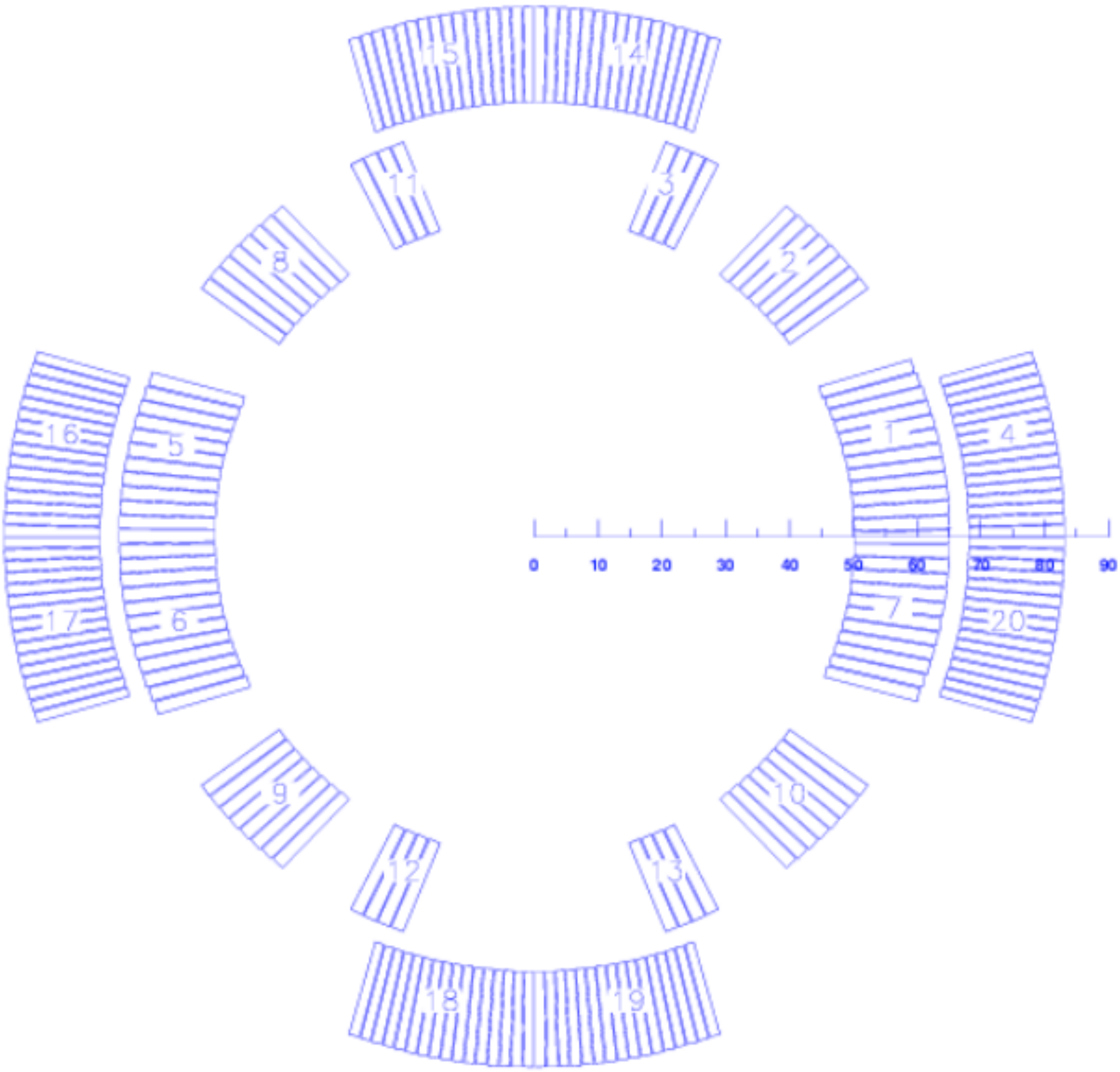


Fig. 11.5: Two layers, an inner dipole and an outer quadrupole. Note that all blocks (and conductors) are assigned numbers when the layer option is used.

11.1.4 Rectangular cross-section

The standard input option for coil cross-sections is the cosine-theta coil. If other magnet times are to be modeled, this has to be explicitly stated in the input file. The second-most common design variant has rectangular conductor- and block shapes (different window-frame designs, conventional magnets).

The standard option is the "Window Frames"-option in the "Global Variables"-widget. For the input we use same tables and symmetry/layer options as for cosine-theta magnets. Only the meaning of the geometry-data in the "Block Data 2-D"-table changes. The r-variable becomes the x-variable of the block position and the φ- becomes the y-variable. The α-angle is mostly 0 or 90 degrees for window-frame magnets. The following input produces the geometry in Fig. 11.6.

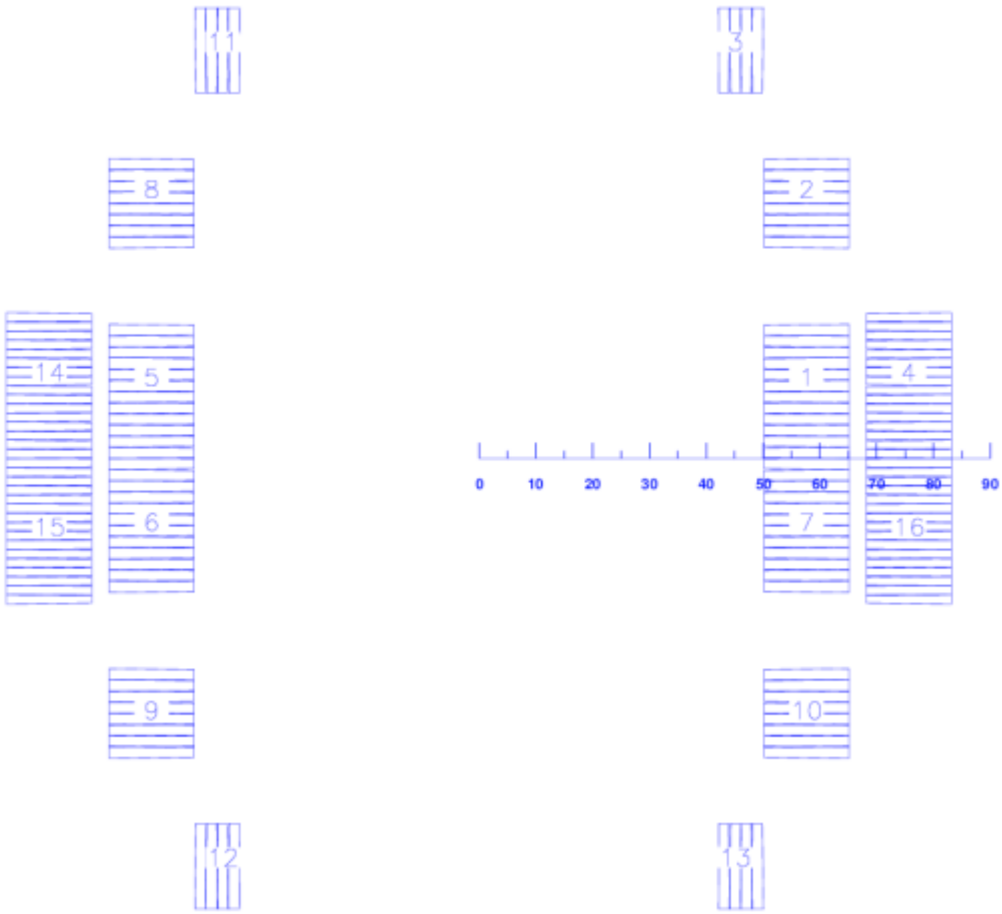


Fig. 11.6: Window-frame magnet design obtained from setting the "Window Frames"-option ’on’, setting the layer-geometry to "Dipole" and setting the inclination angles to 0 or 90 degrees, compare with Fig. 11.5

Layers

No	Symm	Blocks
1	2	1-4

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	12	50	0.01	0	1000	YELLOWIN	2	18	0	0
2	8	50	37	0	1000	YELLOWIN	2	18	0	0
3	4	50	64	90.0	1000	YELLOWIN	2	18	0	0
4	16	68	0.01	0	1000	YELLOWOU	2	18	0	0

- Note that with the the "**Window Frames**"-option switched 'on', ROXIE stacks keystoned cables onto each other keeping their mid-planes parallel. The inner width of the conductor defines the conductor spacing. The use of keystoned conductors will thus not make sense, although the program is not going to abort. Keystoned conductors will overlap in a rectangular cross-section.

11.1.5 Elliptical cross-section

The "ELLB"-option in the "others"-tab of the "Design Variables" allows to allign conductors on an ellipse, rather than a circle. The ellipse uses the radius of the "Block Data 2-D"-table as half-axis along the x-axis and the value specified for "ELLB" for the half-axis along the y-axis. The following input yields the output in Fig. 11.7.

Layers

No	Symm	Blocks
1	2	1
2	2	2

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	8	50	37	35.3	1000	YELLOWIN	2	18	0	0
1	8	50	45	42	1000	YELLOWIN	2	18	0	0

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	30	30	30	ELLB	1
2	80	80	80	ELLB	2

Fig. 11.7: Conductors wound on ellipses.

11.1.6 Wires on the mandrel

A third cross-section option is that of individual wires on the mandrel. In that case r- and φ-variables act as in the cosine-theta case, but α becomes the increment angle between individual wires in the block. To use wires on the mandrel the "Single wires on mandrel"-option needs to be clicked. The following input yields the output in Fig. 11.8.

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	8	30	0.01	7	1000	YELLOWIN	1	1	0	0

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	2	2	2	DWIOC	1-8
1	2	2	2	DHIC	1-8

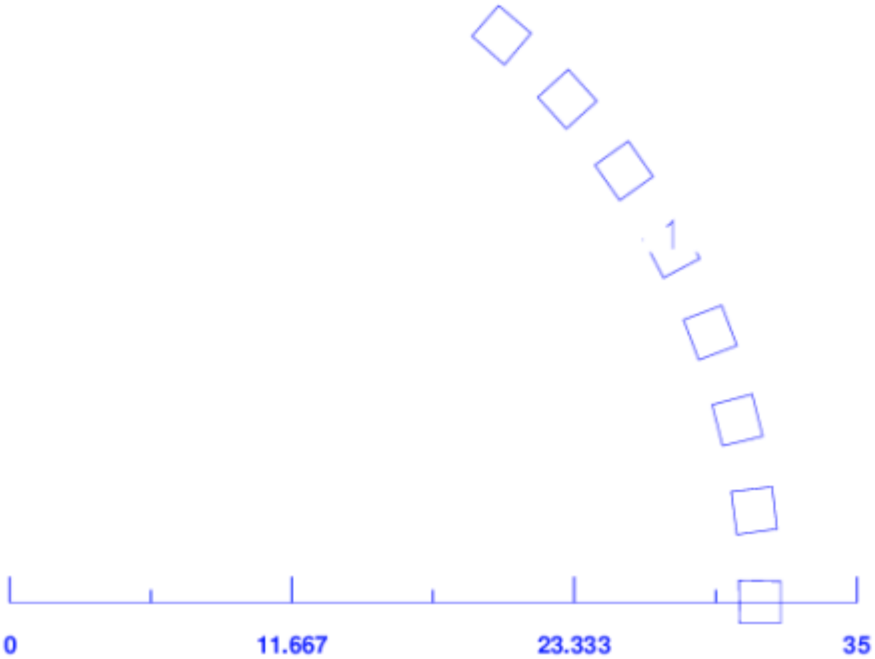


Fig. 11.8: Conductors wound on ellipses.

11.1.7 Solenoidal magnets

To solve a 2-D solenoidal problem, the Maxwell Equations are solved in cylindrical coordinates. When the "Axi-Symmetry"-option in the "Main Options" is chosen, every wire in the ROXIE model represents a full circular current loop. ROXIE assumes the solenoid axis to lie on the x-axis. Therefore solenoid models are built only in the upper half-plane. The following input (with "Window-Frames"-option clicked) leads to the coil model of Fig. 11.9 (left) and the field shown in 11.9 (right).

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	20	30	0	0	1000	YELLOWIN	2	18	1	90
2	20	30	0	0	1000	YELLOWIN	2	18	0	90

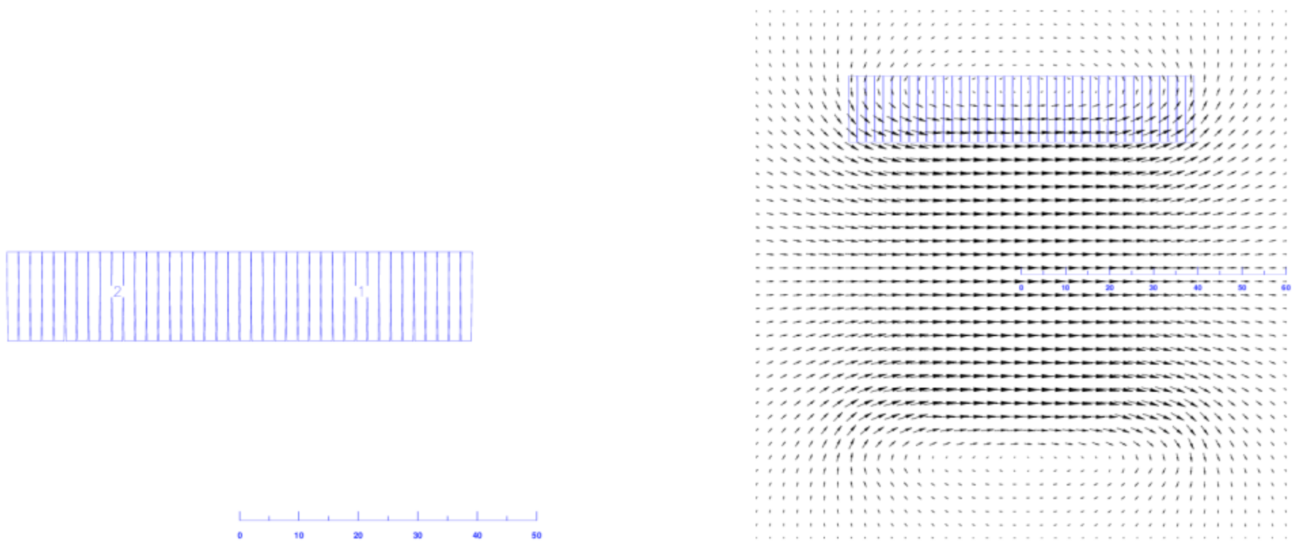


Fig. 11.9: Left: Model of a solenoid coil. Each strand in the cables represents a current loop around the x-axis. Right: Solenoid field.

11.1.8 Examples of design variable transformations

Coil-blocks (cross-section):

The following input produces the output in Fig. 11.10 (left):

Layers

No	Symm	Blocks
1	2	1-3
2	4	4

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	12	50	0.01	0	1000	YELLOWIN	2	18	0	0
2	8	50	37	35.3	1000	YELLOWIN	2	18	0	0
3	4	50	64	62.4	1000	YELLOWIN	2	18	0	0
4	16	68	0.01	0	1000	YELLOWOU	2	18	0	0

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	5	5	5	NUMCBL	1
2	10	10	10	PHI0	1
3	10	10	10	ALPH0	1
3	5	5	5	PHIR	2
4	9	9	9	ALPHR	2
5	10	10	10	PHIRS	3
6	37	37	37	PHIALP	8
7	-10	-10	-10	PHIV	11
8	-10	-10	-10	RSHIFT	11
9	15	15	15	ALPH0V	12
10	0	0	0	RECTBL	5-6 16-17
11	15	15	15	TILT	5
12	15	15	15	INCL	16
13	15	15	15	ALPH0	6
14	1.5	1.5	1.5	DFAK	14
15	3	3	3	DJFACH	15

The transformations that have been applied to the design of Fig. 11.5 (all values are either degrees or millimeters or integer numbers) are summarized as follows. Note that the blocks in the fourth quadrant have not been altered and can be used for comparison.

- The number of conductors in Block 1 was reduced to 5.
- Block 1 was repositioned at φ1 and α1.
- Block 2 was positioned relative to Block 1 with φ2 = φ1 + 5 and α2 = α1 +9.
- Block 3 was positioned at φ3 = φ2 + 10. The angle α3 is chosen such that the resulting wedge between Blocks 2 and 3 is symmetric. (This eliminates a source of error during the coil assembly and helps to reduce costs.)
- Block 8 was reset to φ8 = α8 = 37.
- The Block 11 was shifted 10 degrees towards the y-axis and 10 mm towards the center.
- The inclination angle of block 12 was augmented by 15 degrees.
- The blocks 5, 6, 16, and 17 were set to be of rectangular shape. Thus the input in the "Block Data 2-D" is read as if the "Window Frames"-option was clicked 'on'.
- The blocks 5, 6, and 16 are turned in different ways: The "TILT"-option for Block 5 inclines the conductors while leaving the block in upright position; The "INCL"-option for Block 6 leaves the conductors flat but the block is built up in an inclined way; The "ALPH0"-option does the same that a none-zero α angle in the "Block Data 2-D"-table would do: it inclines the entire block and its conductors, the block-shape remaining rectangular.
- The cable width in Block 14 is increased by a factor of 1.5.
- The cable height in Block 15 is increased by a factor of 3 - the current in the line currents is increased such that the current density remains unchanged.

Layer:

The "Layer"-options in the design variables apply to either an entire layer or to a block in the "Block Data 2-D"-table and all the blocks generated from that one. Several options are used in the following example, compare Fig. 11.10 (right):

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	5	5	5	NUMLBL	1
2	40	40	40	DRIL	2
3	75	75	75	PHI0L	3
4	15	15	15	TURNL	2
5	0	0	0	RECTLA	2

- Block number 1 and hence the Blocks 5, 6, and 7 are assigned five conductors.
- Block number 2 and hence the Blocks 8, 9, and 10 are set to a mandrel radius of 40 mm.
- Block 3 and Blocks 11, 12, and 13 are assigned a positioning-angle φ of 75 degrees.
- Layer 2 is turned by 15 degrees. and all its block are set to be of rectangular type, compare RECTBL-option above.

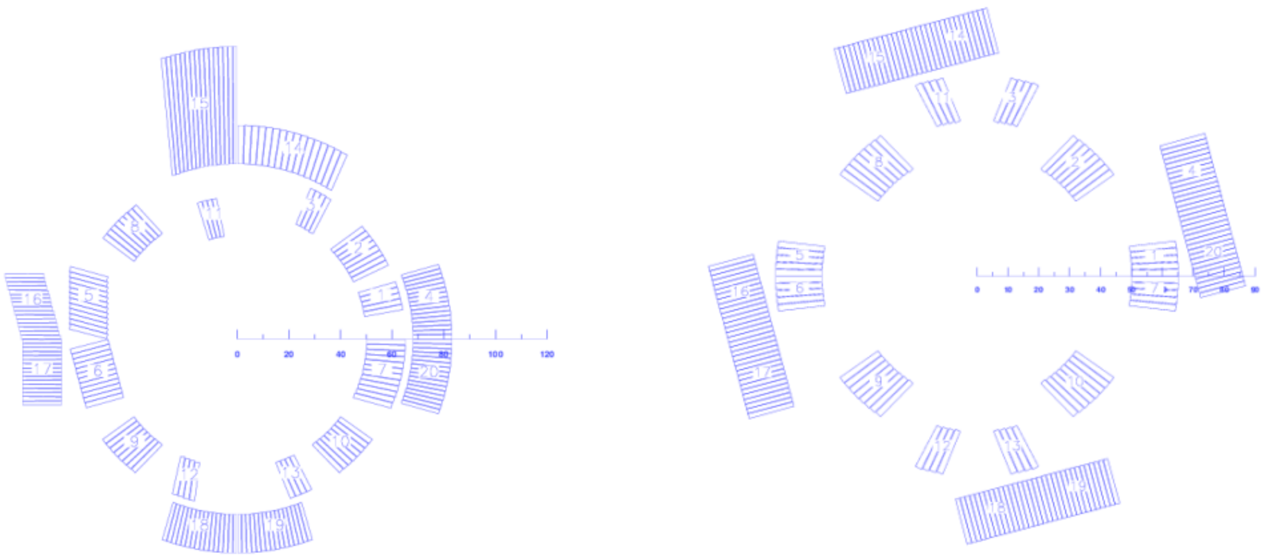


Fig. 11.10: A number of design parameters applied block-wise (left)
or layer-wise (right) to the design of Fig. 11.5.

Conductors:

In the "Conductors"-section of the design variables the geometry of conductors can be altered individually or block-wise. The following input yields the coil in Fig. 11.11 (left, the second layer has been omitted).

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	6	6	6	DWO	3
2	30	30	30	DRIC	3
3	10	10	10	XSH34	13

- The outer width of the conductors in Block 3 is set to 6 mm.
- Conductor number 3 is repositioned on a mandrel radius of 30 mm.
- The outer front of conductor number 13 is shifted in x-direction by 10 mm.

2-D transform (layers and blocks):

In the "2-D Transform (layers and blocks)"-section of the design variables blocks and layers can be shifted and turned. The following input yields the coil in Fig. 11.11 (right).

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	90	90	90	SHIFLX	1
2	45	45	45	SHIFLF	2
3	-90	-90	-90	SHIFLX	2 3

- Layers 1 and 2 are shifted by 90 mm in opposite x-direction.
- Layer 2 is turned by 45 degrees. The order is important here
- Conductor number 3 is repositioned on a mandrel radius of 30 mm.
- The outer front of conductor number 13 is shifted in x-direction by 10 mm.

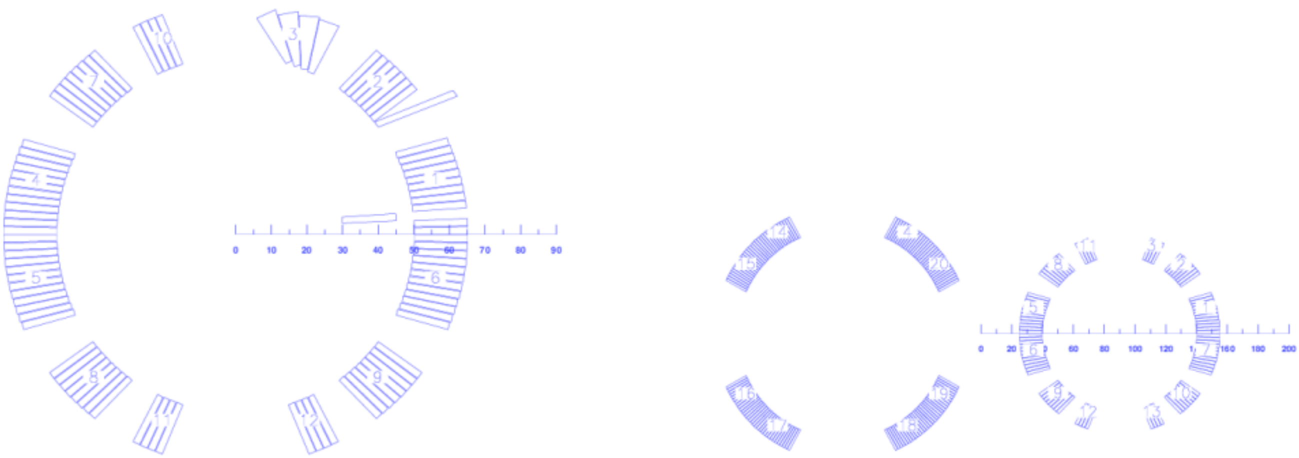


Fig. 11.11: Design options from the "Conductors"-menu (left) and the "2-D Transform (layers and blocks)"-menu (right) applied to the design of Fig. 11.5.

11.1.9 Cable in Conduit

The N1- and N2-parameters in the "Block Data 2-D"-table can be used to define round hollow conductors. To use this feature the N2-parameter is set to 0 while the N1-parameter gives the number of of round conductors to be inscribed into the mantle of the cylinder. This parameter implicitly defines the inner radius of the cylinder. The following input yields the output in Fig. 11.12.

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	5	70	0.01	0	1000	YELLOWIN	10	0	0	0

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	10	10	10	DHIC	1-5
2	10	10	10	DWIOC	1-5

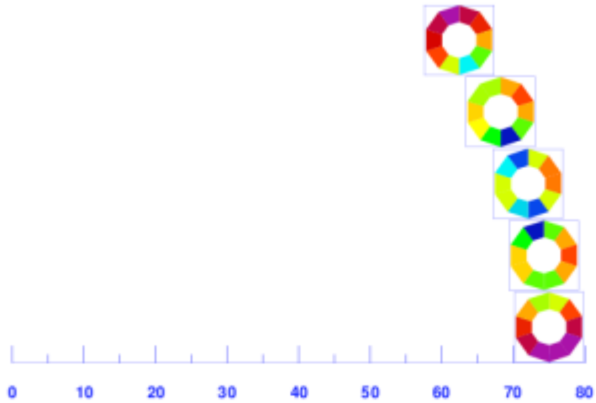


Fig. 11.12: Setting the conductor discretization parameter N2 to 0 yields a hollow conductor.

11.2 Coil Modeling 3-D

11.2.1 The constant-perimeter coil end

We design a coil end for the cross-section in Fig. 11.5. To this end we switch the "3-D Coil Geometry"-option 'on' in the "Main Options" and enter the following data. The output can be seen in Fig. 11.13 (left).

Global Information 3D

- Additional Bricks (LBRICK)
- 3D Peak Field Calc. (LFIELD3)
- 3D Field Harmonics (LF3INT)
- Additional Leads (LLEAD)
- Rutherford Cable Model (LRUTHER)
- Super-Elliptical Coil-End (LSMOOTH
- Coil imaged at z=0 Plane (LZSPIE)

Maximum size of Coil Ends	300
Number of Blocks in Outer Layer	1
Cable Size Increase in Ends	0
Number of Cuts in Z-Plane	22
Length of Extension into -Z Dir.	0

Layers

No	Symm	Blocks
1	4	1
2	2	2-4

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn	Ne
1	16	68	0.01	0	1000	YELLOWOU	2	18	0	0	1
2	12	50	0.01	0	1000	YELLOWIN	2	18	0	0	2
3	8	50	37	35.3	1000	YELLOWIN	2	18	0	0	3
4	4	50	64	62.4	1000	YELLOWIN	2	18	0	0	4

Block Data 3D

Ne	Beta	Bo	Zo	Wi	Wo	Hwed	Tend	Etype
1	65	60	110	0	0	0	4	11
2	40	100	88	0	0	0	2	11
3	57	75	68	0	0	0	2	11
4	72	30	70	0	0	0	2	11

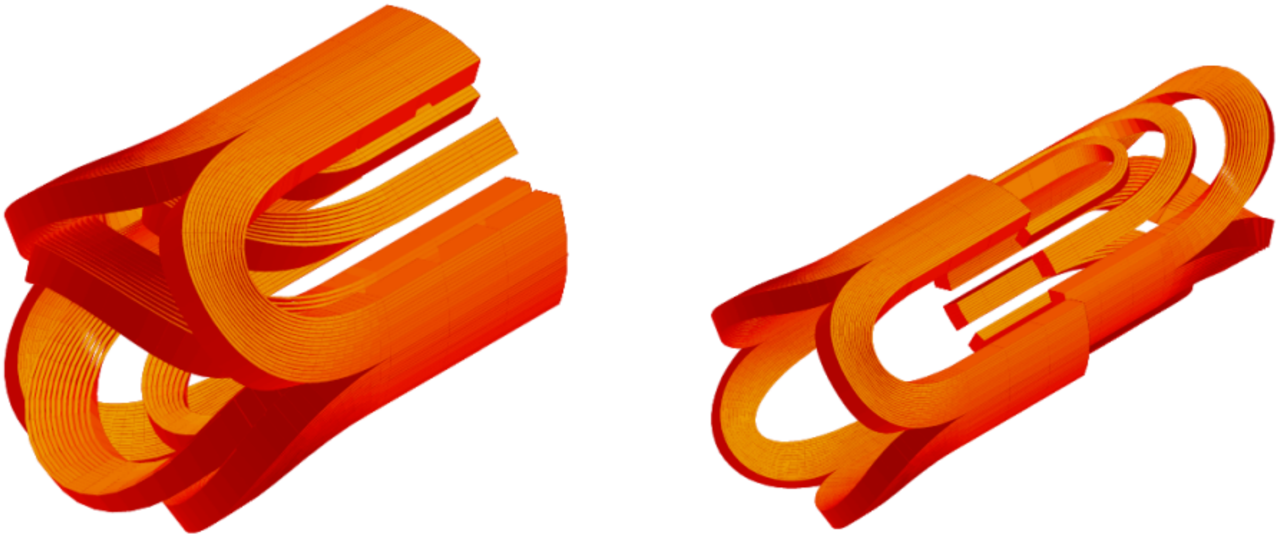


Fig. 11.13: Coil end design of the 2-layer cross-section in Fig. 5.
Right: TRAILZ-option applied to the inner layer.

The coil end in Fig. 11.13](#fig:11_13) is starting point and basically only ensures that the 3-D coil topology is correct. The mechanical quality can be determined from a table given in the .output-file of every 3-D run.

```
PERIMETER OF CABLE EDGES (XYZ PLANE, WITHOUT STRAIGHT SECTION) (mm)

       INNER SIDE       OUTER SIDE       CURVATURE (1/MM)    ISOMETRY FACT.
       UPPER LOWER      UPPER LOWER      GEODESIC  NORMAL    MAXIMUM MAXIMUM
COND.     4     1          3     2                           SQUEEZE STRETCH
   1  230.64  230.67  233.17  233.21 -0.00001    0.00158     0.999  1.141
   2  227.72  227.76  230.24  230.29 -0.00001    0.00160     0.998  1.121
   3  224.79  224.84  227.31  227.37 -0.00001    0.00162     0.997  1.101
   4  221.86  221.92  224.38  224.44 -0.00002    0.00164     0.996  1.082
   5  218.93  219.00  221.44  221.51 -0.00002    0.00165     0.994  1.064
   6  216.00  216.07  218.49  218.57 -0.00002    0.00167     0.993  1.047
 ...     ...     ...     ...     ...      ...        ...       ...    ...
```

In the case of Fig. 11.13](#fig:11_13) case we find a minimum isometry-value of 0.79. A perfect constant-perimeter end would have 1.0. Optimization of the shape is required (use the BULGE- and CURVAT-options in the "Objectives"-table).

For the plot in Fig. 11.13](#fig:11_13) (right) we use the TRAILZ-option in the "Transform 3-D"-menu of the "Design Variables" and applied it to layer 2, i.e., the inner layer. To set the plot-range right we needed to click the "No shift of Plot Center"-option in the "Plotting Information 3-D"-widget. Note that if you use "Transform 3-D"-options you also have to ensure the correct powering of the transformed blocks or layers. In the case of Fig. 11.13](#fig:11_13) (right) the sign of the currents of blocks 2-4 in the "Block Data 2-D"-table needs to be inversed.

Figure 11.14 shows the effect of the "Super-Elliptical Coil-End"-option in the "Global Information 3-D". The baseline ellipse is replaced by a super-ellips which has a slightly more "rectangular" shape.

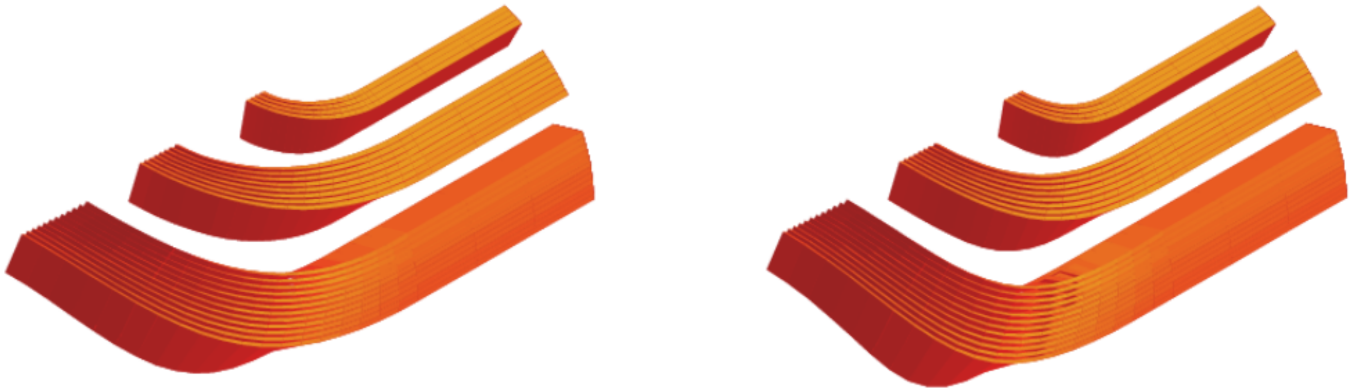
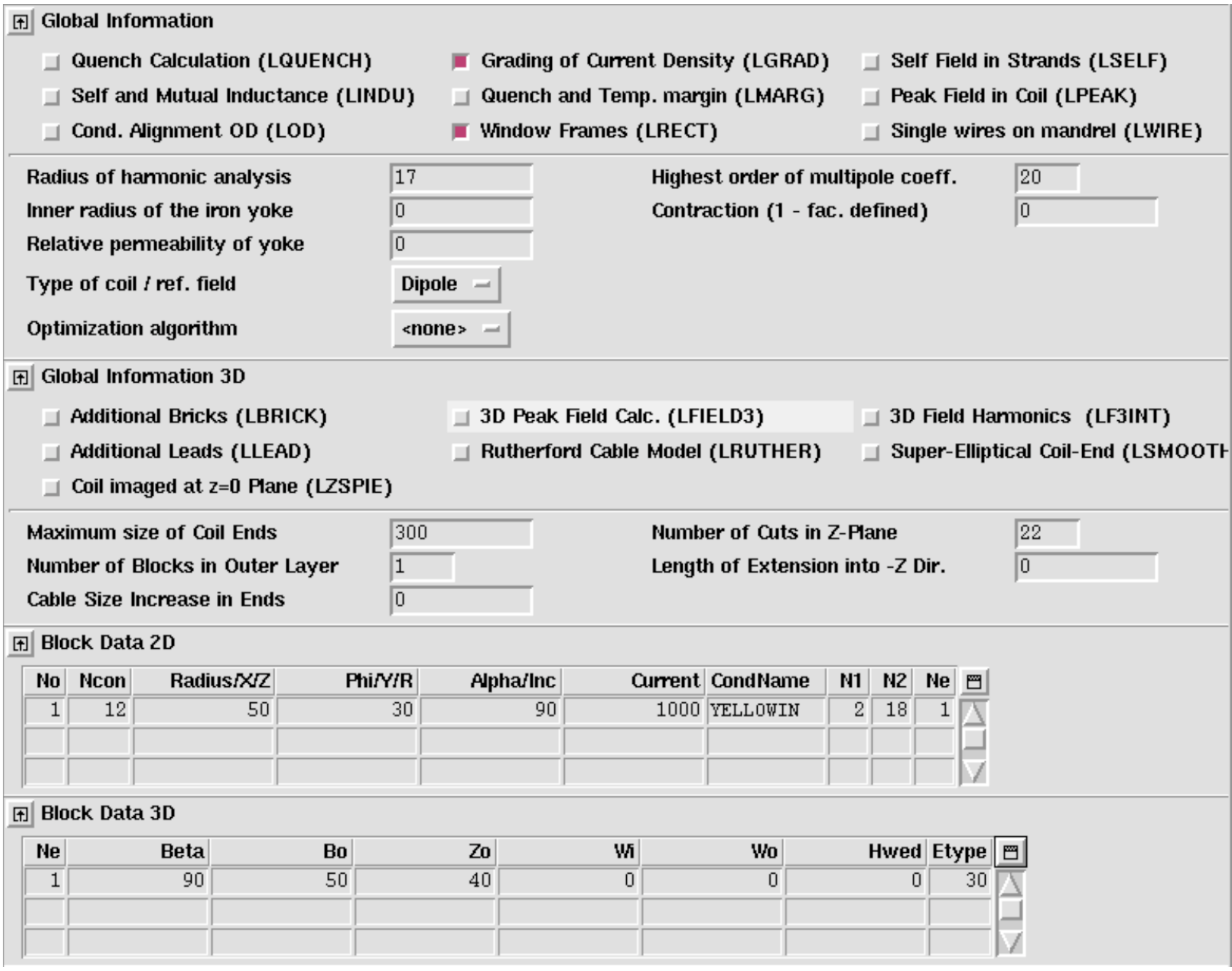


Fig. 11.14: Quadrant of an iso-parametric coil end of a cosine-theta magnet. Left: with an elliptical baseline; Right: with a super-elliptical baseline.

11.2.2 Racetrack coil

The only coil-end option for Window Frame magnets implemented in ROXIE is the Racetrack Coil. The following input yields the coil end in Fig. 11.15 (left). The "Symmetric Coil"-option from the "Main Options" is selected, as well as the "Plot Imaged at z=0 Plane"-option in the "Plot Information 3-D".



Global Information

- [ ] Quench Calculation (LQUENCH)
- [x] Grading of Current Density (LGRAD)
- [ ] Self Field in Strands (LSELF)
- [ ] Self and Mutual Inductance (LINDU)
- [ ] Quench and Temp. margin (LMARG)
- [ ] Peak Field in Coil (LPEAK)
- [ ] Cond. Alignment OD (LOD)
- [x] Window Frames (LRECT)
- [ ] Single wires on mandrel (LWIRE)

Radius of harmonic analysis: 17
Highest order of multipole coeff.: 20
Inner radius of the iron yoke: 0
Contraction (1 - fac. defined): 0
Relative permeability of yoke: 0
Type of coil / ref. field: Dipole
Optimization algorithm: <none>

Global Information 3D

- [ ] Additional Bricks (LBRICK)
- [ ] 3D Peak Field Calc. (LFIELD3)
- [ ] 3D Field Harmonics (LF3INT)
- [ ] Additional Leads (LLEAD)
- [ ] Rutherford Cable Model (LRUTHER)
- [ ] Super-Elliptical Coil-End (LSMOOTH
- [ ] Coil imaged at z=0 Plane (LZSPIE)

Maximum size of Coil Ends: 300
Number of Cuts in Z-Plane: 22
Number of Blocks in Outer Layer: 1
Length of Extension into -Z Dir.: 0
Cable Size Increase in Ends: 0

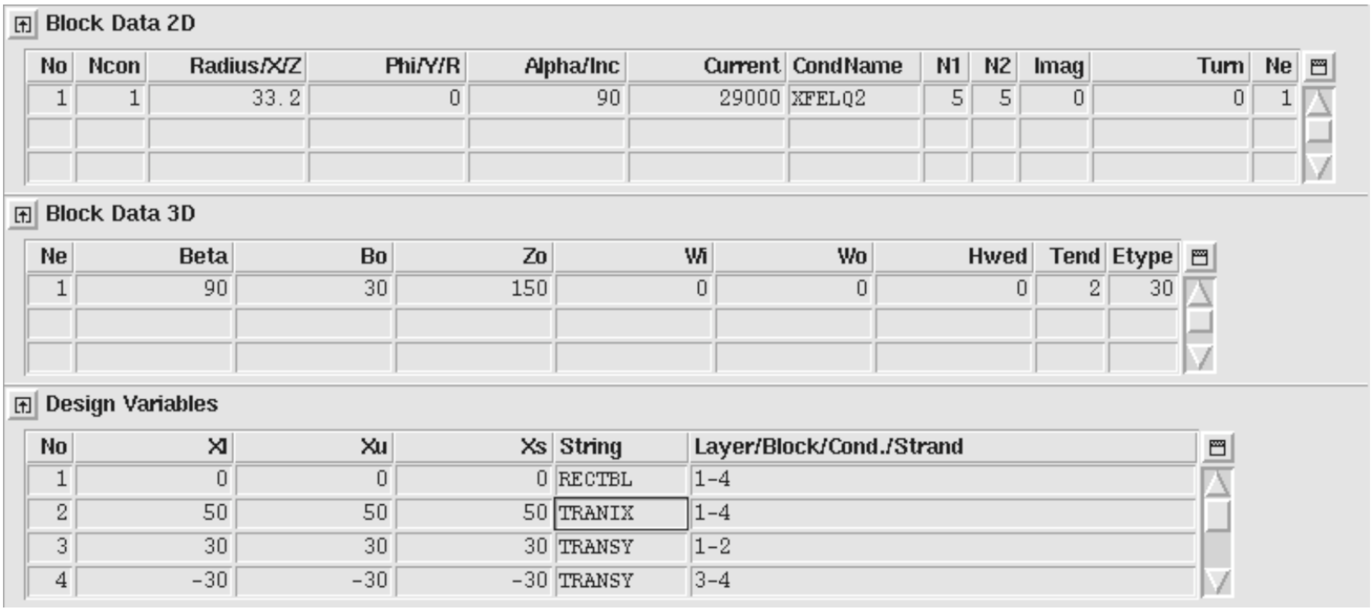
Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Ne
1	12	50	30	90	1000	YELLOWIN	2	18	1

Block Data 3D

Ne	Beta	Bo	Zo	Wi	Wo	Hwed	Etype
1	90	50	40	0	0	0	30

With the following input (option TRANIX) we can introduce a straight part in the racetrack ends, compare Fig. 11.15 (right). The Inserted straight section shifts the straight section apart.



Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn	Ne
1	1	33.2	0	90	29000	XFELQ2	5	5	0	0	1

Block Data 3D

Ne	Beta	Bo	Zo	Wi	Wo	Hwed	Tend	Etype
1	90	30	150	0	0	0	2	30

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	0	0	0	RECTBL	1-4
2	50	50	50	TRANIX	1-4
3	30	30	30	TRANSY	1-2
4	-30	-30	-30	TRANSY	3-4

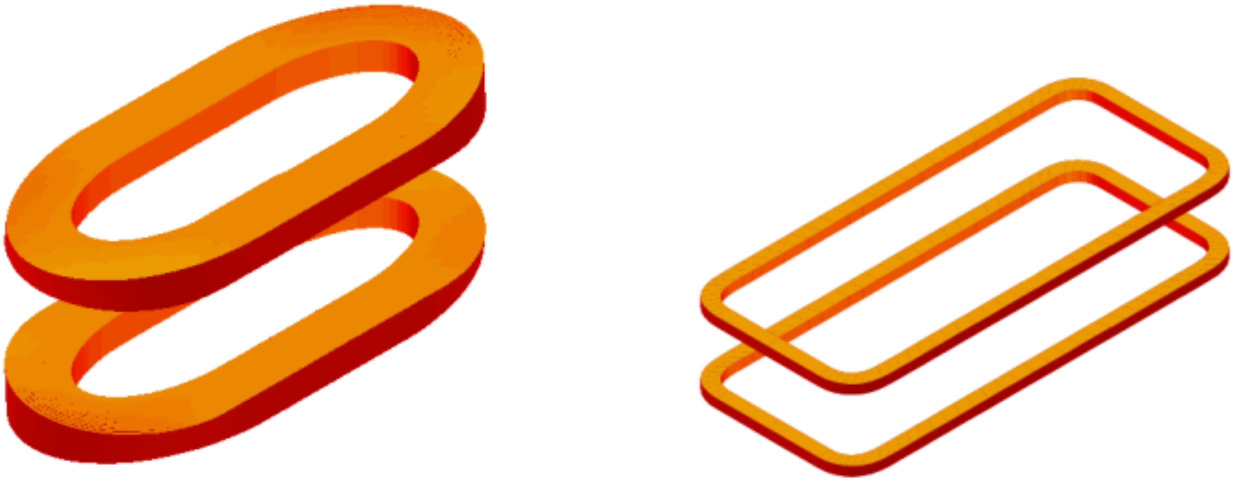


Fig. 11.15: Left: Racetrack-shaped coil end for Window Frame magnet. Right: Racetrack-shaped coil end with additional straight part.

11.2.3 Alternative racetrack coil feature

For lagacy reasons, above method to model racetrack coils uses the same algorithms as the cosine-theta ends. It therefore lacks some flexibility. We propose novel algorithms which reinterprete the "Block Data 3-D"-variables in a way that allows for more flexible racetrack coil-end design.

The new option is selected through the "Etype" (end type) value in the "Block Data 3-D" table. In any case, the "Window Frame"-option in the "Global Information" widget must be switched on.

Soft-way bend racetrack ends

To generate a soft-way (easy-way) bend, the "Alpha"-value of the specific block in the "Block Data 2-D" table must be 90 degrees, the "Beta"-value in "Block Data 3-D" must equally be 90 degrees and the "Etype" value set to 70.

Block data 3-D

Variable	Description
Ne	Row number/number of coil-end definition.
Beta	Must be 90 degrees.
B0	Half-axis in x-direction of the ellipse. B0 is measured from the "Radius/X/Z"-variable in the "Block Data 2-D" table towards the origin.
Z0	Straight section in z-direction.
Wi	B0 + Wi gives the half-axis in y direction of the ellipse. (Wi = 0 yields a circle.)
Wo	Angle in degrees where the coil end stops. Measured from the center of the ellipse. Wo = 0 yields a 90 degree coil end with a straight section towards the (x=0)-plane.
Hwed	Not assigned, set to 0.
Tend	Not assigned, set to 0.
Etype	70

Hard-way bend racetrack ends

To generate a hard-way bend, the "Alpha"-value of the specific block in the "Block Data 2-D" table must be 0 degrees, the "Beta"-value in "Block Data 3-D" must equally be 0 degrees and the "Etype" value set to 60.

Block data 3-D

Variable	Description
Ne	Row number/number of coil-end definition.
Beta	Must be 0 degrees.
B0	Half-axis in y-direction of the ellipse.
Z0	Straight section in z-direction.
Wi	Not assigned, set to 0.
Wo	Angle in degrees where the coil end stops. Measured from the center of the ellipse. Wo = 0 yields a 90 degree coil end with a straight section towards the (x=0)-plane.
Hwed	Hwed gives the half-axis in x-direction of the ellipse. It is measured from the "Radius/X/Z"-variable in the "Block Data 2-D" table towards the origin.
Tend	Not assigned, set to 0.
Etype	60

Examples

The above-introduced variables are illustrated in Fig. 11.16. The geometry of Fig. 11.16 was generated with the following input

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn	Ne
1	5	60	0	0	5000	NEDM1	1	1	0	0	1
2	15	120	40	0	5000	NEDM1	1	1	0	0	2
3	5	100	0	90	5000	NEDM1	1	1	1	180	3
4	15	200	0	90	5000	NEDM1	1	1	1	180	4

Block Data 3D

Ne	Beta	Bo	Zo	Wi	Wo	Hwed	Tend	Etype
1	0	50	80	0	0	40	2	60
2	0	150	100	0	60	150	2	60
3	90	60	120	30	0	0	2	70
4	90	150	100	0	20	0	2	70

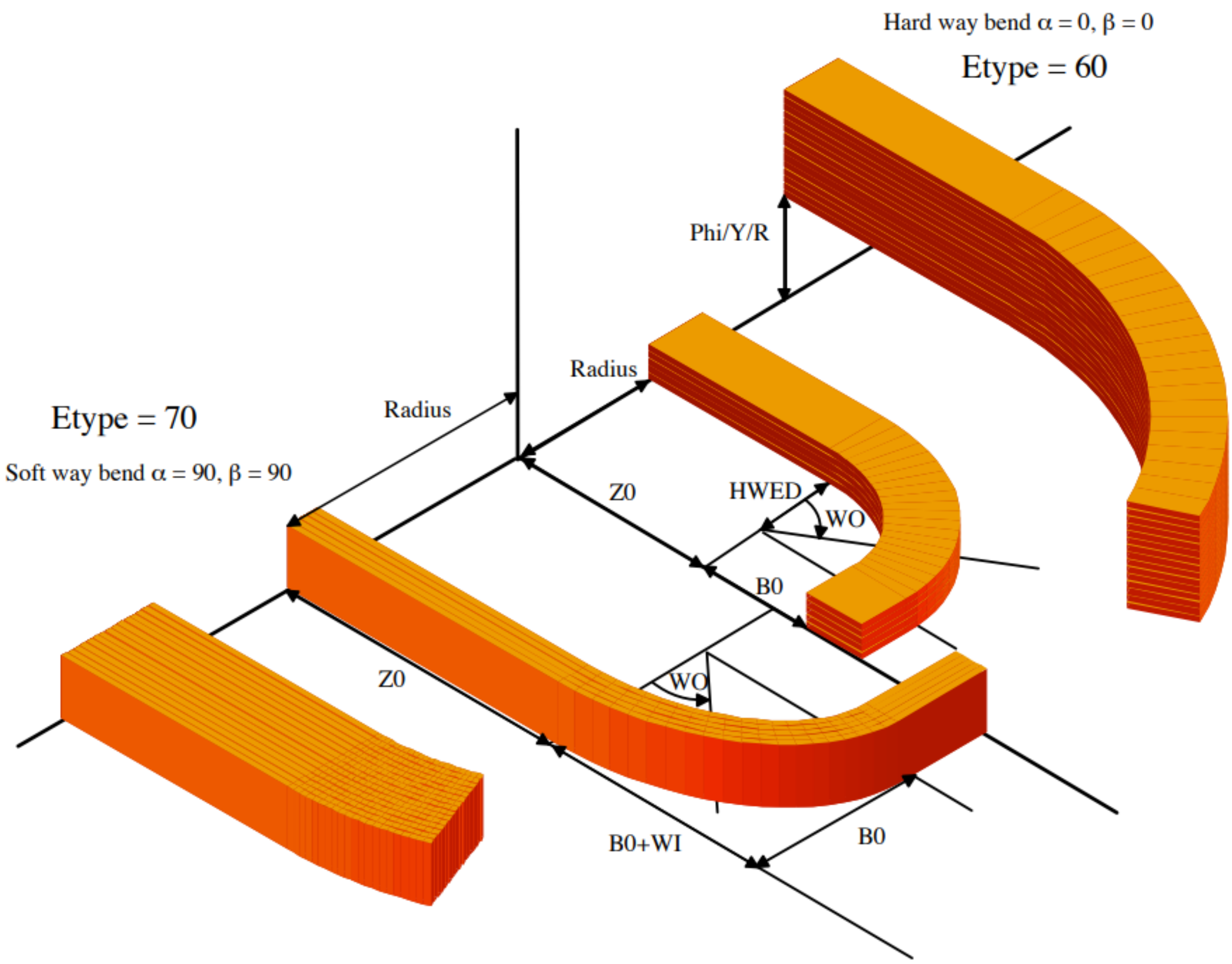


Fig. 11.16: Variables in soft-way and hard-way bend racetrack geometries using "Etype" 60 and 70 in the "Block Data 3-D" table.

The following input yields the racetrack coil end in Fig. 1.9 (left).

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn	Ne
1	1	60	0	90	5000	RHICCOD3	1	1	0	0	1
2	1	90	0	90	5000	RHICCOD3	1	1	0	0	2
3	1	60	0	90	5000	RHICCOD3	1	1	0	0	1
4	1	90	0	90	5000	RHICCOD3	1	1	0	0	2
5	1	60	0	90	5000	RHICCOD3	1	1	0	0	1
6	1	90	0	90	5000	RHICCOD3	1	1	0	0	2
7	1	60	0	90	5000	RHICCOD3	1	1	0	0	1
8	1	90	0	90	5000	RHICCOD3	1	1	0	0	2

Block Data 3D

Ne	Beta	Bo	Zo	Wi	Wo	Hwed	Tend	Etype
1	90	60	390	0	45	0	2	70
2	90	90	0	0	0	0	2	70

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	30	30	30	DHI	1-8
2	30	30	30	DWIOC	1-8
3	-90	-90	-90	TRANSF	1 3 5 7
4	45	45	45	TRANST	2 4 6 8
5	432	432	432	TRANSZ	2 4 6 8
6	60	60	60	TRANSX	1 3 5 7
7	0	0	0	TRIMYZ	3-6
8	0	0	0	TRIMXZ	5-8
9	60	60	60	TRANSY	1 3
10	-60	-60	-60	TRANSY	5 7
11	18	18	18	TRANSY	2 4
12	-18	-18	-18	TRANSY	6 8

The following input yields the bedstead coil end in Fig. 11.17 (right).

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn	Ne
1	1	40	0	90	5000	RHICCOD3	1	1	0	0	1
2	1	40	0	90	5000	RHICCOD3	1	1	0	0	1
3	1	40	0	90	5000	RHICCOD3	1	1	0	0	1
4	1	40	0	90	5000	RHICCOD3	1	1	0	0	1
5	1	40	0	90	5000	RHICCOD3	1	1	0	0	2
6	1	40	0	90	5000	RHICCOD3	1	1	0	0	2
7	1	40	0	90	5000	RHICCOD3	1	1	0	0	2
8	1	40	0	90	5000	RHICCOD3	1	1	0	0	2

Block Data 3D

Ne	Beta	Bo	Zo	Wi	Wo	Hwed	Tend	Etype
1	90	40	390	0	0	0	2	70
2	90	60	100	0	180	0	2	70

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	30	30	30	DHI	1-8
2	30	30	30	DWIOC	1-8
3	0	0	0	TRIMYZ	3-4
4	-100	-100	-100	TRANSX	1-2
5	100	100	100	TRANSX	3-4
6	-30	-30	-30	TRANSY	2 4
7	90	90	90	TRANSO	5-8
8	90	90	90	TRANST	5-8
9	0	0	0	TRIMXZ	5 7
10	0	0	0	TRIMYZ	6-7
11	80	80	80	TRANSY	6 8
12	-80	-80	-80	TRANSY	5 7
13	430	430	430	TRANSZ	5-8

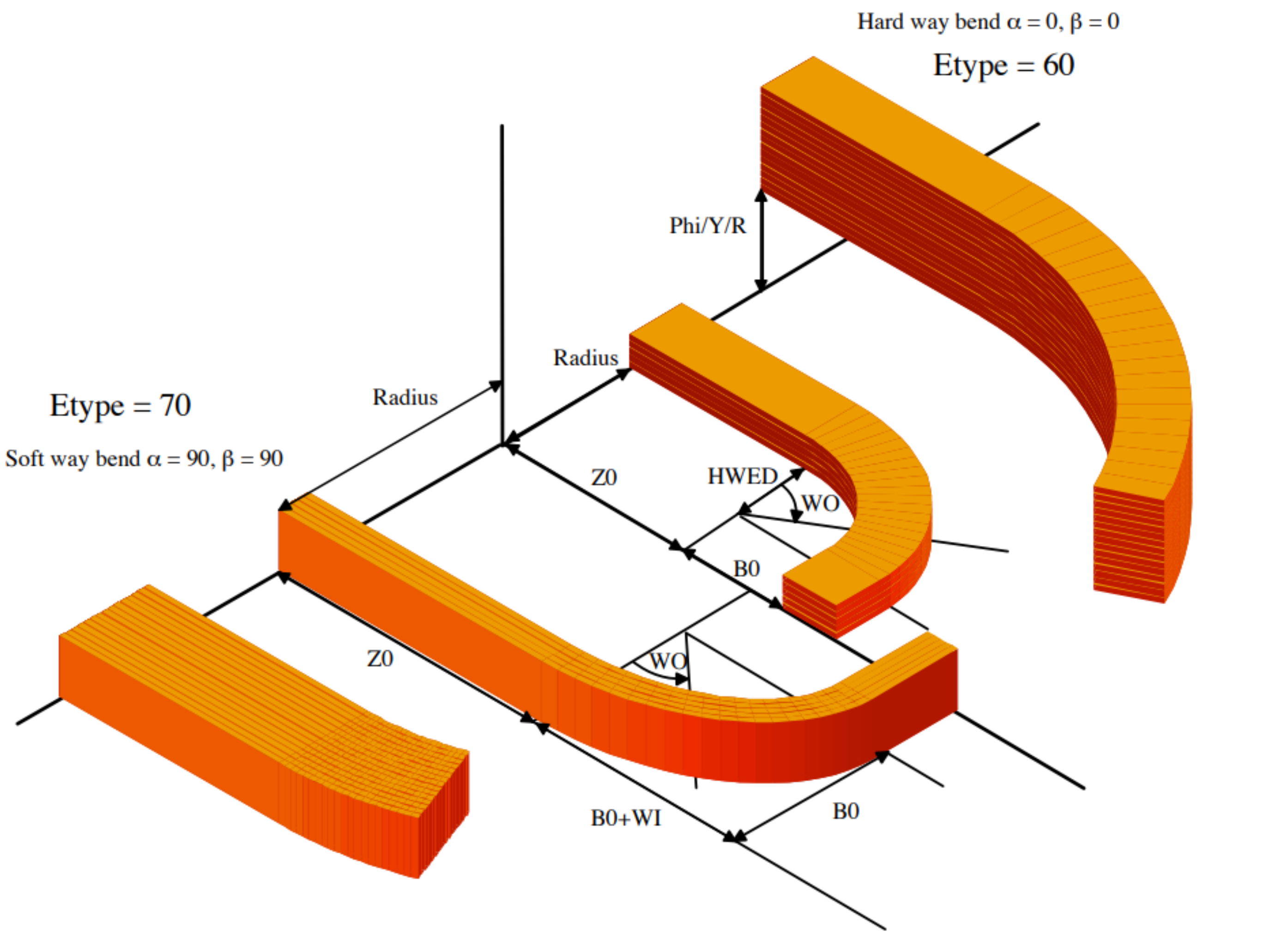


Fig. 11.17: Two coil ends. Left: racetrack coil end with hard-way bend. Right: "bedstead" coil end.

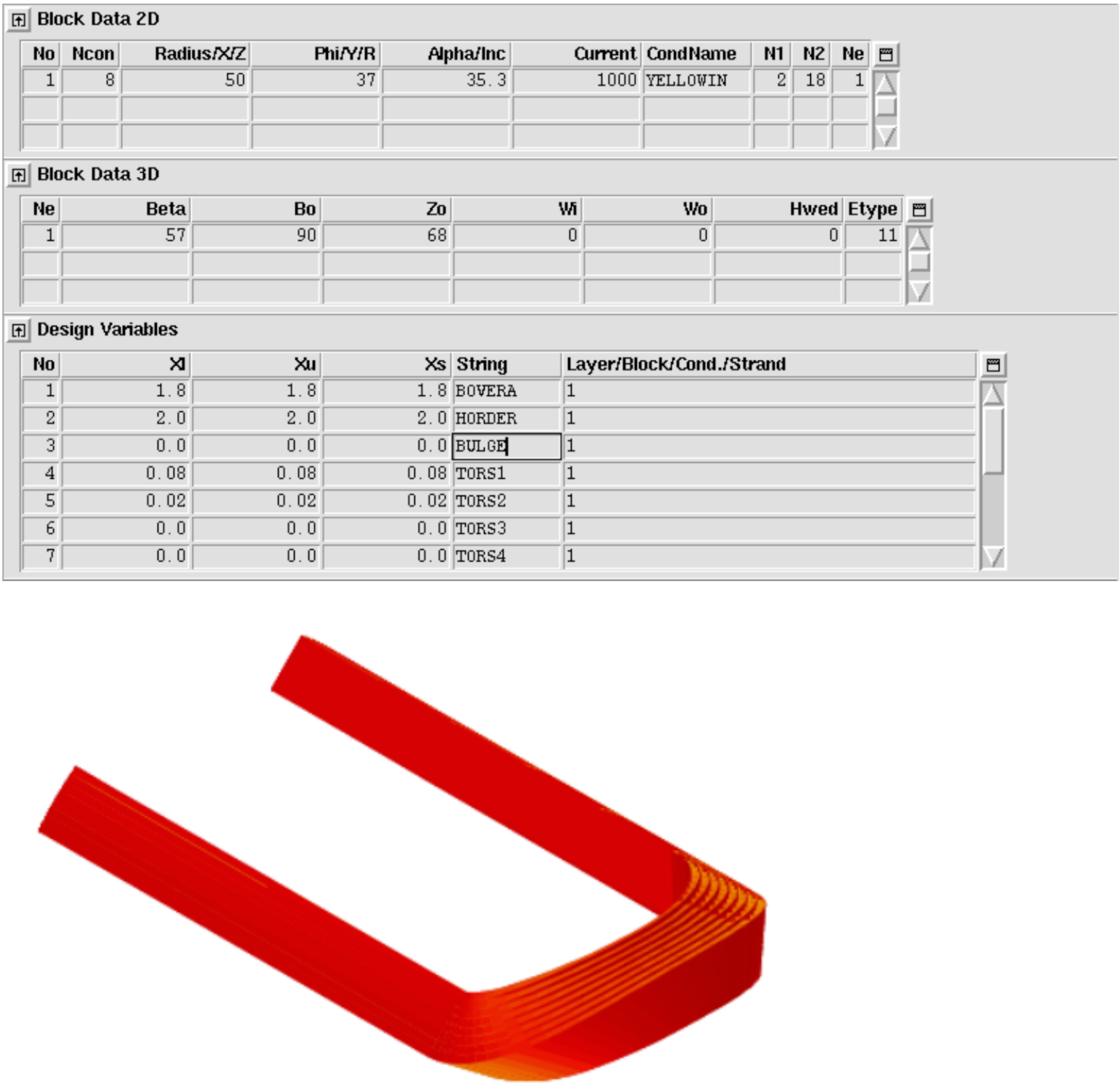
11.2.4 Differential geometry for coil end design

The differential-geometry method for coil-end design yields a more accurate mechanical model of cables in coil ends than the constant-perimeter method. More involved endspacer designs, e.g., for brittle conductors such as Ribbon-type conductors or Rutherford-type cables with a steel core, have a higher chance of success with this method.

Lately we have enabled ROXIE to use coil-end models from the differential-geometry method for field calculation and field-quality optimization. Also the post-processing has been improved. ROXIE can now display differential-geometry coil ends the way it displays constant-perimeter coil ends. 2-D projections of the coils, and endspacer pictures, however, are still bugged.

Differential-geometry coil ends use the same input format in the "Block Data 3-D"-table. All data entered in this table is read and processed in the way it would be for constant-perimeter coil ends. In addition, the user has to specify a number of "Design Variables" from the "Coil Ends (Differential Forms)"-tab. For optimization, the user can choose curvature parameters from the "Coil Ends (Differential Forms)"-tab in the "Objectives"-table. To use differential-geometry coil ends, the "Strips from Darboux Vec."-option in the "Interface options" must be switched on! Otherwise the design-variable input is ignored and a constant-perimeter coil end is produced from the "Block Data 3-D"-table.

The following input generates the output of Fig. 11.18.



Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Ne
1	8	50	37	35.3	1000	YELLOWIN	2	18	1

Block Data 3D

Ne	Beta	Bo	Zo	Wi	Wo	Hwed	Etype
1	57	90	68	0	0	0	11

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	1.8	1.8	1.8	BOVERA	1
2	2.0	2.0	2.0	HORDER	1
3	0.0	0.0	0.0	BULGE	1
4	0.08	0.08	0.08	TORS1	1
5	0.02	0.02	0.02	TORS2	1
6	0.0	0.0	0.0	TORS3	1
7	0.0	0.0	0.0	TORS4	1

Fig. 11.18: Coil end design with differential geometry methods.

11.2.5 Helical Coils

ROXIE provides a feature to generate helical coils (tilted solenoids, ...). It must be said that helical coils do not quite fit into the program structure of ROXIE which had initially been foreseen for 2-D simulation of cosine-theta magnets. Internally, the helical-coil option creates "additional bricks" (see "Additional Bricks" option). The user might therefore run into a storage-space limitation with the standard ROXIE executable. If this is the case, please contact us and we can compile a version with increased "additonal-bricks capability".

The data in the "Block Data 2-D" and "Block Data 3-D" widget is assigned a different meaning when the "Helical Coil"-option in the "Global Information 3-D" is switched 'on'.

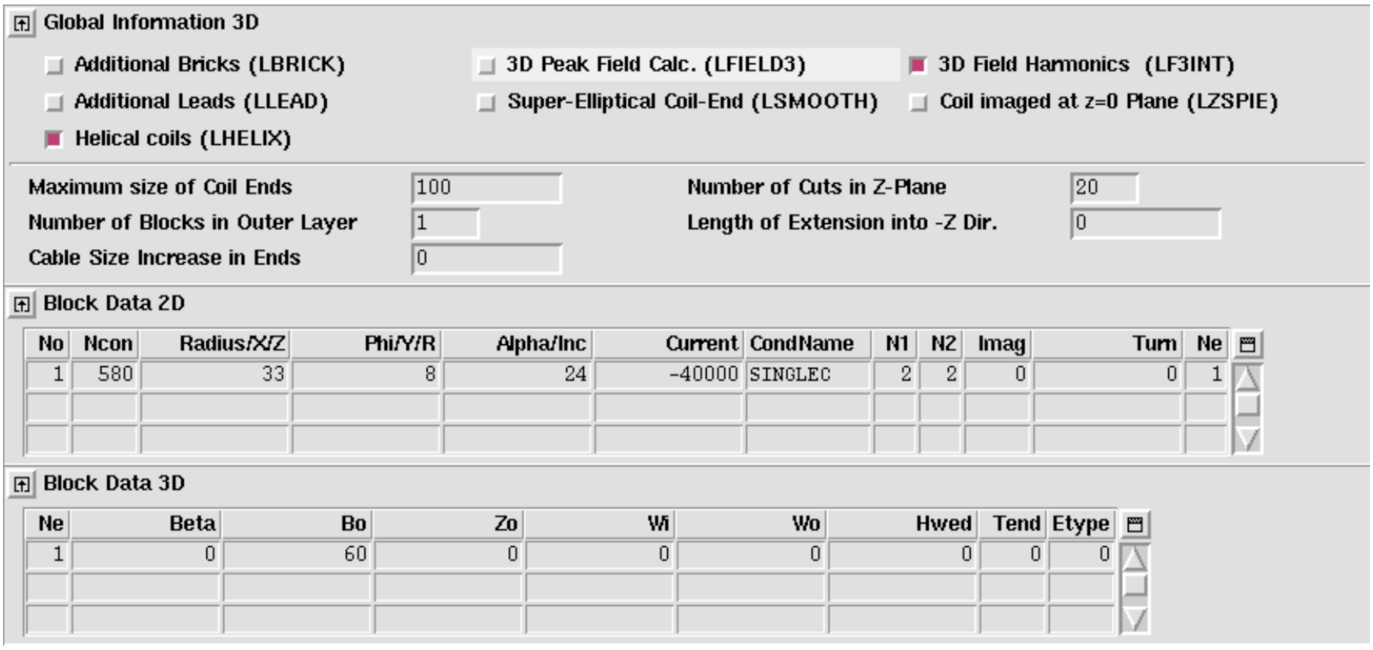
Block data 2-D

Variable	Description
No	Coil number.
Ncon	Number of cutplanes.
Radius/X/Z	Radius in mm.
Phi/Y/R	Pitch in mm.
Alpha/Inc	Number of pitches.
Current	Conductor current.
CondName	Conductor Name.
N1	Radial discretization of conductor.
N2	Azimuthal discretization of conductor.
Imag	0: left-handed screw; 1: right-handed screw.
Turn	Starting angle (grad).
Ne	Number of coil-end definition that applies to this coil.

Block data 3-D

Variable	Description
Ne	Row number/number of coil-end definition.
Beta	Swing angle; Inclination of helix around y-axis.
B0	Tilt angle; Inclination of helix around x-axis.
Z0	Factor for ellipse half-axis: r_x = r_y (1+Z_0), wind helix on elliptical mandrel.
Wi	x-shift.
Wo	y-shift.
Hwed	z-shift.
Tend	Not assigned, set to 0.
Etype	Not assigned, set to 0.

The following input yields the geometry in Fig. 11.19.



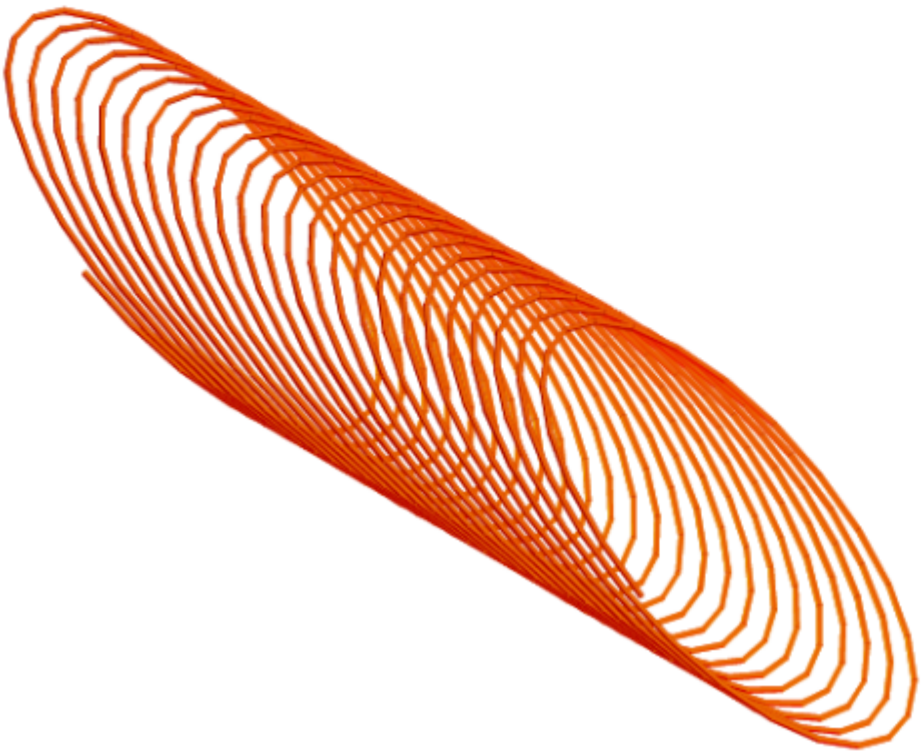


Fig. 11.19: 3-D helical-coil geometry.

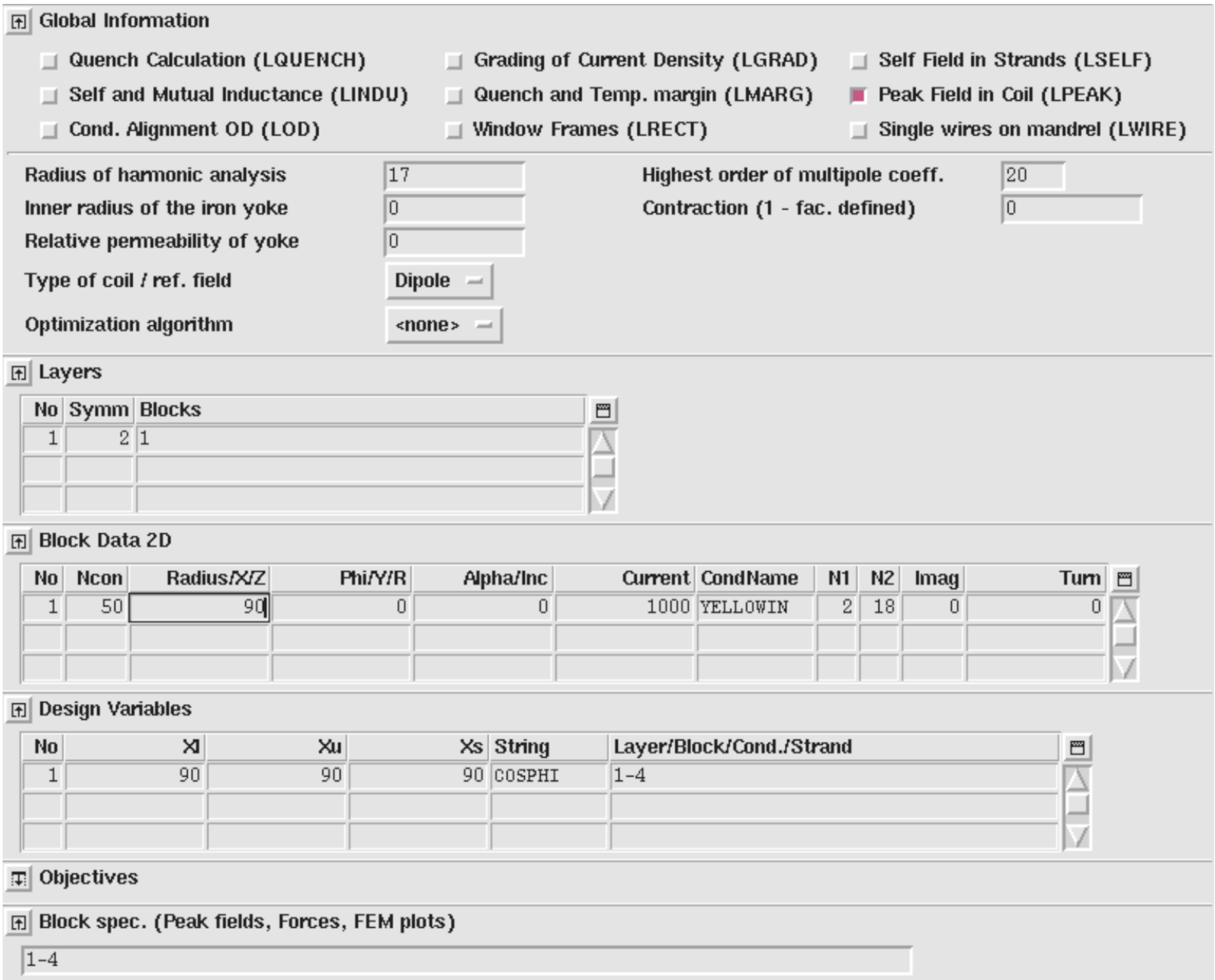
12. Examples of Analytical Field Calculation

12.1 2-D field calculation

12.1.1 Modeling ideal *cos Θ* current distributions

To model a shell with an ideal cos Θ current distributions we use the COSPHI-option from the "Design Variables"-table. The COSPHI-option distributes conductors in the specified blocks over the given angle by adapting the inner outer conductor width such that ideal sector geometries are generated. It then varies the strand currents according to their angular position and according to the "Type of Coil/Ref. Field"-variable from "Global Information". The specified block current in the "Block Data 2-D"-table is used as the amplitude of the cos Θ current distribution. The number of conductors serves thus no other purpose than to specify a discretization of the cos Θ current distribution. About 50 conductors are used for the generation of the current distribution shown in Fig. 12.1 (left).

The following input produces the field configuration in Fig. 12.1 (left). The "Layer Definition"-option is 'on', but the COSPHI option works with the "Symmetric Coil"-option as well.



To obtain the pure sextupole field shown in Fig. 12.1 below (right) we specify the COSPHI angle in the design variable block to 30 deg. The number of conductors can be reduced to 20.

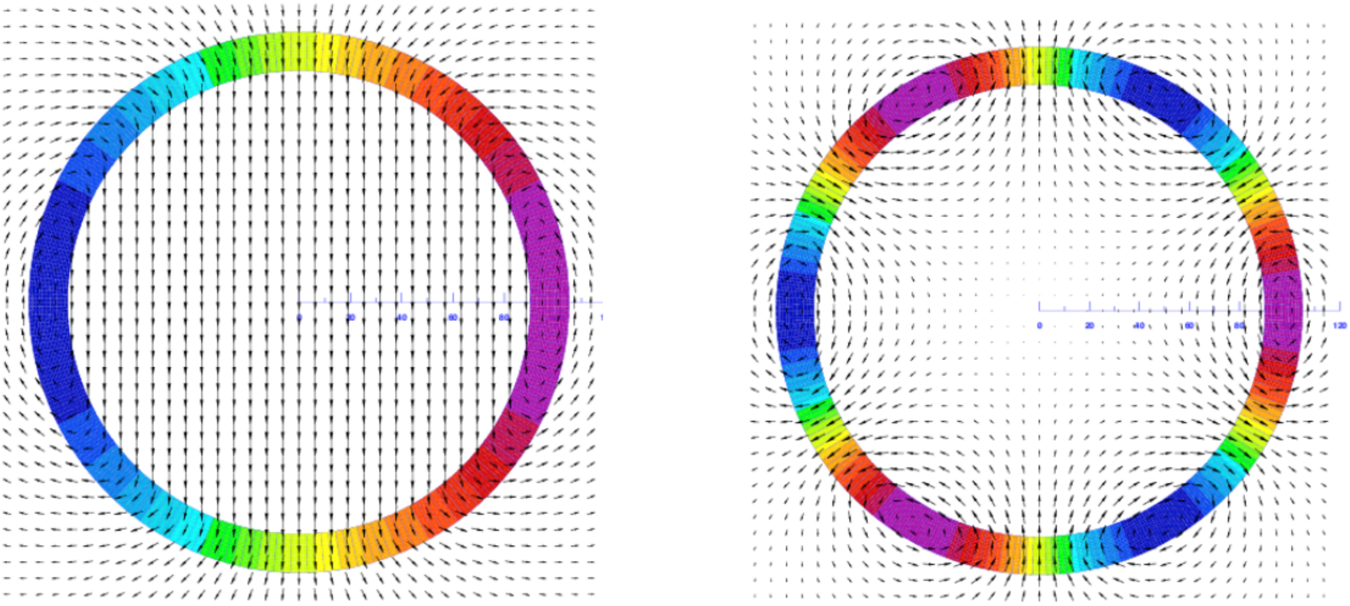
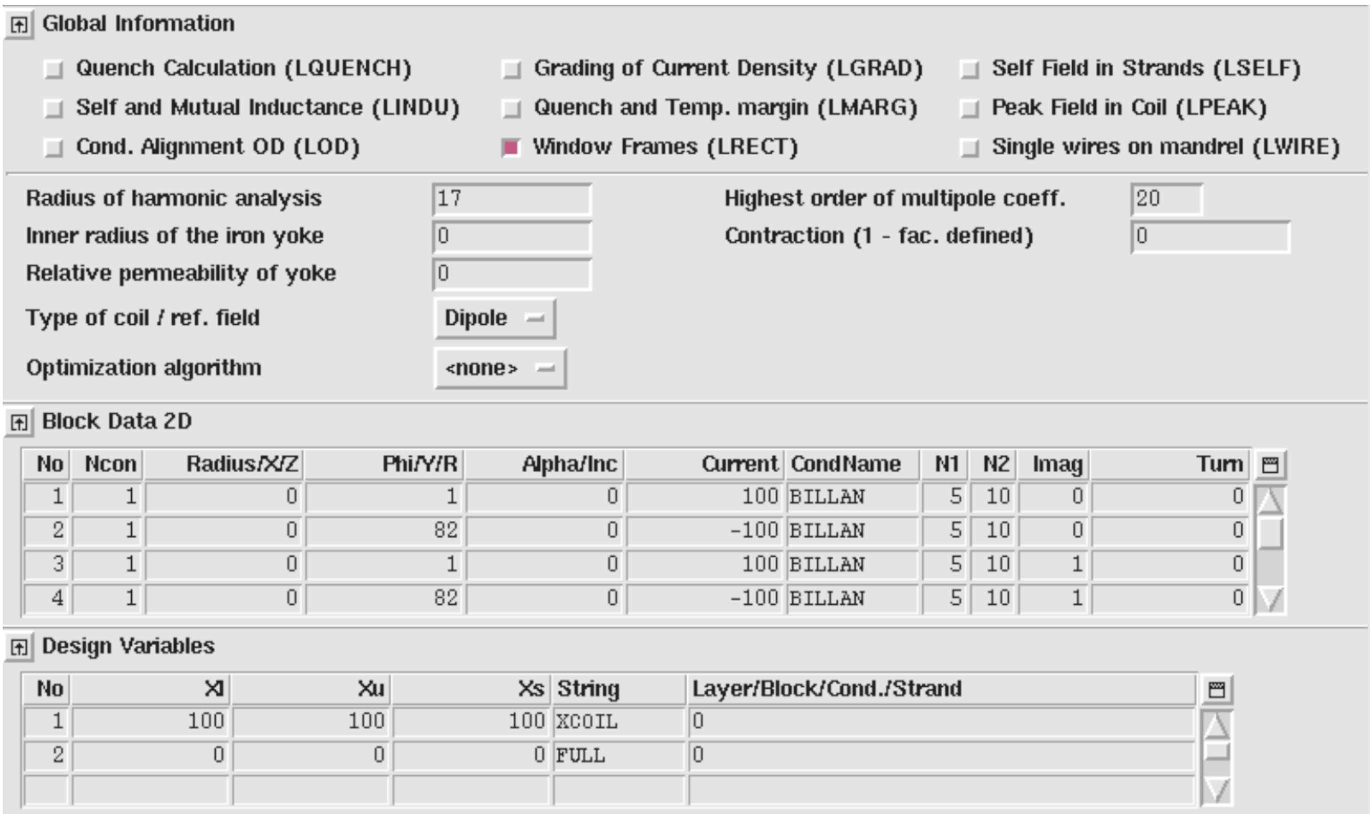


Fig. 11.19: Pure dipole (left) and sextupole (right) field produced with the COSHPI option in the "Design Variable".

13. Examples of Numerical Field Calculation

13.1 Permanent magnets in 2-D

A 2-D calculation with permanent magnets is considerably more sophisticated than standard calculations with ferro-magnetic material. In a first step we create a standard model of the configuration with some kind of excitation coil. The following input illustrates this first step, compare Fig. 13.1. Note the shift of the radius of harmonic analysis by the XCOIL option. This is necessary as the origin for the finite element mesh generation was not chosen as the center of the aperture.



The .iron-file of this case is listed below, compare Fig. 13.1 (left).

```
-- IRON YOKE MODELLING FOR PERMANENET MAGNET CALCULATION
HyperMesh;

-- VARIABLES AND PARAMETERS
mm    = 0.001;
xpos1 = -52.0 * mm;     xpos2 = -2.0 * mm;      xpos3 = 150.0 * mm;       xpos4 = 2.0 * mm;
ypos1 = 0.0 * mm;       ypos2 = 32.0 * mm;      ypos3 = 80.0 * mm;

-- KEYPOINTS
kp1  = [xpos1,ypos1];       kp2  = [xpos2,ypos1];
kp3  = [xpos1,ypos2];       kp4  = [xpos2,ypos2];
kp5  = [xpos1,ypos3];       kp6  = [xpos2,ypos3];
kp7  = [xpos3,ypos3];       kp8  = [xpos3,ypos2];
kp9  = [xpos4,ypos3];       kp10 = [xpos4,ypos2];

-- LINES
ln1  = HyperLine(kp3,kp1,"Line",0.5);
ln2  = HyperLine(kp3,kp4,"Line",0.5);
ln3  = HyperLine(kp4,kp2,"Line",0.5);
ln4  = HyperLine(kp1,kp2,"Line",0.5);
ln5  = HyperLine(kp5,kp3,"Line",0.5);
ln6  = HyperLine(kp5,kp6,"Line",0.5);
ln7  = HyperLine(kp6,kp4,"Line",0.5);
ln8  = HyperLine(kp6,kp9,"Line",0.5);
ln9  = HyperLine(kp4,kp10,"Line",0.5);
ln10 = HyperLine(kp9,kp10,"Line",0.5);
ln11 = HyperLine(kp10,kp8,"Line",0.5);
ln12 = HyperLine(kp9,kp7,"Line",0.5);
ln13 = HyperLine(kp7,kp8,"Line",0.5);

-- AREAS
ar1 = Area(ln7,ln6,ln5,ln2,BHiron2);
```

```
ar2 = Area(ln13,ln12,ln10,ln11,BHiron2);
ar3 = Area(ln3,ln2,ln1,ln4,BHiron8);
ar4 = Area(ln10,ln8,ln7,ln9,BHiron9);

-- NUMBER OF ELEMENTS / LINE
Lmesh(ln1,6);

-- MIRRORING
Mirrorx;
```

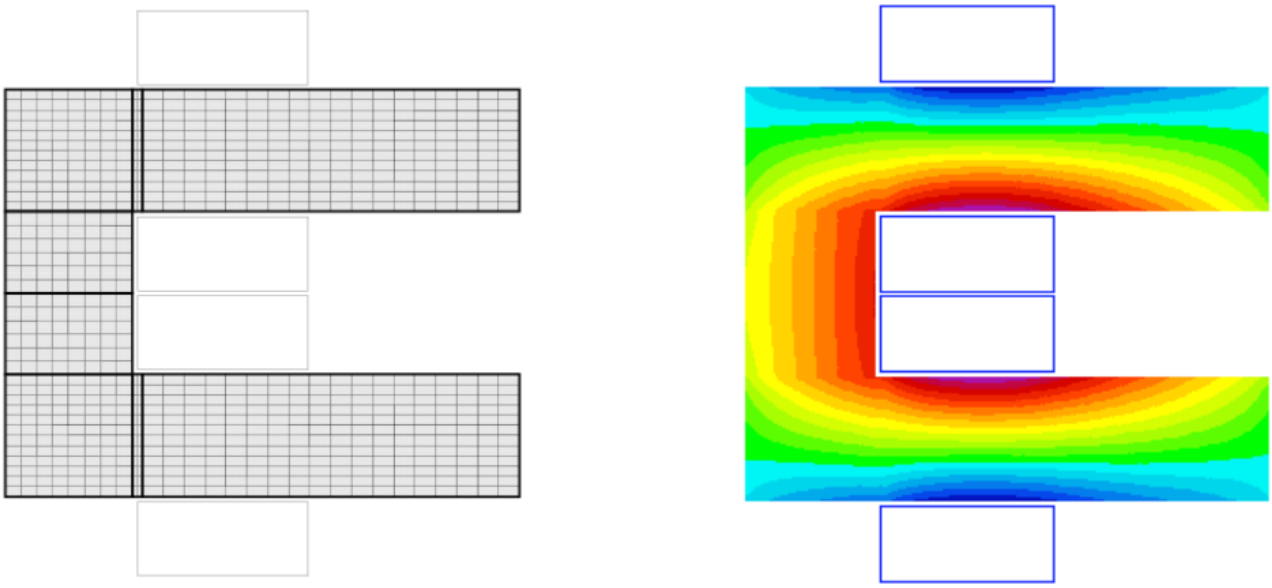


Fig. 13.1: C-shaped magnet with coil-excitation. Left: Finite Element Mesh. The areas `ar3` and its mirror image with material `BHiron8` are situated in the centre of the arc; The areas `ar4` and its image with `BHiron9` can be identified as the thin areas in the branches. Right: Vector potential inside the C-magnet.

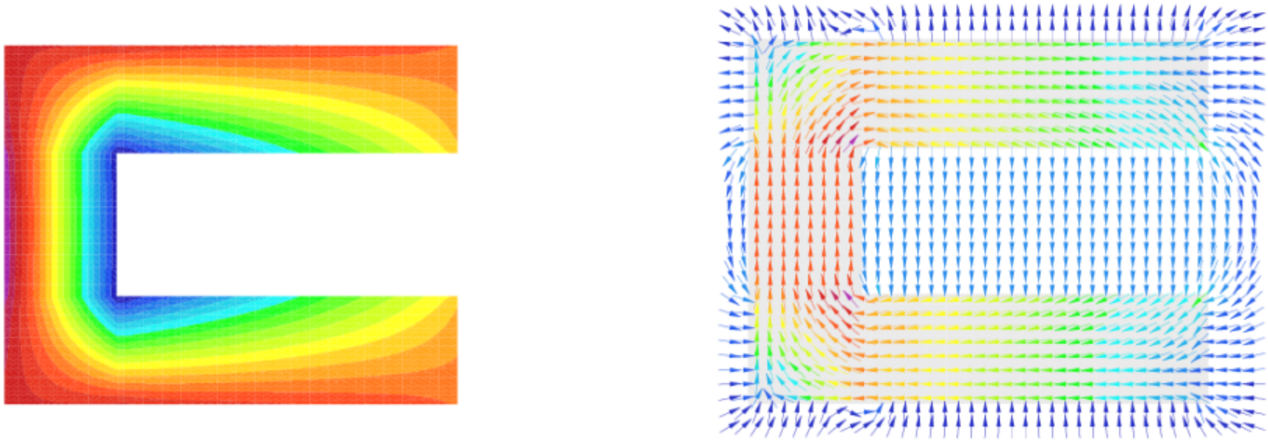


Fig. 13.2: C-shaped magnet driven by permanent magnets. Left: Magnetic vector potential. Right: Magnetic Induction.

The materials `BHiron8` and `BHiron9` are defined in the roxie.bhdata-file as permanent magnetic material. Their definition reads

```
BHiron8
3 1.0
```

```
0.000    0.
0.9 7.0E+05
1.8 1.4E+06       permanent magnet material
BHiron9
3 1.0
0.000    0.
0.9 7.0E+05
1.8 1.4E+06       permanent magnet material
```

The definition of twice the same curve is necessary as two different vector fields (directions) will later be assigned to the materials. We can now identify the so-called collector-numbers of the areas with materials `BHiron8` and `BHiron9` in the .hmo-file generated by the HERMES pre-processor.

```
# HYPERMESH OUTPUT FOR EDYSON CREATED WITH MGEN2HMO; VERSION=1.3
BEG_COMP_DATA
       4
       1 BHiron9
       2 BHiron8
       3 BHiron2
       4 SuperCoils
END_COMP_DATA
BEG_NODL_DATA
    2473
       1  -0.00200000   0.08000000   0.00000000
       2  -0.00825000   0.08000000   0.00000000
       3  -0.01450000   0.08000000   0.00000000
       4  -0.02075000   0.08000000   0.00000000
          ...
```

`BHiron9` has been assigned number 1 and `BHiron8` has number 2. Finally we can proceed to define two vector fields in a .VEFI-file, compare Section 8.8.

```
    2    3
    1    1    0.9
    1    0    1   +2    0    0    0
  0.0  0.0  0.0  0.0  0.0  0.0
    2    2    0.9
    1    0    1   +1    0    2    0
  0.0  0.0  0.0  0.0  0.0  0.0
    2    0    1   -1    0    1    0
  0.0  0.0  0.0  0.0  0.0  0.0
```

This file defines 2 vector fields. The first one pointing in +y-direction and the second one pointing in +x-direction in the upper half plane and in -x-direction in the lower half plane.

In a final step we assign the vector fields to the respective areas (materials, collector numbers). The following input produces the output of Fig. Fig. 13.2. Note that all currents in the "Block Data 2-D"-table are now set to zero.

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	1	0	1	0	0	BILLAN	5	10	0	0
2	1	0	82	0	0	BILLAN	5	10	0	0
3	1	0	1	0	0	BILLAN	5	10	1	0
4	1	0	82	0	0	BILLAN	5	10	1	0

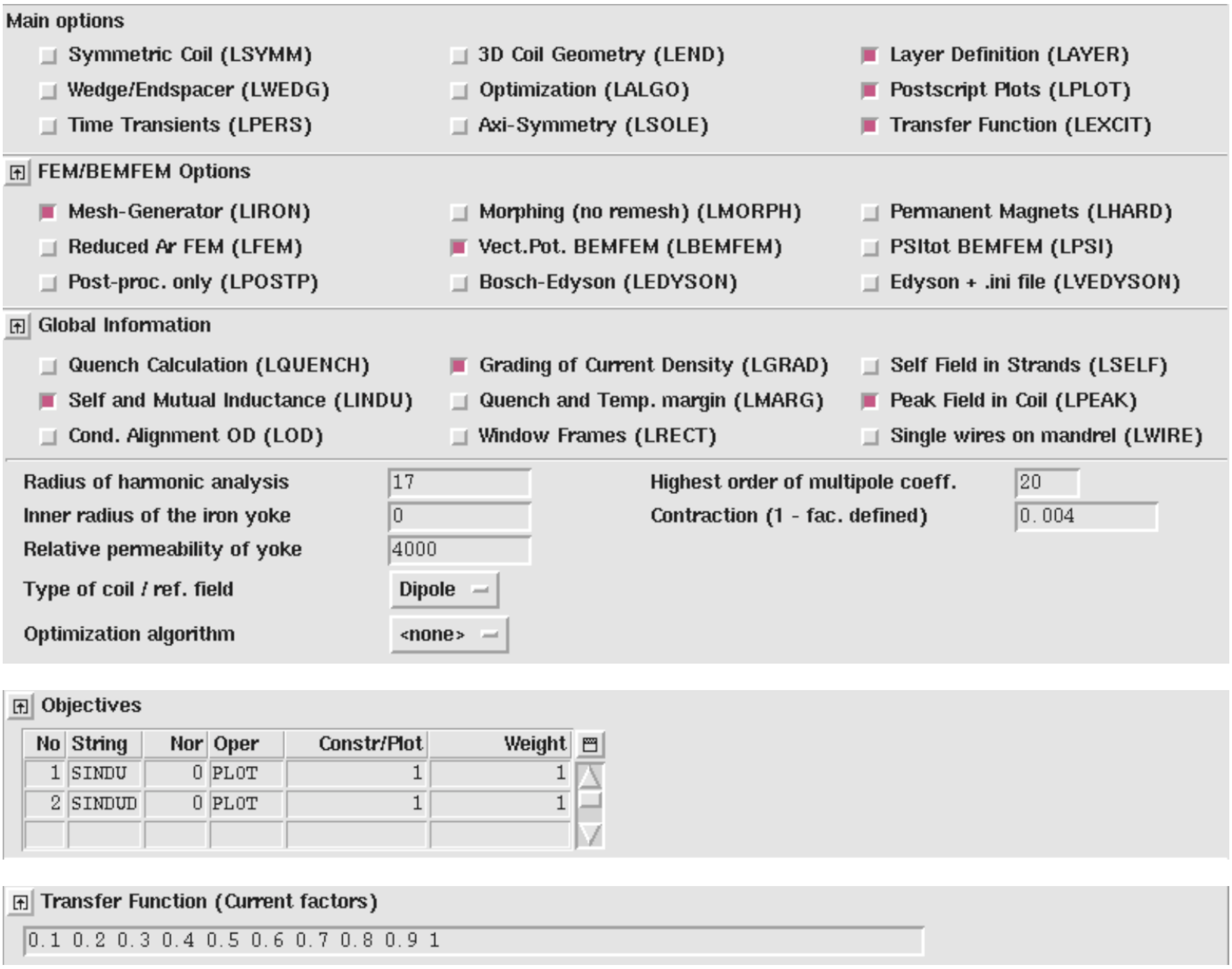
Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	100	100	100	XCOIL	0
2	0	0	0	FULL	0
3	2	2	2	HARD	1
4	1	1	1	HARD	2

In Fig. Fig. 13.2 we used the NOCND-option in the "Plotting Information 2-D"-table to suppress the plotting of the current-void coil blocks.

13.2 Differential inductance

The calculation of a differential inductance of a magnetic circuit (compare is done during a transfer-function evaluation. If the induced voltage is measured during the ramping of the magnet, then it is the differential inductance that can be derived from these measurements. The following input automatically generates the output and plot shown in Fig. Fig. 13.3. Figure 13.4 shows the geometry with the iron yoke. On the yoke, the relative magnetic permeability is displayed at low field (left) and at high field (right).



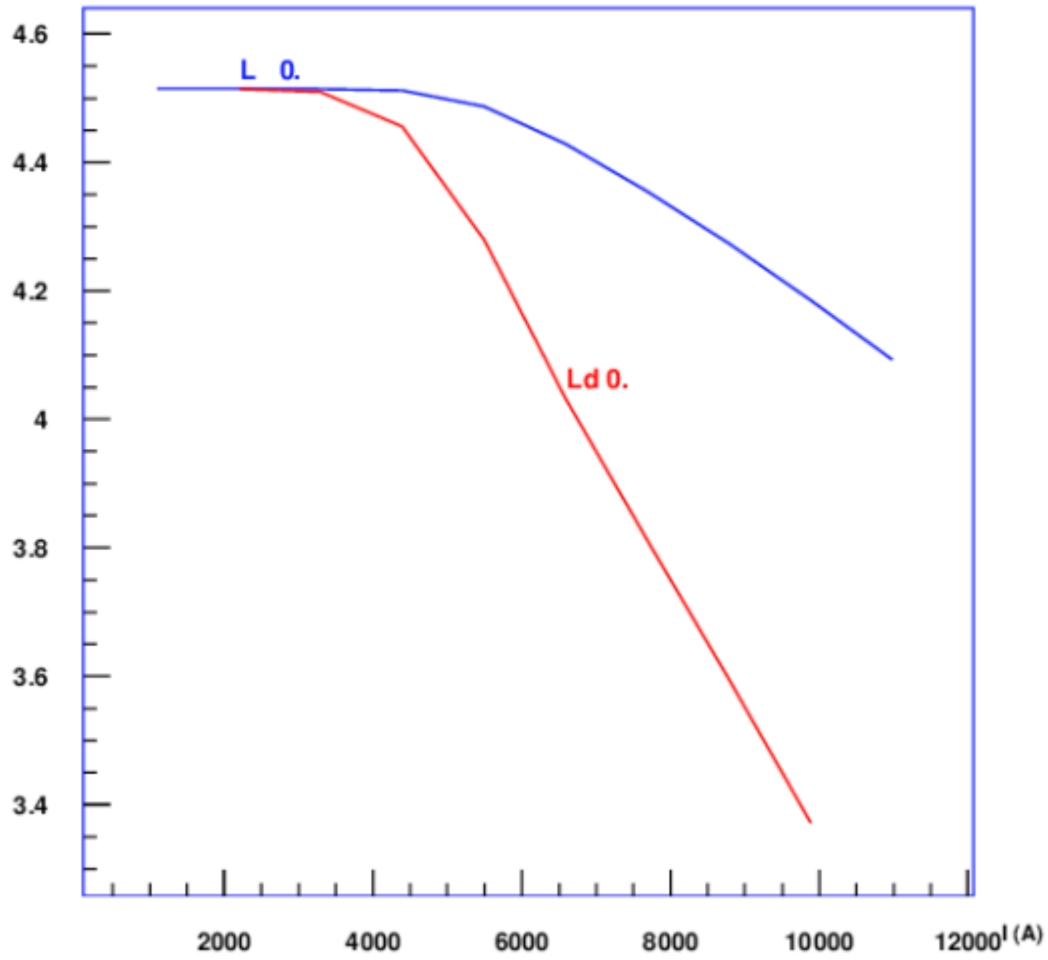


Fig. 13.3: Self inductance (in mH/m) and differential inductance for the geometry in Fig. 13.4 as a function of excitation.

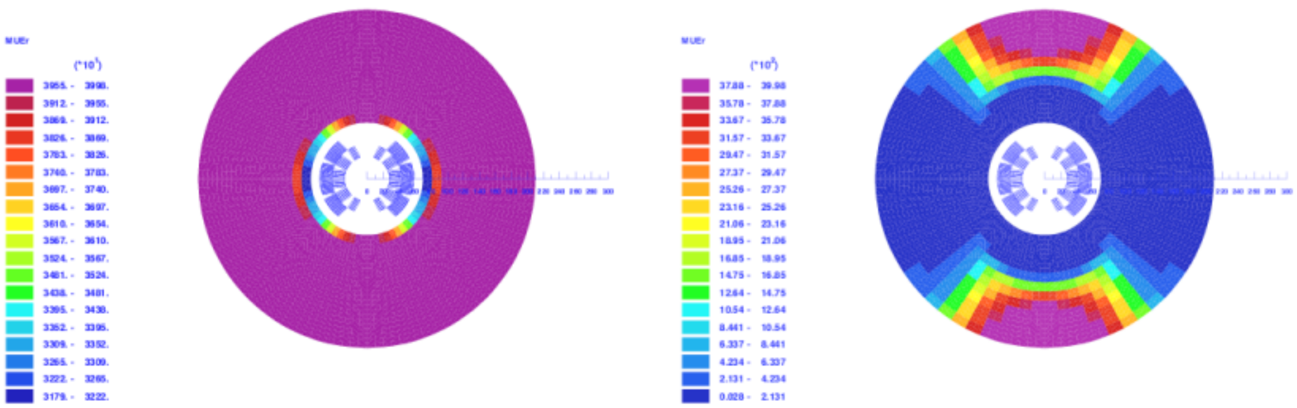


Fig. 13.4: Self inductance (in mH/m) and differential inductance for the geometry in Fig. 13.4 as a function of excitation.

13.3 Peak-field Calculation 3-D

To calculate peak fields in 3-D coil geometries, including the non-linear iron yoke magnetization, is a three-fold task:

- In the first step the user finds the peak-field in the coil without iron yoke. To do this, we switch on the "3-D Peak Field Calc." option in the "Global Information 3-D", as well as the "3-D Field Map in Coil" in the "Interface options". Running the case without iron yields the peak field per block in the .output-file. The number of the conductor, which is exposed to the peak-field per block, is also given in the .output-file. From the .map3d-file we can then read the strand number where the peak-field occurs.
- We now switch on the "Field along a line"-option in the "Interface Options" and supply dummy variables. Furthermore we choose the "STRFEL" ('strand field') option from the "Peak Fields"-menu in the "Objectives". For "Nor" we specify the peak-field strand number, for "Oper" the option "PLOT" and '1' for "Constr/Plot" and "Weight". The option "STRFEL" makes ROXIE calculate the field along a line, where the line is given by the strand geometry, from the straight section to the apex of the coil end. The output of the "Field along a line"-calculation is printed to the .output-file (see below) and a postscript plot is produced.
- To make sure that the peak-field in the coil ends has not moved to another strand as a result of iron saturation, we have to repeat the calculation in the neighbouring strands. Which strands are adjacent to the specified strand can be found (relatively) easily from the first table in the .map3d-file and the preview window.

3-D peak-field printout in the .output-file:

```
RESULTS OF THE 3D PEAK FIELD CALCULATION:

BLOCK NUMBER ..............................          8

B  ABSOLUTE IN TESLA ......................     5.3837
B  TRANSVERSAL TO CURRENT DIRECTION (T) ....     5.3837
B  IN DIRECTION OF CURRENT (T) ............     0.0027
B  PARALLEL TO BROAD SIDE OF CABLE (T) .....    -5.1528
B  PERPENDICULAR TO BROAD SIDE OF CABLE (T).     1.3407
POSITION IN Z DIRECTION (NUMBER OF LAYER)...          3
NUMBER OF CONDUCTOR WITH PEAKFIELD .........         70
X KOORDINATE ..............................    14.4897
Y KOORDINATE ..............................    50.0588
Z KOORDINATE ..............................   314.4236
```

Corresponding .map3d-file entries.

```
     NFIL  NCUT  NCON      X         Y          Z
   1   1   1     62.1332     24.3131     0.0000
   1   2   1     62.1332     24.3131   314.8884
   1   3   1     62.1179     24.3614   333.4033
  ... ... ...       ...        ...        ...
NFIL  NCUT  NCON      Bx        By       Bz        |B|
   1   1   1     -1.4857     -0.7931     -0.0090     1.6841
   1   2   1     -1.5525     -0.9637     -0.0062     1.8273
   1   3   1     -1.6063     -1.0023      0.0265     1.8935
  ... ... ...       ...        ...        ...         ...
2488  19  70     -0.0326     -4.8824      0.6349     4.9236
2488  20  70     -0.0110     -4.8769      0.6403     4.9188
2488  21  70      0.0000      0.0000      0.0000     0.0000
2489   1  70     -0.3210     -5.0882     -0.0190     5.0983
2489   2  70     -0.3659     -5.3612      0.0973     5.3746
2489   3  70     -0.3678     -5.3695      0.1322     5.3837
2489   4  70     -0.3665     -5.3673      0.1582     5.3821
2489   5  70     -0.3630     -5.3604      0.1863     5.3759
2489   6  70     -0.3570     -5.3492      0.2163     5.3655
2489   7  70     -0.3482     -5.3341      0.2482     5.3512
2489   8  70     -0.3364     -5.3156      0.2814     5.3337
  ... ... ...       ...        ...        ...         ...
```

We see that the peak-field in block 8, conductor 70 is located in strand number 2489, position 3 (along the z-axis).

"Field along a line"-option with dummy variables:

The strand-field option specifies the strand number 2489 for the "Field along a line" option.

Objectives

No	String	Nor	Oper	Constr/Plot	Weight
1	STRFEL	2489	PLOT	1	1

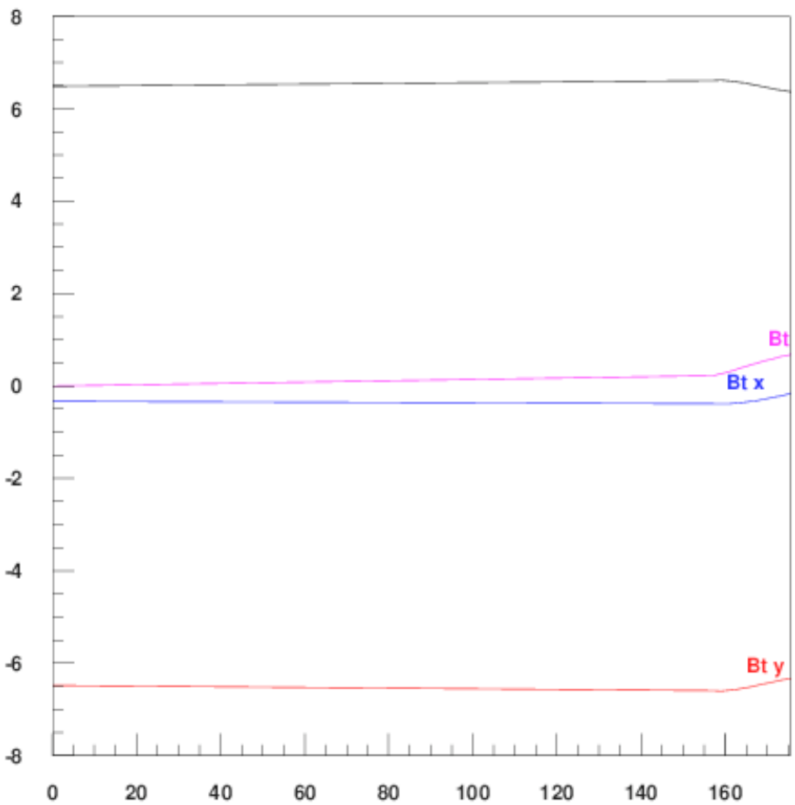
The field-values along the strand number 2489 are printed to the .output-file.

```
    FIELD CALCULATION ALONG A LINE (TOTAL)

     I    X-POS   Y-POS   Z-POS   DIST      BX          BY          BZ         |B|
      1   14.56   50.04  156.08    0.00 -0.3338E+00 -0.6476E+01 -0.7835E-03  0.6484E+01
      2   14.52   50.05  313.30  157.22 -0.3818E+00 -0.6595E+01  0.2236E+00  0.6610E+01
      3   14.43   50.08  315.00  158.92 -0.3836E+00 -0.6599E+01  0.2612E+00  0.6615E+01
      4   14.29   50.12  316.12  160.05 -0.3821E+00 -0.6594E+01  0.2890E+00  0.6612E+01
      5   14.09   50.18  317.25  161.20 -0.3784E+00 -0.6585E+01  0.3190E+00  0.6603E+01
      6   13.83   50.26  318.40  162.38 -0.3722E+00 -0.6570E+01  0.3511E+00  0.6590E+01
      7   13.49   50.36  319.57  163.60 -0.3630E+00 -0.6552E+01  0.3851E+00  0.6574E+01
      8   13.07   50.48  320.76  164.87 -0.3507E+00 -0.6531E+01  0.4206E+00  0.6554E+01
      9   12.56   50.62  321.94  166.17 -0.3351E+00 -0.6507E+01  0.4569E+00  0.6531E+01
     10   11.95   50.77  323.12  167.50 -0.3161E+00 -0.6480E+01  0.4936E+00  0.6507E+01
     11   11.23   50.94  324.28  168.87 -0.2940E+00 -0.6453E+01  0.5300E+00  0.6481E+01
     12   10.41   51.12  325.40  170.27 -0.2691E+00 -0.6425E+01  0.5656E+00  0.6455E+01
     13    9.49   51.30  326.46  171.69 -0.2418E+00 -0.6397E+01  0.5997E+00  0.6430E+01
     14    8.46   51.48  327.44  173.12 -0.2127E+00 -0.6371E+01  0.6317E+00  0.6406E+01
     15    7.35   51.65  328.32  174.55 -0.1821E+00 -0.6347E+01  0.6607E+00  0.6384E+01
     16    6.15   51.80  329.09  175.98 -0.1504E+00 -0.6325E+01  0.6862E+00  0.6364E+01
     17    4.87   51.93  329.72  177.42 -0.1178E+00 -0.6307E+01  0.7075E+00  0.6348E+01
     18    3.53   52.04  330.21  178.85 -0.8457E-01 -0.6293E+01  0.7241E+00  0.6336E+01
     19    2.15   52.11  330.55  180.27 -0.5119E-01 -0.6284E+01  0.7354E+00  0.6327E+01
     20    0.73   52.15  330.72  181.70 -0.1724E-01 -0.6279E+01  0.7412E+00  0.6323E+01

        MAXIMUM OF THE FIELD COMPONENTS BX,BY,BZ (ABS):    0.3835986
      6.599093       0.7412140
        MAXIMUM OF THE FIELD |B|:     6.615391
```

A postscript plot is produced:



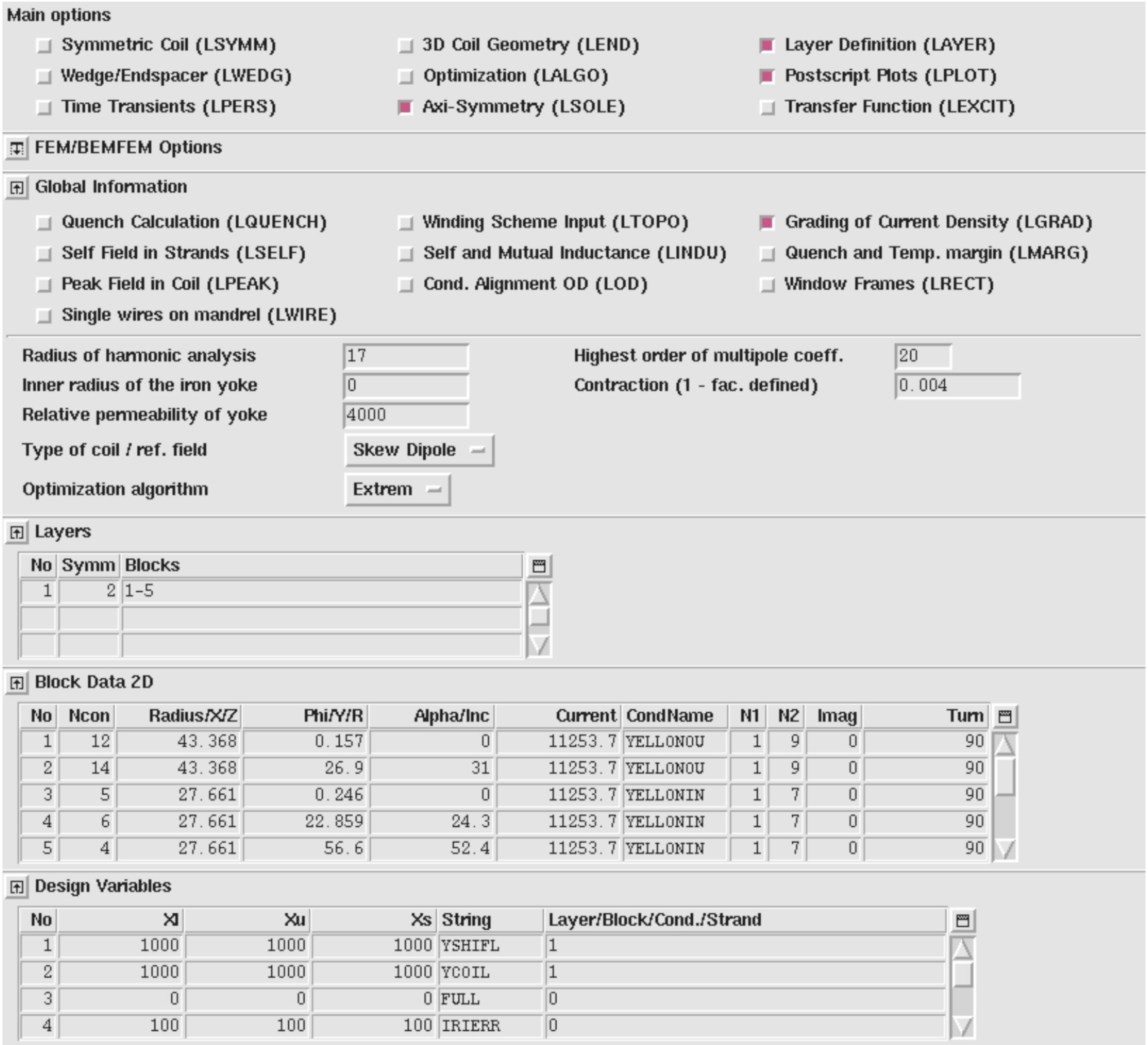
13.4 Field Quality in a Bent Magnet

ROXIE can calculate the field quality in a long, bent magnet in a 2-D calculation. To this end we use the "Axi-Symmetry"-option in the "Main Options", which assumes that the x-axis is the axis of rotation.

If the magnet has a bending radius of 10 m, then we need to place the magnet 10 m above the x-axis. Moreover, we need to tilt the magnet by 90 degrees to make the bend axis coincide with the x-axis. We must create a full mesh of the iron yoke.

Peak-field and field-quality calculations will work. Time-transient calculations, however, are not implemented for the axi-symmetric case. They can be simulated for a "straight" cross-section.

The following input yields the plots in Fig. 13.5.



Main options

- [ ] Symmetric Coil (LSYMM)
- [ ] 3D Coil Geometry (LEND)
- [x] Layer Definition (LAYER)
- [ ] Wedge/Endspacer (LWEDG)
- [ ] Optimization (LALGO)
- [x] Postscript Plots (LPLOT)
- [ ] Time Transients (LPERS)
- [x] Axi-Symmetry (LSOLE)
- [ ] Transfer Function (LEXCIT)

FEM/BEMFEM Options

Global Information

- [ ] Quench Calculation (LQUENCH)
- [ ] Winding Scheme Input (LTOPO)
- [x] Grading of Current Density (LGRAD)
- [ ] Self Field in Strands (LSELF)
- [ ] Self and Mutual Inductance (LINDU)
- [ ] Quench and Temp. margin (LMARG)
- [ ] Peak Field in Coil (LPEAK)
- [ ] Cond. Alignment OD (LOD)
- [ ] Window Frames (LRECT)
- [ ] Single wires on mandrel (LWIRE)

Radius of harmonic analysis: 17
Inner radius of the iron yoke: 0
Relative permeability of yoke: 4000
Type of coil / ref. field: Skew Dipole
Optimization algorithm: Extrem
Highest order of multipole coeff.: 20
Contraction (1 - fac. defined): 0.004

Layers

No	Symm	Blocks
1	2	1-5

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	12	43.368	0.157	0	11253.7	YELLONOU	1	9	0	90
2	14	43.368	26.9	31	11253.7	YELLONOU	1	9	0	90
3	5	27.661	0.246	0	11253.7	YELLONIN	1	7	0	90
4	6	27.661	22.859	24.3	11253.7	YELLONIN	1	7	0	90
5	4	27.661	56.6	52.4	11253.7	YELLONIN	1	7	0	90

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	1000	1000	1000	YSHIFL	1
2	1000	1000	1000	YCOIL	1
3	0	0	0	FULL	0
4	100	100	100	IRIERR	0

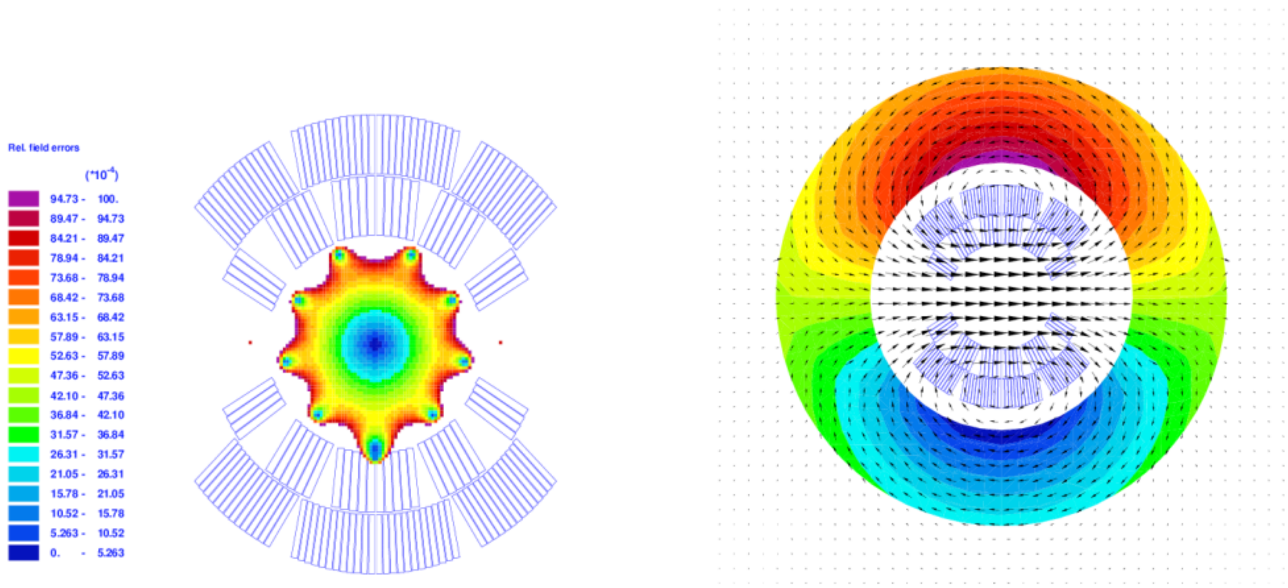
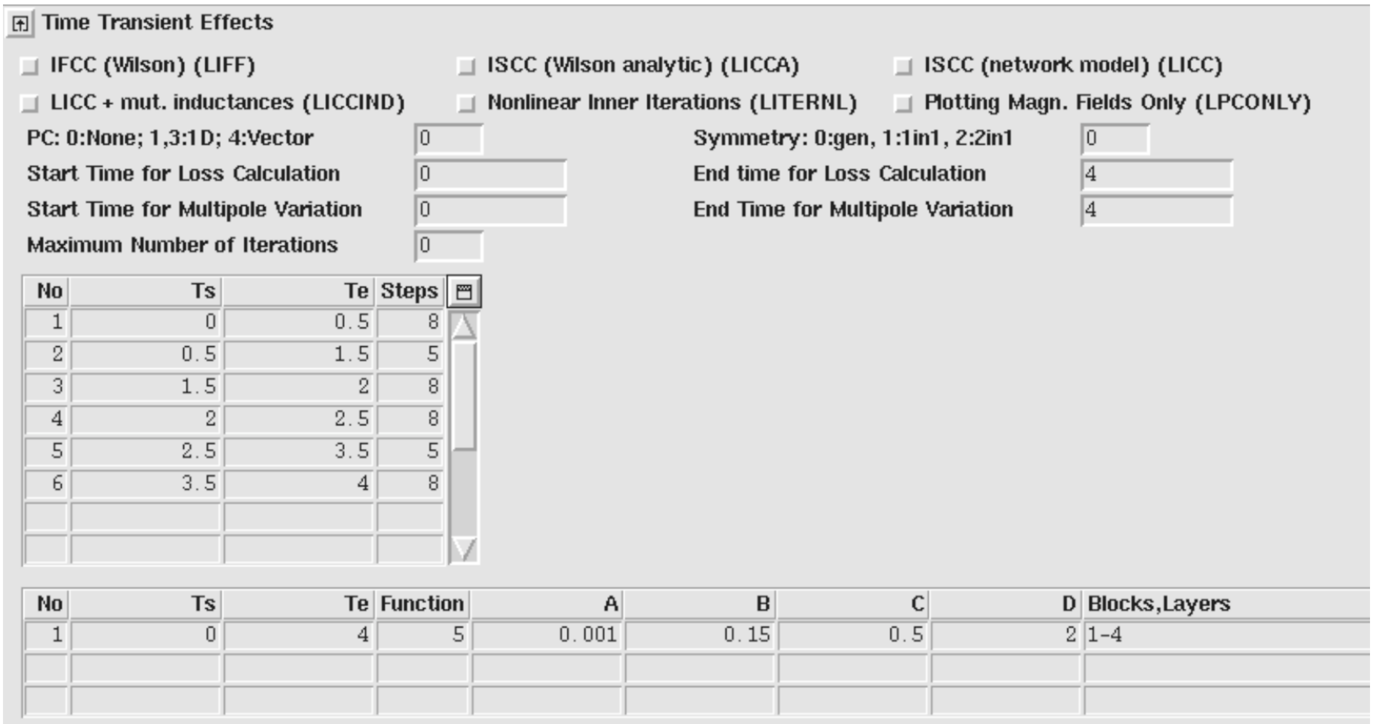


Fig. 13.5: Bent dipole magnet with a bending radius of only 1 m. We can see the resulting asymmetry in the iris plot and in the field lines.

14. Examples of SC-Related Time-Transient Effects

14.1 The analytical models of SC magnetization

This section presents an example magnet and ramp cycle. The Persistent Current (PC) effects, the Interfilament Coupling Currents (IFCCs) and the Interstrand Coupling Currents (ISCCs) are simulated, their influence on field quality and loss-contribution are discussed. We use the following input in the "Time Transient Effects"-widget.



Time Transient Effects

IFCC (Wilson) (LIFF) | ISCC (Wilson analytic) (LICCA) | ISCC (network model) (LICC)

LICC + mut. inductances (LICCIND) | Nonlinear Inner Iterations (LITERNL) | Plotting Magn. Fields Only (LPCONLY)

PC: 0:None; 1,3:1D; 4:Vector	0	Symmetry: 0:gen, 1:1in1, 2:2in1	0
Start Time for Loss Calculation	0	End time for Loss Calculation	4
Start Time for Multipole Variation	0	End Time for Multipole Variation	4
Maximum Number of Iterations	0		

No	Ts	Te	Steps
1	0	0.5	8
2	0.5	1.5	5
3	1.5	2	8
4	2	2.5	8
5	2.5	3.5	5
6	3.5	4	8

No	Ts	Te	Function	A	B	C	D	Blocks,Layers
1	0	4	5	0.001	0.15	0.5	2	1-4

The excitation function thus defined is shown in Fig. 14.1 (right). The left plot shows the magnet cross-section and exciting magnetic field.

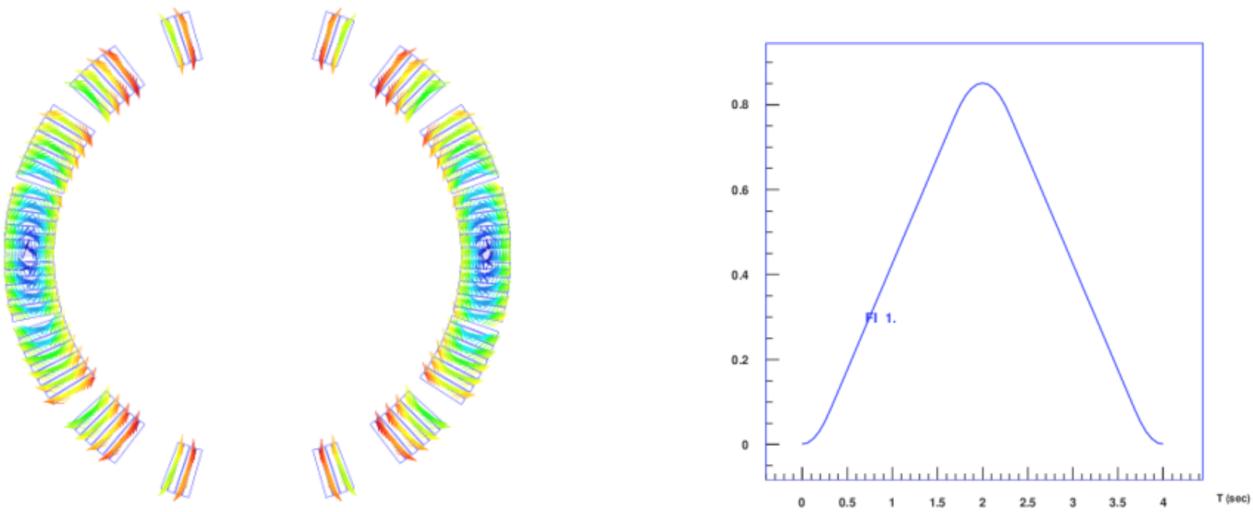


Fig. 14.1: Left: Dipole magnet cross-section (RHIC dipole magnet) with excitation field. Right: Excitation function of block 1. The option DTRF was used in the "Objectives"-table to obtain the plot. Furthermore the "PC: 0: None; 1,3: 1D; 4: Vector"-parameter was set

to zero as PC calculations would produce a plot of Excitation over current rather than excitation over time.

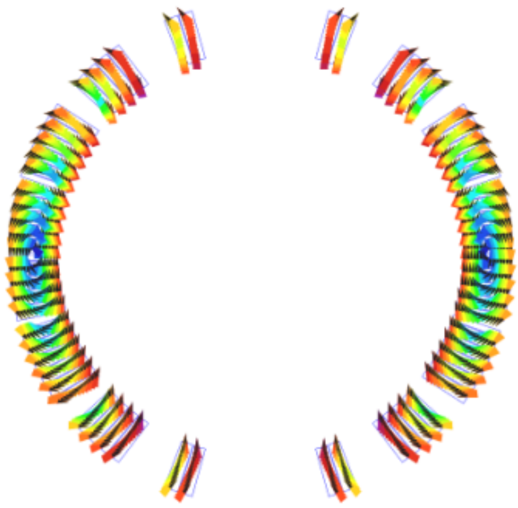


Fig. 14.2: PC-induced magnetization in SC strands. Left: Magnetization at low field. Right: Magnetizaton at high field. All strands but the center ones are saturated.

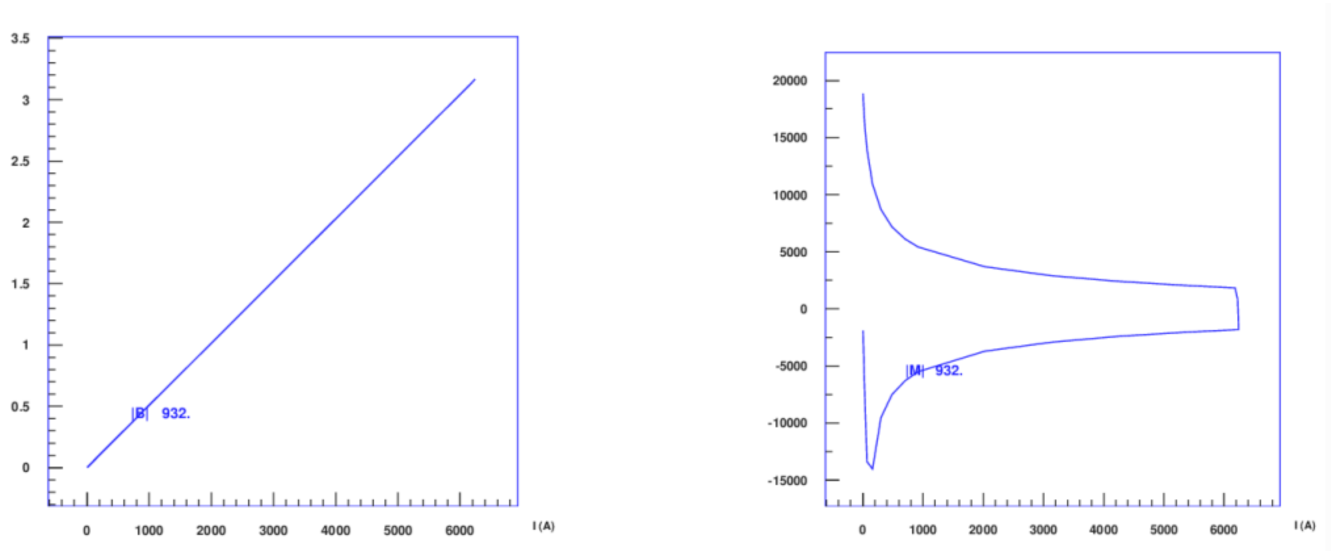


Fig. 14.3: Excitation field (left) and magnetization (right) of a single strand. The options BSTR and MSTR were used from the "Objectives"-table.

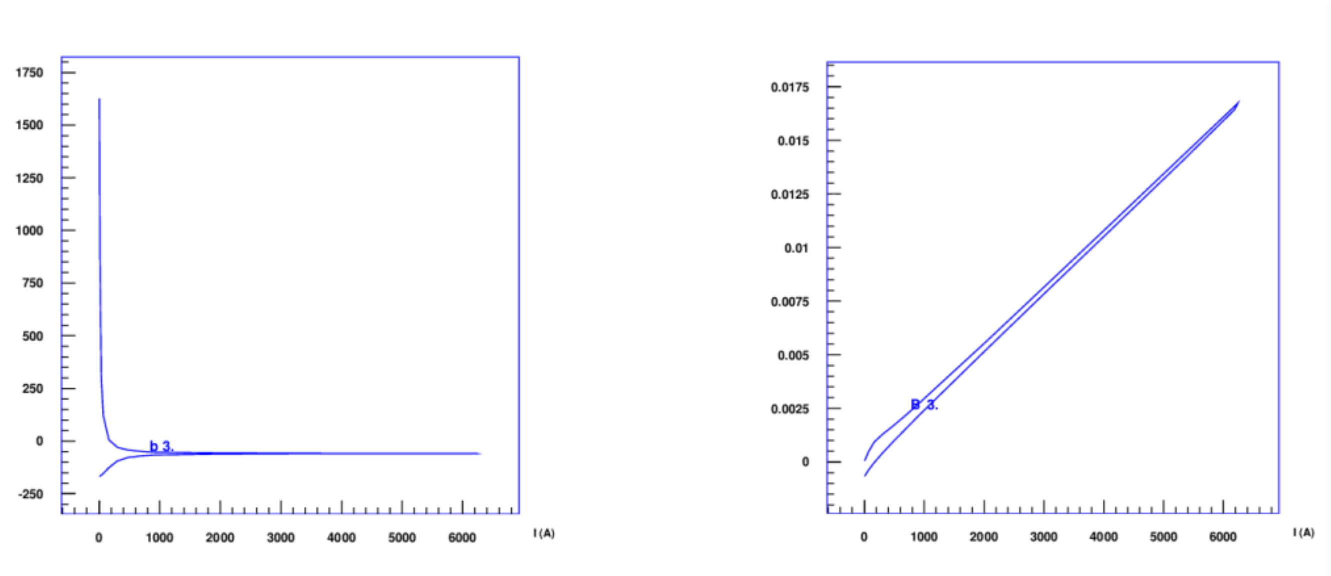


Fig. 14.4: The magnet's sextupole error as a function of the excitation. Left: Relative field error. Right: Absolute field error. The B and BR options from the "Objectives"-table were used.

14.1.1 Persistent currents

The PC-magnetization of SC filaments is shown in Fig. 14.2. Figure 14.3 shows the excitation and magnetization curve of a single strand. Figure Fig. 14.4 yields the absolute and relative sextupole component of the field as a function of excitation current.

14.1.2 Interfilament coupling currents

The IFCC-magnetization of SC strands is shown in Fig. 14.5 (left). The right plot shows the magnetization curve of a single strand.

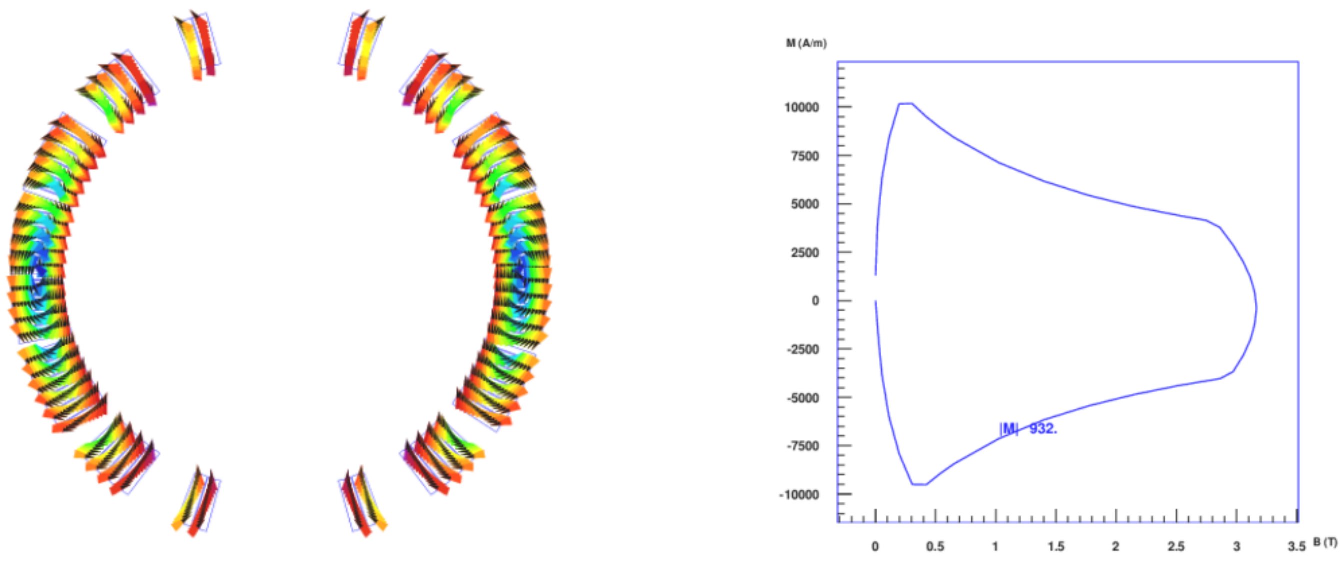


Fig. 14.5: Left: Strand magnetization pattern due to IFCCs. Right: Magnetization curve of a single strand. The difference between ramp up and down is due to the use of forward differences in the calculation of the time-derivative of the magnetic induction.

14.1.3 Interstrand coupling currents

The ISCC-magnetization of SC cables is shown in Fig. 14.6. Fig. 14.7 (left) shows the magnetization curve of a single strand in a cable. The right plot gives the angular information, including a jump by 180 degrees at the peak-excitation.

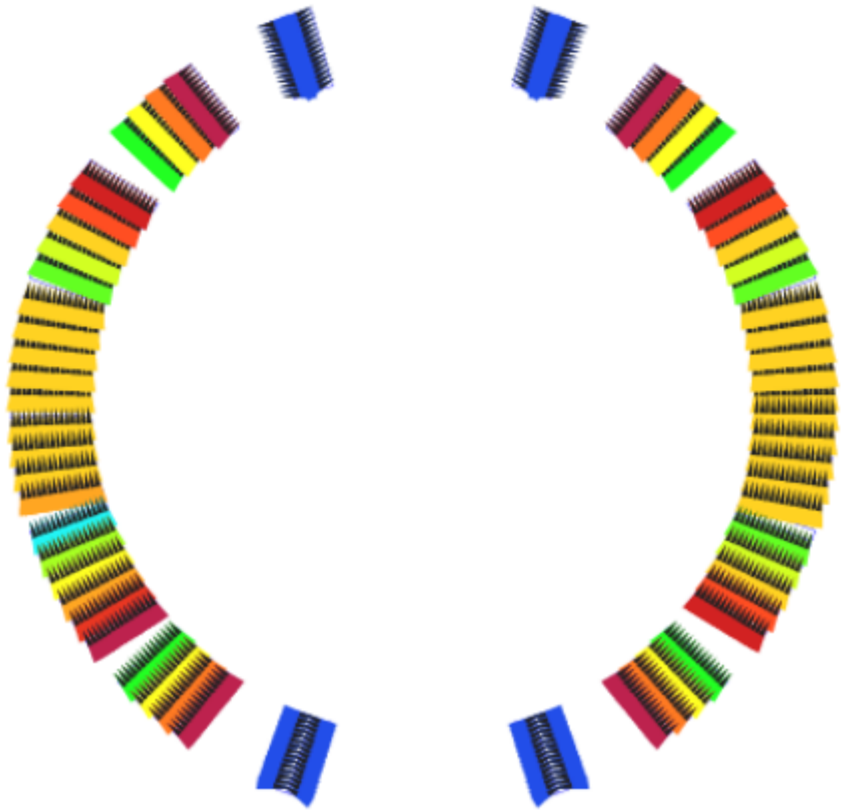


Fig. 14.6: Strand magnetization pattern due to ISCCs.

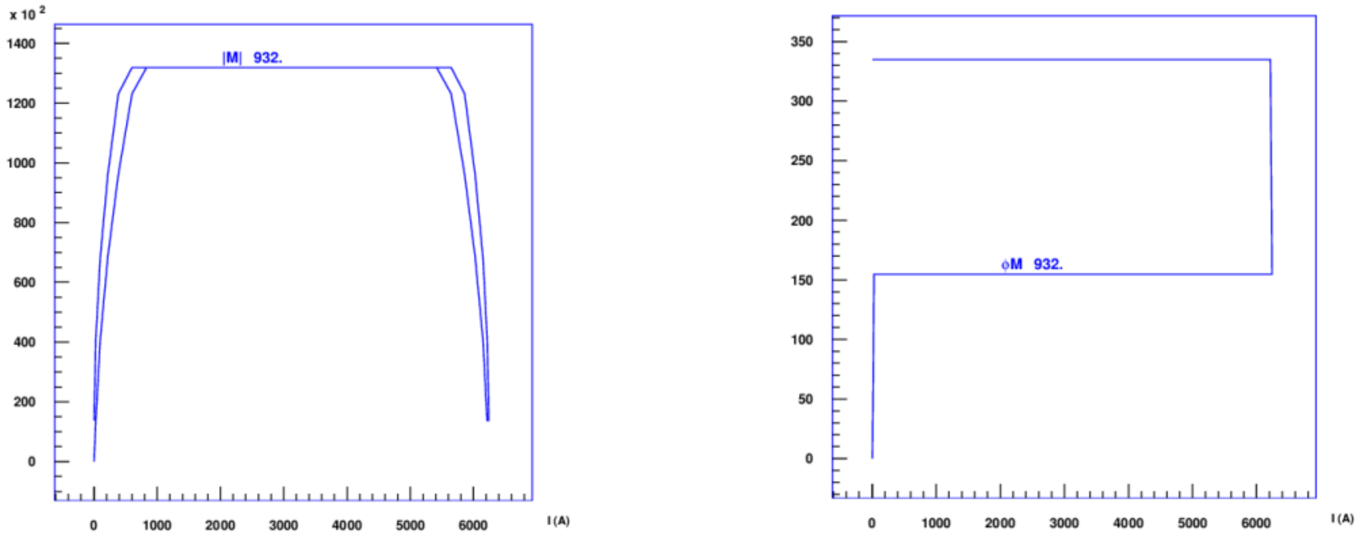


Fig. 14.7: Left: Magnetization curve of a single strand in a cable. Right: Angular information on cable magnetization. The difference between ramp up and down is due to the use of forward differences in the calculation of the time-derivative of the magnetic induction.

Note that analytical models of interstrand coupling currents can only give an estimate. Especially in terms of losses the implemented model tends to underestimate the real losses. This happens mostly when there are blocks with a field vertex, i.e., the magnetic field in a block shows in up on one side and down on the other, with zero field in the midle. In this case the cable-magnetization will underestimate the losses. The network model of Section 14.2 gives accurate results.

14.2 Network model of ISCCs

The same excitation as in the previous section is used to evaluate interstrand coupling currents from a network model which represents the cross-over- and adjacent resistances in a Rutherford-type cable. The coupling current pattern is plotted in Fig. 14.8.

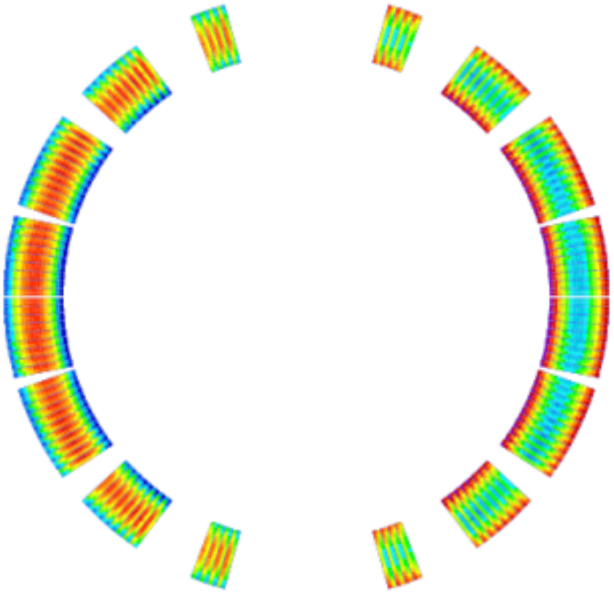


Fig. 14.8: Interstrand coupling-current pattern in the coil cross-section. Note that the Eddy-Current loops in the outer blocks close over the cross-over resistances, while in the central blocks they close over the adjacent resistances.

14.3 Quench calculations

Quench simulation is, almost by definition, an ill-posed problem. The engineer can come up with an arbitrarily high number of design parameters, such as

- for the the electrical network: power-supply, diode, dump resistor, ...,
- for the electromagnetic problem: the geometry, material parameters of the yoke iron, cable parameters (adjacent- and cross-resistivities, time-constants...) ...,
- for the protection instrumentation: detection thresholds, delays, quench heaters (heater power, discharge curve),
- for the thermal problem: thermal conductivities, the cooling mechanism.

And at the same time there are only very few observables:

- the current decay during a quench,
- depending on the instrumentation of the quenching magnet, some voltage signals.

Moreover, many of the model parameters are notoriously difficult to determine.

The user must be aware that almost any quench simulation software, independent of its level of sophistication, will have enough parameters to fit a measured current decay curve. This does, however, not mean, that the quench behaviour of a magnet is understood and that the peak temperature is accurately predicted. On the contrary, for identical current decay curves, different models (with different sophistication) will yield differences in peak-voltages and peak temperatures of up to 50 percent.

We are nonetheless striving for more sophisticated quench modelling, because we wish to

- understand the sensitivity of peak temperature and peak voltage to different model parameters, e.g.: Is an increase in RRR admissible? Can quench heaters be placed more efficiently? How do peak-voltages change if some quench heaters fail? By how much must the cooling increase to keep the peak temperature below specified values? What is the impact of increased/ decreased adjacent and cross-over resistances? and many more questions.
- avoid linearization where it is not applicable. The inductance of a magnet changes depending on the yoke saturation. For high-field magnets this effect is not negligible and can be modelled effectively.
- have a qualitative understanding of a quenching magnet.

It is inevitable that the user studies the concepts of quench simulation in some detail. Moreover, a lot of information must be supplied to ROXIE to perform meaningful simulations. The theory of the present quench simulation algorithm in ROXIE is presented in the IEEE paper [@Schwerg:2007lr] by Nikolai Schwerg.

14.3.1 Winding Scheme

Until now the ROXIE program did not deal with coils as such, but with blocks and layers of conductors that were assigned excitation currents. For the calculation of internal voltages in coils during a quench, ROXIE must know the exact winding scheme, i.e. the succession of all conductors in the coil (or coil assembly). To provide this topological information, the user must use the "Layer"-option in the "Main Options". Only "Symm"-values 0 and 1 are admissible in the "Layers" widget.

The winding scheme can be previewed in the preview window if the "Winding Scheme Input"-option in the "Global Information" is 'on'. Then the conductor numbering according to the winding scheme is displayed after two successive clicks on the "1,2 ..."-button.

In order to obtain a correct winding scheme, the user can change the winding direction of individual layers: If the number of conductors "Ncon" in the "Block Data 2D" of at least one block in a layer has a negative sign, then the winding direction of the entire layer is inverted.

Don't forget that the winding-scheme numbering, which is displayed in the preview window if the "Winding Scheme Input"-option in the "Global Information" is 'on', is only used for the calculation of internal voltages. For all conductor-specific input in the design variables the conventional ROXIE numbering must be used, which can be previewed if the "Winding Scheme Input"-option is 'off'. The "Winding Scheme Input"-option only serves the purpose to toggle the conductor numbering in the preview window.

The following input produces conductor numbers with and without "Winding Scheme Input"-option that are displayed in Fig. 14.9.

Layers

No	Symm	Blocks
1	1	1-2
2	1	3-6
3	1	7-10
4	1	11-12

Block Data 2D

No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	9	43.9	0.157	0	12000	YELLONOU	1	9	1	0
2	16	43.9	21.9	27	12000	YELLONOU	1	9	1	0
3	-5	28	0.246	0	12000	YELLONIN	1	9	1	0
4	5	28	22.02	24.08	12000	YELLONIN	1	9	1	0
5	3	28	47.71	48	12000	YELLONIN	1	9	1	0
6	2	28	66.71	68.5	12000	YELLONIN	1	9	1	0
7	5	28	0.246	0	12000	YELLONIN	1	9	0	0
8	5	28	22.02	24.08	12000	YELLONIN	1	9	0	0
9	3	28	47.71	48	12000	YELLONIN	1	9	0	0
10	2	28	66.71	68.5	12000	YELLONIN	1	9	0	0
11	-9	43.9	0.157	0	12000	YELLONOU	1	9	0	0
12	16	43.9	21.9	27	12000	YELLONOU	1	9	0	0

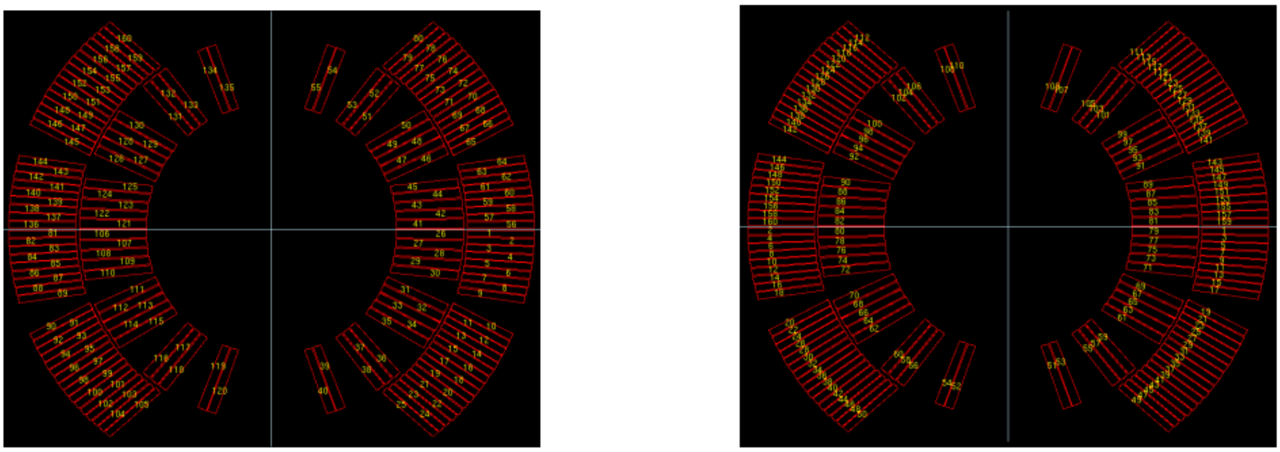


Fig. 14.9: Left: Conventional ROXIE conductor numbering in a dipole without "Winding Scheme Input"-option. This numbering is relevant for design-variables. Right: Conductor numbering with "Winding Scheme Input"-option. The winding information is important for quench simulation.

Note that the following input in the "Block Data 2-D"-table produces an identical winding scheme as the above one.

Block Data 2D

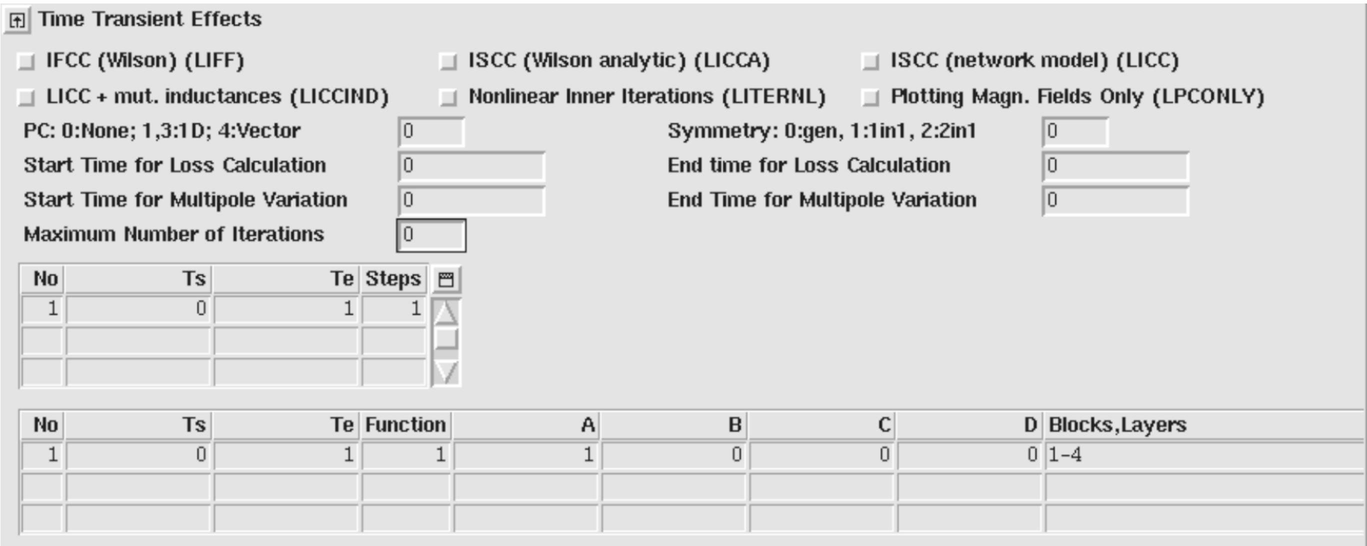
No	Ncon	Radius/X/Z	Phi/Y/R	Alpha/Inc	Current	CondName	N1	N2	Imag	Turn
1	9	43.9	0.157	0	12000	YELLONOU	1	9	1	0
2	16	43.9	21.9	27	12000	YELLONOU	1	9	1	0
3	-5	28	0.246	0	12000	YELLONIN	1	9	1	0
4	-5	28	22.02	24.08	12000	YELLONIN	1	9	1	0
5	-3	28	47.71	48	12000	YELLONIN	1	9	1	0
6	-2	28	66.71	68.5	12000	YELLONIN	1	9	1	0
7	5	28	0.246	0	12000	YELLONIN	1	9	0	0
8	5	28	22.02	24.08	12000	YELLONIN	1	9	0	0
9	3	28	47.71	48	12000	YELLONIN	1	9	0	0
10	2	28	66.71	68.5	12000	YELLONIN	1	9	0	0
11	-9	43.9	0.157	0	12000	YELLONOU	1	9	0	0
12	-16	43.9	21.9	27	12000	YELLONOU	1	9	0	0

14.3.2 Transient Widget

Not all data in the transient widget is used for quench simulation. To take into account the quench-back effect, the user can choose between interfilament coupling current and/or interstrand coupling current models, see the respective sections in Chapter 9. Persistent-current losses are not considered for quench simulation at this stage of development.

We suggest only to use the "IFCC (Wilson)" option and the "ISCC (Wilson analytic)" option. All other options should be 'off', and the individual values all set to zero. The time-step table is not being used as the quench algorithm has an adaptive time-stepping algorithm.

At a later stage of development, ROXIE will be able to simulate a quench that occurs not at steady-state nominal conditions, but during an arbitrary excitation cycle. For the time being, however, the user has to supply a steady-state excitation of which the quench routine will only read the first time-step.



No	Ts	Te	Steps
1	0	1	1

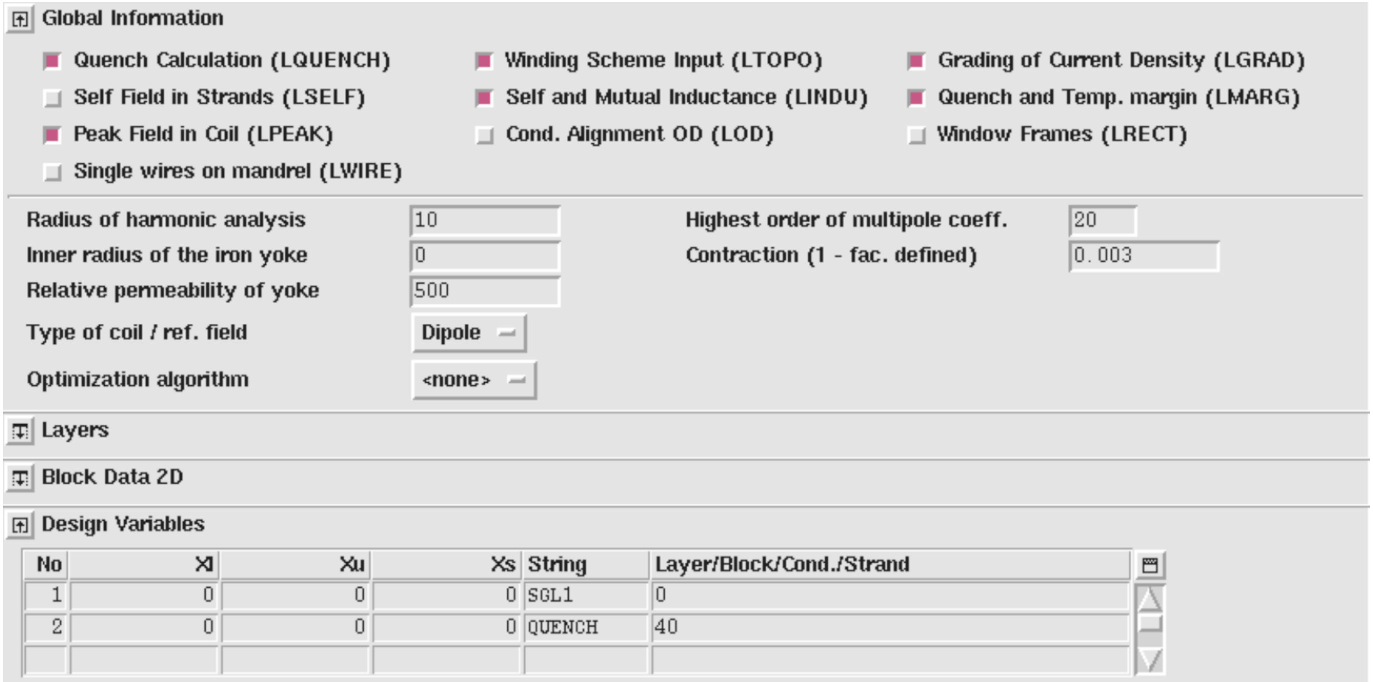
No	Ts	Te	Function	A	B	C	D	Blocks,Layers
1	0	1	1	1	0	0	0	1-4

14.3.3 Basic quench

To do quench simulation, the following options must be set

- "Quench Calculation" in "Global Information".
- "Self and Mutual Inductance" in "Global Information".
- "Quench and Temperature Margin" in "Global Information".
- "Peak Field in Coil" in "Global Information".
- "Time Transients" in "Main Options". For a description of the "Time Transients"-widget in the context of quench, see Section 14.3.
- "Layer Definition" in "Main Options".
- All conductors must be specified in the "Block spec." widget.
- A winding scheme needs to be specified, see Section 14.3.

A minimum set of input parameters is given in the following screenshot:



In this case, a quench originates in conductor 40 (compare left (!) picture in Fig. 14.9. There are no heaters, no delays, no diode threshold voltage, no dump resistors. The magnet is shortcircuited from t=0 s and dissipates its stored energy in the quenching zone. The RRR value is being read from the roxie.cadata-file. No quench back is considered. Azimuthal quench-propagation is not considered.

14.3.4 The full model

The full set of design variables is used in the following table

Design Variables

No	Xl	Xu	Xs	String	Layer/Block/Cond./Strand
1	0	0	0	SGL1	0
2	0	0	0	QUENCH	40
3	0.03	0.03	0.03	HEATER	5-15
4	0.03	0.03	0.03	HEATER	60-70
5	0.03	0.03	0.03	HEATER	85-95
6	0.03	0.03	0.03	HEATER	140-150
7	10	10	10	HEATP0	0
8	0.075	0.075	0.075	HEATTA	0
9	0.06	0.06	0.06	DUMPT	0
10	0.01	0.01	0.01	DUMPR	0
11	5	5	5	QDIOD	0
12	0.0001	0.0001	0.0001	QDIODR	0
13	0.1	0.1	0.1	QUTH	0
14	0.1	0.1	0.1	HEATTT	0
15	30	30	30	QCD	0
16	0.0001	0.0001	0.0001	RUNGES	0
17	0.1	0.1	0.1	QIMF	0

Furthermore a number of objective variables are implemented

Objectives

No	String	Nor	Oper	Constr/Plot	Weight
1	T	0	PLOT	3	1
2	T	23	PLOT	3	1
3	I	0	PLOT	2	1
4	B	0	PLOT	4	1
5	R	0	PLOT	1	1
6	V	0	PLOT	8	1
7	V	23	PLOT	8	1
8	MIITS	0	PLOT	10	1
9	UMAX	0	PLOT	11	1

Note however that, if you use the objectives to produce figures, ROXIE is only capable to depict the first 200 timesteps (due to legacy). The parameters can be used without restriction in an optimization.

Cross-section plots of temperature and potential distribution can be produced

Plotting Information 2D

- [x] Coordiante Axes (LAXIS)
- [x] Legend (LEGEND)
- [ ] Image Iron at X-Axis (LIMAGX)
- [ ] Image Iron at Y-Axis (LIMAGY)
- [ ] Area Boundary (LRAEND)
- [ ] Poly-Marker (LMARKER)
- [ ] More Plot Options (LPLOP)

No	X-axis	Color	4quad	Field
1	90	Y	Y	T
1	90	Y	Y	V

Extensive postprocessing is available via gnuplot files, e.g. the plots in Figs. 14.10 and Fig. 14.11, compare Section 9.3.

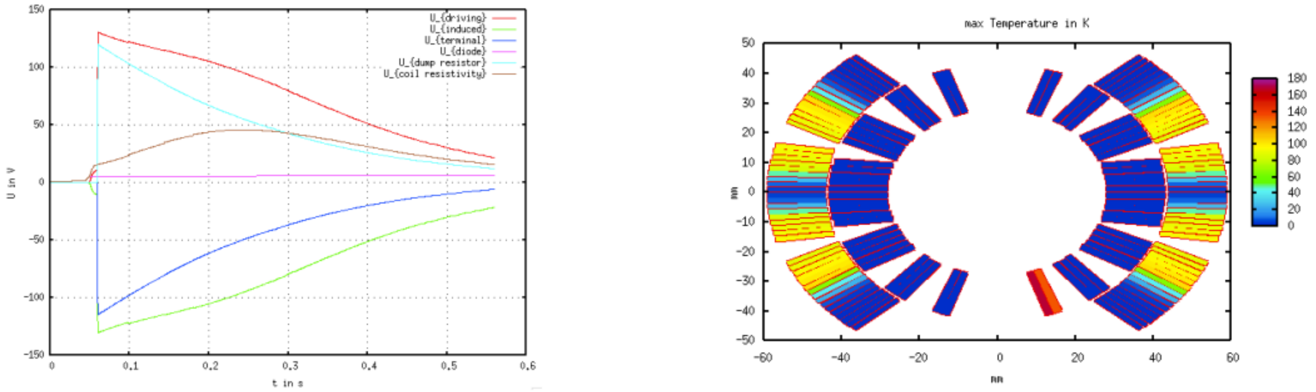


Fig. 14.10: Left: Voltages during a quench. Plot obtained from the Voltages.gnu file. Right: Temperature distribution over the cross-section at the end of a quench. Plot obtained from the TEMPERATURE_maximum.xsp file.

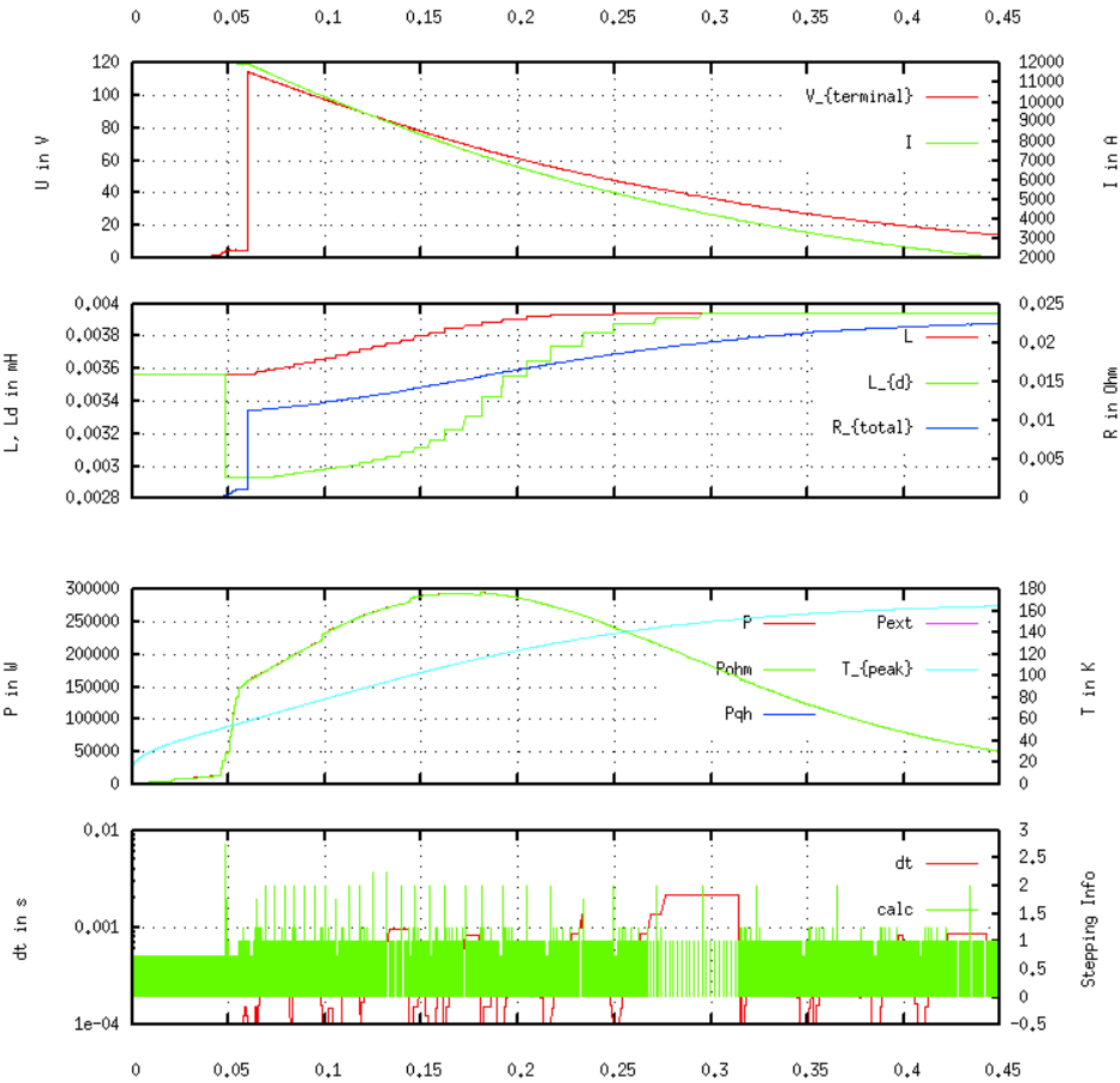


Fig. 14.11: Summary of various relevant parameters during a quench. The plot was obtained from the Overview.gnu file.

15. Examples of Interfaces

15.1 Interfaces for 2-D calculations

In this section we present interface files for the nested quadrupole-/dipole-model in Fig. 11.5.

15.1.1 Field-vector matrix (Map)

The "Field-Vector Matrix (Map)"-option in the "Interface Options"-widget produces an output file. In 2-D this happens only if a matrix-option (MATR, MATRC or MATRP from the "Aperture"-menu) is selected in the "Plotting Information 2-D"-widget.

```
   I   J         X          Y          BX         BY         |B|     DOMAIN
   1   1    -90.000000  -90.000000   -0.009448    0.043838    0.044844   B
   2   1    -80.526316  -90.000000   -0.016277    0.051280    0.053801   B
   3   1    -71.052632  -90.000000   -0.025893    0.058876    0.064319   B
   4   1    -61.578947  -90.000000   -0.038789    0.066333    0.076842   B
   5   1    -52.105263  -90.000000   -0.056004    0.073666    0.092538   B
   6   1    -42.631579  -90.000000   -0.080640    0.080640    0.114042   B
   7   1    -33.157895  -90.000000   -0.119580    0.082117    0.145060   B
   8   1    -23.684211  -90.000000   -0.172218    0.058646    0.181929   B
   9   1    -14.210526  -90.000000   -0.211407    0.001016    0.211409   B
  10   1     -4.736842  -90.000000   -0.219440   -0.072235    0.231023   B
  11   1      4.736842  -90.000000   -0.196080   -0.144229    0.243412   B
  12   1     14.210526  -90.000000   -0.144123   -0.203070    0.249015   B
  13   1     23.684211  -90.000000   -0.069422   -0.234215    0.244287   B
  14   1     33.157895  -90.000000    0.006643   -0.224513    0.224611   B
  15   1     42.631579  -90.000000    0.057199   -0.188974    0.197441   B
  16   1     52.105263  -90.000000    0.084098   -0.150712    0.172588   B
  17   1     61.578947  -90.000000    0.097002   -0.116668    0.151726   B
  18   1     71.052632  -90.000000    0.101551   -0.087620    0.134126   B
  19   1     80.526316  -90.000000    0.100762   -0.063251    0.118969   B
  20   1     90.000000  -90.000000    0.096463   -0.043178    0.105686   B
   1   2    -90.000000  -80.526316   -0.000995    0.049057    0.049067   B
   2   2    -80.526316  -80.526316   -0.007223    0.059286    0.059724   B
 ...  ...          ...        ...         ...         ...         ...  ...
```

The DOMAIN-column features 'F' or 'B', where 'F' means that the evaluation point is in a FEM domain and 'B' stands for a BEM domain.

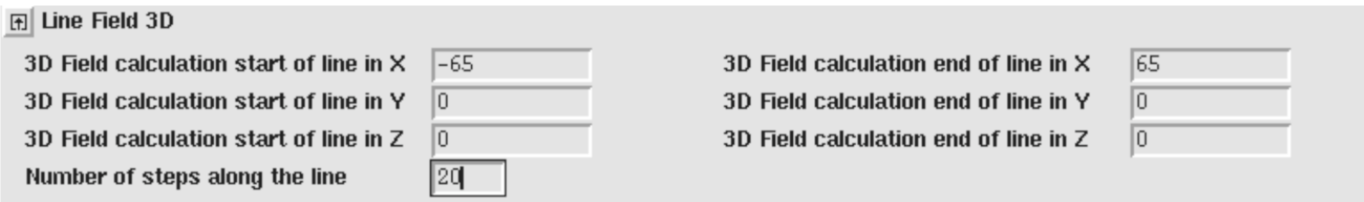
The call of the "Field-Vector Matrix (Map)"-option together with a matrix-option (MATR, MATRC or MATRP from the "Aperture"-menu) prints the following lines to the .output-file:

```
    2-D MATRIX FIELD CALCULATION
    LONGEST VECTOR IN PLOT=    0.5439613      T
```

This output can be used to select a value for the "Vmax"-entry in the "Plotting Information 2-D"-table with the "More Plot Options"-option switched 'on'. This feature is used in BEM-FEM calculations when the evaluation of the field on BEM-FEM domain-boundaries yields unphysical singularities. The respective field vector is then calculated as a mean value of the surrounding field points. The output to the .matrf-file is adjusted in the same way.

15.1.2 Field along a line (2-D, 3-D)

The "Field Along a Line (2-D, 3-D)"-option produces a postscript plot, compare Fig. 15.1 with the following input.



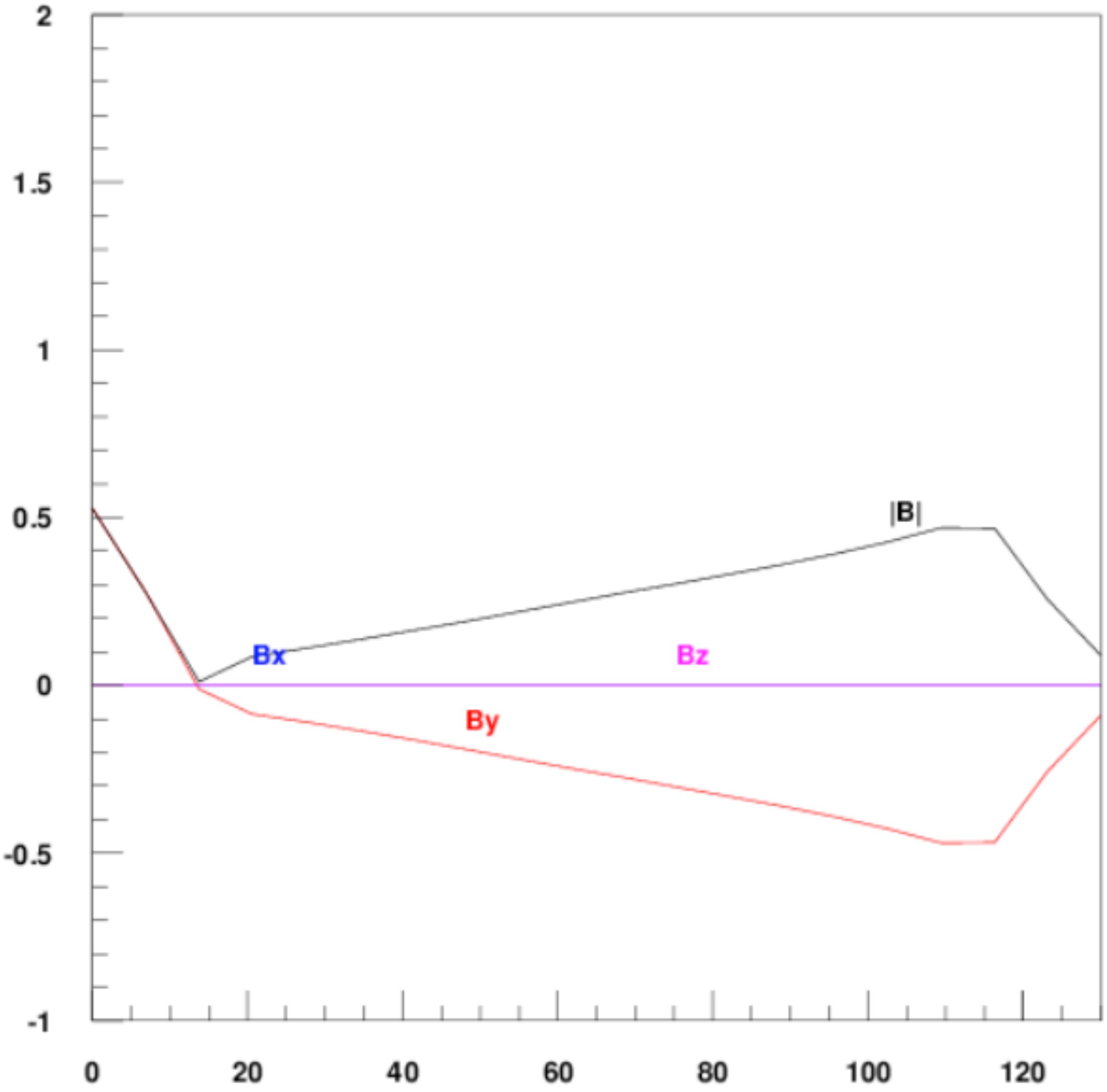


Fig: 15.1: Field along the x-axis of the cross-section in Fig. 11.5. Note the gradient of the quadrupole field in the aperture, shifted by a dipole-component.

The line-field is also printed to the .output-file:

```
      CALL OF 3-D FIELD ALONG A LINE

  FIELD CALCULATION ALONG A LINE (SOURCE)

 I    X-POS   Y-POS   Z-POS   DIST      BX          BY         BZ        |B|
  1  -65.00    0.00    0.00    0.00  0.5767E-15  0.5270E+00  0.00E+00  0.53E+00
  2  -58.16    0.00    0.00    6.84  0.6543E-15  0.2775E+00  0.00E+00  0.28E+00
  3  -51.32    0.00    0.00   13.68  0.5068E-15 -0.1123E-01  0.00E+00  0.11E-01
  4  -44.47    0.00    0.00   20.53 -0.6157E-16 -0.8537E-01  0.00E+00  0.85E-01
  5  -37.63    0.00    0.00   27.37  0.2154E-16 -0.1097E+00  0.00E+00  0.11E+00
  6  -30.79    0.00    0.00   34.21 -0.1347E-15 -0.1351E+00  0.00E+00  0.14E+00
  7  -23.95    0.00    0.00   41.05  0.2429E-16 -0.1621E+00  0.00E+00  0.16E+00
  8  -17.11    0.00    0.00   47.89  0.5974E-16 -0.1900E+00  0.00E+00  0.19E+00
  9  -10.26    0.00    0.00   54.74 -0.8568E-16 -0.2183E+00  0.00E+00  0.22E+00
 10   -3.42    0.00    0.00   61.58 -0.9502E-16 -0.2467E+00  0.00E+00  0.25E+00
 11    3.42    0.00    0.00   68.42  0.1283E-16 -0.2749E+00  0.00E+00  0.27E+00
 12   10.26    0.00    0.00   75.26  0.4646E-16 -0.3029E+00  0.00E+00  0.30E+00
 13   17.11    0.00    0.00   82.11  0.2118E-16 -0.3311E+00  0.00E+00  0.33E+00
 14   23.95    0.00    0.00   88.95 -0.2125E-15 -0.3602E+00  0.00E+00  0.36E+00
 15   30.79    0.00    0.00   95.79  0.1845E-16 -0.3917E+00  0.00E+00  0.39E+00
 16   37.63    0.00    0.00  102.63  0.5219E-16 -0.4276E+00  0.00E+00  0.43E+00
```

```
 17   44.47    0.00    0.00  109.47 -0.1697E-15 -0.4692E+00  0.00E+00  0.47E+00
 18   51.32    0.00    0.00  116.32  0.1063E-15 -0.4675E+00  0.00E+00  0.47E+00
 19   58.16    0.00    0.00  123.16  0.6014E-16 -0.2577E+00  0.00E+00  0.26E+00
 20   65.00    0.00    0.00  130.00 -0.2660E-15 -0.8968E-01  0.00E+00  0.90E-01

      MAXIMUM OF THE FIELD COMPONENTS BX,BY:    6.5427821E-16   0.5269822
```

15.1.3 Coilmesh File

The "Ansys"-option creates a coilmesh.iron-file which contains one area-definition for each conductor in the cross-section.

```
kpcon1_1=[  0.070129,  0.001852];
kpcon1_2=[  0.070149,  0.000132];
kpcon1_3=[  0.085150,  0.000132];
kpcon1_4=[  0.085126,  0.002192];
lncon1_1=Line(kpcon1_1,kpcon1_2);
lncon1_2=Line(kpcon1_2,kpcon1_3);
lncon1_3=Line(kpcon1_3,kpcon1_4);
lncon1_4=Line(kpcon1_4,kpcon1_1);
arcon1=Area(lncon1_1,lncon1_2,lncon1_3,lncon1_4,BHiron7);
Lmesh(lncon1_1,1);
Lmesh(lncon1_4,8);
kpcon2_1=[  0.070061,  0.003811];
kpcon2_2=[  0.070119,  0.002092];
kpcon2_3=[  0.085117,  0.002432];
kpcon2_4=[  0.085046,  0.004491];
  ...
```

15.1.4 Autocad

The "Autocad"-option produces a filename.dxfxy-file which contains an autocad-model of the coil cross-section.

```
 0
SECTION
 2
ENTITIES
 0
POLYLINE
 8
25
66
   1
 10
0.0
 20
0.0
 30
0.0
 70
   1
 0
VERTEX
 8
25
10
  50.12915678993
 20
   1.84861619463
 30
0.0
 0
VERTEX
 8
25
...
```

15.1.5 MS Excel

The "MS Excel"-option creates a filename.excel file that has the geometrical information of the bare cables in the cross-section. A second table gives the coordinates of the corners of each cable block. The tables are comma-delimitted.

```
     CONDUCTOR POSITION IN THE CROSS-SECTION
     NO., COND., BLOCK , CORNER ,    X(mm) ,    Y(mm)
        , NO.  , NO.   , NO.    ,          ,
     1,    1,    1,    1,        50.1292,        1.8486
     2,    1,    1,    2,        50.1486,        0.1287
     3,    1,    1,    3,        65.1496,        0.1287
     4,    1,    1,    4,        65.1263,        2.1886
     5,    1,    1,    1,        50.1292,        1.8486
     6,    2,    1,    1,        50.0488,        3.8072
     7,    2,    1,    2,        50.1073,        2.0882
     8,    2,    1,    3,        65.1044,        2.4282
```

```
      9,    2,    1,    4,         65.0344,         4.4870
     10,    2,    1,    1,         50.0488,         3.8072
     11,    3,    1,    1,         49.8919,         5.7620
     12,    3,    1,    2,         49.9893,         4.0447
     13,    3,    1,    3,         64.9749,         4.7245
     14,    3,    1,    4,         64.8582,         6.7812
     15,    3,    1,    1,         49.8919,         5.7620
     16,    4,    1,    1,         49.6585,         7.7105
     17,    4,    1,    2,         49.7948,         5.9959

      BLOCK POSITION IN THE CROSS-SECTION
      NO., BLOCK , CORNER ,    X(mm) ,    Y(mm)
         , NO.   , NO.    ,           ,
      1,    1,    1,       63.3850,      25.0434
      2,    1,    2,       68.0000,       0.0119
      3,    1,    3,       83.3006,       0.0119
      4,    1,    4,       78.1010,      29.2325
      5,    1,    1,       63.3850,      25.0434
      6,    2,    1,       44.8894,      22.8527
      7,    2,    2,       50.0000,       0.0087
      8,    2,    3,       65.3010,       0.0087
    ...   ...   ...            ...           ...
```

15.1.6 2-D Field Map in Coil

The "2-D Field Map in Coil"-option creates a filename.map2-D-file. The file contains the magnetic induction in the position of every strand in the cross-section.

```
    UNSPECIFIED

&MAGNET
    NPOLE=  0, NBLOKS= 20,SCX=0.001,SCB=1.0,ORIGIN='ROXIE',VERSION=9.0,
    RIRON=  0.0000,BREF=  1.0000,XREF= 0.017000,/
 BL. COND. NO.  X-POS/MM  Y-POS/MM   BX/T      BY/T     AREA/MM**2 CURRENT FILL FAC.
  1   1    1    50.5506    1.4257   -0.0125   -0.4930   0.7206    27.78  0.3698
  1   1    2    50.5604    0.5611   -0.0018   -0.4932   0.7206    27.78  0.3698
  1   1    3    51.3839    1.4399   -0.0139   -0.4640   0.7285    27.78  0.3658
  1   1    4    51.3938    0.5658   -0.0017   -0.4642   0.7285    27.78  0.3658
  1   1    5    52.2171    1.4541   -0.0148   -0.4360   0.7363    27.78  0.3619
  1   1    6    52.2271    0.5705   -0.0020   -0.4362   0.7363    27.78  0.3619
  1   1    7    53.0503    1.4682   -0.0157   -0.4089   0.7442    27.78  0.3581
  1   1    8    53.0604    0.5752   -0.0024   -0.4091   0.7442    27.78  0.3581
  1   1    9    53.8835    1.4824   -0.0166   -0.3825   0.7521    27.78  0.3543
  1   1   10    53.8938    0.5799   -0.0028   -0.3827   0.7521    27.78  0.3543
... ...  ...        ...       ...       ...       ...      ...      ...     ...
```

15.1.7 2-D line currents

The "2-D Line Currents"-option creates a filename.fila2-D-file. The file contains information on the current-carrying areas in every discretized conductor (compare the N1-, N2-parameters in the "Block Data 2-D"-table), as well as on the position of each line current. The file therefore contains two tables:

```
  POSITIONS OF CURRENT AREAS  (2-D)
  NO. OF THE FIL.,   CURRENT
  X1 , X2 , X3 ,  X4
  Y1 , Y2,  Y3,   Y4
        1    50.00000
        70.138903   70.129156   71.628868   71.638806
         0.992162    1.852107    1.886105    1.009161
        2    50.00000
        70.148649   70.138903   71.638806   71.648745
         0.132217    0.992162    1.009161    0.132217
        3    50.00000
        71.638806   71.628868   73.128579   73.138710
         1.009161    1.886105    1.920102    1.026160
              ...         ...         ...         ...

  POSITIONS OF CURRENT FILAMENTS  (2-D)
  NO.,   CURRENT         X           Y
        1    50.00000   70.883933    1.434884
        2    50.00000   70.893776    0.566439
        3    50.00000   72.383741    1.460382
        4    50.00000   72.393776    0.574939
        5    50.00000   73.883548    1.485880
        6    50.00000   73.893776    0.583438
        7    50.00000   75.383355    1.511379
      ...         ...         ...         ...
```

15.1.8 Write multipoles for Post-Processing

The "Write Multipoles for Pp."-option creates a filename.txt-file. The file contains the normal- and skew harmonics at every time-step. Every data line yields the step number, the time, the current in block 1, the main field component, and the relative harmonics.

```
Steps Time Current BN bn(n=1-20) an(n=1-20)
           1     0.00000  1000.00000    -0.26080 10000.00000  2685.33092   /
-23.36314     0.00000    12.63201     2.89206     1.27216     0.00000     /
0.01525    -0.00316    -0.01057     0.00000    -0.00231    -0.00001     /
0.00018     0.00000     0.00001     0.00000     0.00000     0.00000     /
0.00000     0.00000     0.00000     0.00000     0.00000     0.00000     /
0.00000     0.00000     0.00000     0.00000     0.00000     0.00000     /
0.00000     0.00000     0.00000     0.00000     0.00000     0.00000     /
0.00000     0.00000
```

15.2 Interfaces for 3-D calculations

In this section we present output files that can be produced to exchange data on 3-D coil end design with other programs. As a model coil end we use the end of Fig. 11.5, compare Fig. 15.2

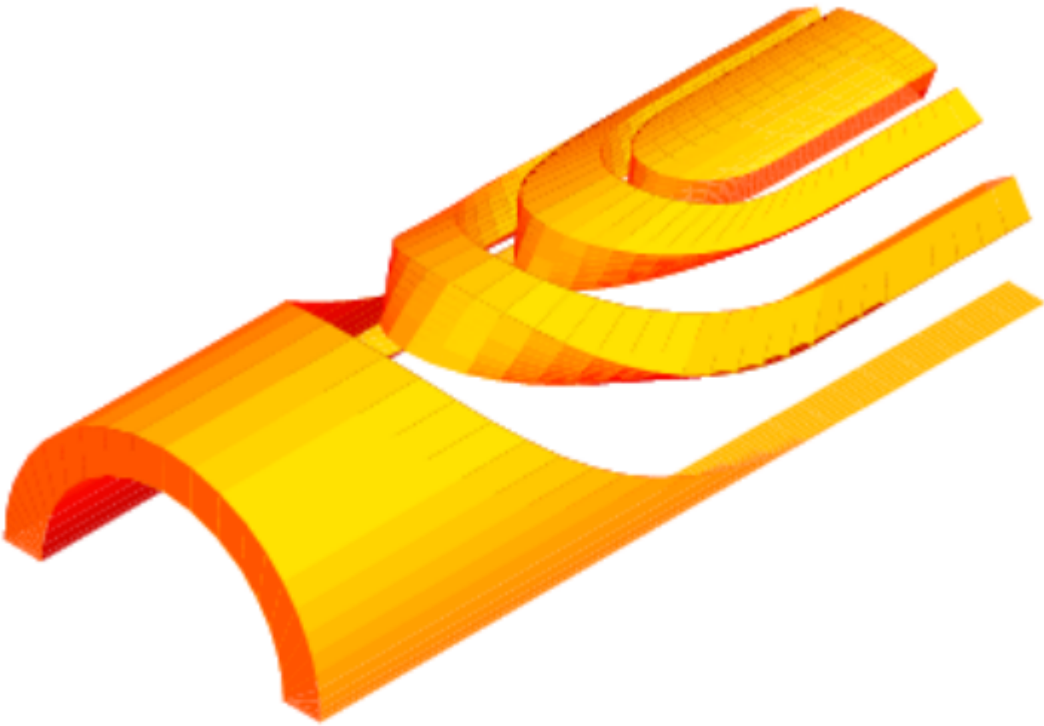


Fig: 15.2: Set of endspacers of the coil en in Fig. 11.5.

15.2.1 Field vector matrix (Map)

The "Field-Vector Matrix (Map)"-option produces a filename.matrf-file which contains the components of the magnetic induction in the respective positions in the matrix.

```
     I , J , KK            1            1            1
     X , Y , Z      -80.000000   -80.000000     0.000000
     BX, BY, BZ      -0.001952     0.026444     0.002581
     I , J , KK            1            1            2
     X , Y , Z      -80.000000   -80.000000     5.128205
     BX, BY, BZ      -0.002208     0.029795     0.002715
     I , J , KK            1            1            3
     X , Y , Z      -80.000000   -80.000000    10.256410
     BX, BY, BZ      -0.002440     0.033063     0.002858
```

```
    I , J , KK            1            1            4
    X , Y , Z      -80.000000   -80.000000    15.384615
    BX, BY, BZ      -0.002637     0.036180     0.003011
       ...              ...          ...          ...
```

15.2.2 Field along a line (2-D, 3-D)

The "Field Along a Line (2-D, 3-D)"-option works in the same way in 3-D- as in 2-D-calculations.

15.2.3 CNC machining fiels

The "CNC Machine Files"-option, together with the "Wedge/Endspacer"-option in the "Main Options" produces a filename.cnc file that can serve as an input for a CNC-machining process of endspacers.

```
    $$ WEDGE    1 INNER, POLYGON    1 P. FOLLOW   23

    $$     X (mm)    Y (mm)    Z (mm)
     p     52.423    38.935     0.000
     p     52.423    38.935     9.313
     p     52.423    38.935    18.628
     p     52.423    38.935    27.946
     p     52.423    38.935    37.268
     p     52.423    38.935    46.592
     p     52.423    38.935    55.912
     p     52.423    38.935    65.219
     p     52.358    39.022    74.527
     p     52.041    39.444    83.813
     p     51.444    40.219    93.075
     p     50.546    41.342   102.274
     p     49.309    42.810   111.384
     p     47.682    44.615   120.383
     p     45.601    46.740   129.208
     p     42.981    49.160   137.807
     p     39.712    51.837   146.108
     p     35.668    54.698   153.982
     p     30.687    57.640   161.276
     p     24.612    60.484   167.723
     p     17.318    62.962   172.945
     p      8.864    64.696   176.413
     p      0.000    65.300   177.589

    $$ WEDGE    1 INNER, POLYGON    2 P. FOLLOW   23

    $$     X (mm)    Y (mm)    Z (mm)
     p     50.862    37.830     0.000
     p     50.862    37.830     9.327
   ...        ...       ...       ...
```

With the "Strips from Darboux Vec."-option the "CNC Machine Files"-option also produces a filename.darbcnc-file from the differential-geometry based coil-end design. The output format differs slightly.

```
$$ WEDGE    1 INNER, POLYGON ON OUTER RADIUS    P. FOLLOW 23

$$   X(mm)   Y(mm)   Z(mm)
p    51.310  40.406   0.000
p    51.391  40.360  102.320
p    51.463  40.326  98.876
p    51.330  40.536  100.616
p    50.859  41.140  106.361
p    50.069  42.085  114.134
p    49.336  42.941  119.923
p    48.722  43.655  123.849
p    48.218  44.255  126.479
p    47.746  44.824  128.473
p    46.890  45.766  131.551
p    45.480  47.192  135.873
p    43.532  49.003  140.894
p    41.065  51.083  146.216
p    38.155  53.276  151.455
p    34.918  55.435  156.288
p    31.320  57.526  160.704
p    27.314  59.513  164.683
p    22.850  61.349  168.177
p    17.851  62.974  171.131
p    12.317  64.281  173.416
p     6.333  65.142  174.880
p     0.000  65.450  175.395

$$ WEDGE    1 INNER, POLYGON ON INNER RADIUS    P. FOLLOW 23

$$   X(mm)   Y(mm)   Z(mm)
p    38.794  31.544   0.000
p    38.725  31.628  114.786
...     ...     ...      ...
```

15.2.4 Opera interface

The "Opera 8/20-Node Bricks"-option yields filename.opera8- and filename.opera20-files. They contain input for Vector Field's OPERA program that describes the coil ends in 3-D.

```
CONDUCTOR GEOMETRY PRINT OUT FOR VF-OPERA 3-D
********************************************

COND
DEFI BR8
0.0 0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
      50.129157      1.848616      0.000000
      50.148649      0.128727      0.000000
      65.149612      0.128727      0.000000
      65.126267      2.188594      0.000000
      50.129157      1.848616     29.333333
      50.148649      0.128727     29.333333
      65.149612      0.128727     29.333333
      65.126267      2.188594     29.333333
     104.238036 , 1 , 0.0
 0 1 1
10.
QUIT
COND
DEFI BR8
0.0 0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
      50.129157      1.848616     29.333333
      50.148649      0.128727     29.333333
            ...           ...           ...
```

15.2.5 Autocad

In 3-D calculations, "Autocad"-option produces not only a filname.dxfxy-file that describes the coil cross-section in an Autocad-readable format, but also a filename.dxfyz-file that yields the geometrical data of a cut through the yz-plane of a coilend.

```
 0
SECTION
 2
ENTITIES
 0
POLYLINE
 8
25
66
   1
 10
0.0
 20
0.0
 30
0.0
 70
   1
 0
VERTEX
 8
25
10
 228.98697156054
...
```

15.2.6 Virtual reality (3-D)

The "Virtual Reality (3-D)"-option produces a filename.wrl-file, which can be read in by any VRML-browser (sometimes called WRL-browser or VMRL-browser). A filename.wrl-file looks like this:

```
#VRML V2.0 utf8

Viewpoint {
  position 2 2 -20
  orientation 0 1 0 3.14
}

Group { children [ Transform {
    scale   0.0871   0.0871   0.0871
    children [ Shape {
      appearance Appearance {
        material Material {
```

```
          ambientIntensity  0.1
          diffuseColor      0.6 0 0
          specularColor     1 0.7 0
          shininess   0.02
     } }
     geometry IndexedFaceSet {
         coord Coordinate {
             point [
  68.1373    1.4818    0.0000,
  68.1489    0.1419    0.0000,
  83.1494    0.1419    0.0000,
  83.1356    1.7418    0.0000,
  68.1373    1.4818   36.6667,
      ...        ...        ...
```

The 3-D-model can be viewed in an interactive browser, compare Fig. 15.3.

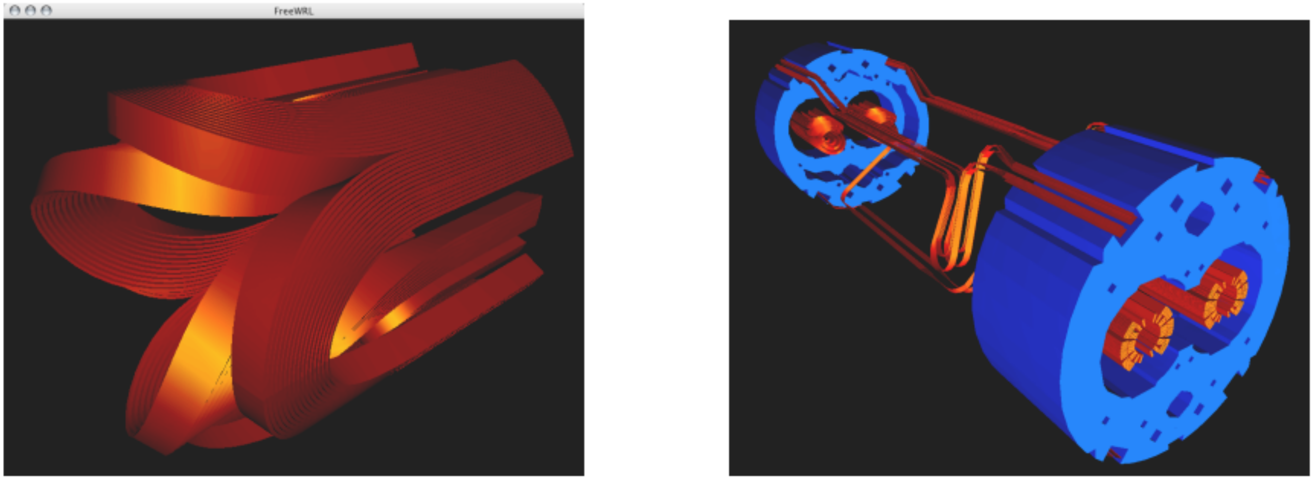


Fig 15.3: Left:The coil end of Fig. 11.3, viewed with a free WRL-browser. Right: Model of the interconnection region of two Main Dipoles in the LHC.

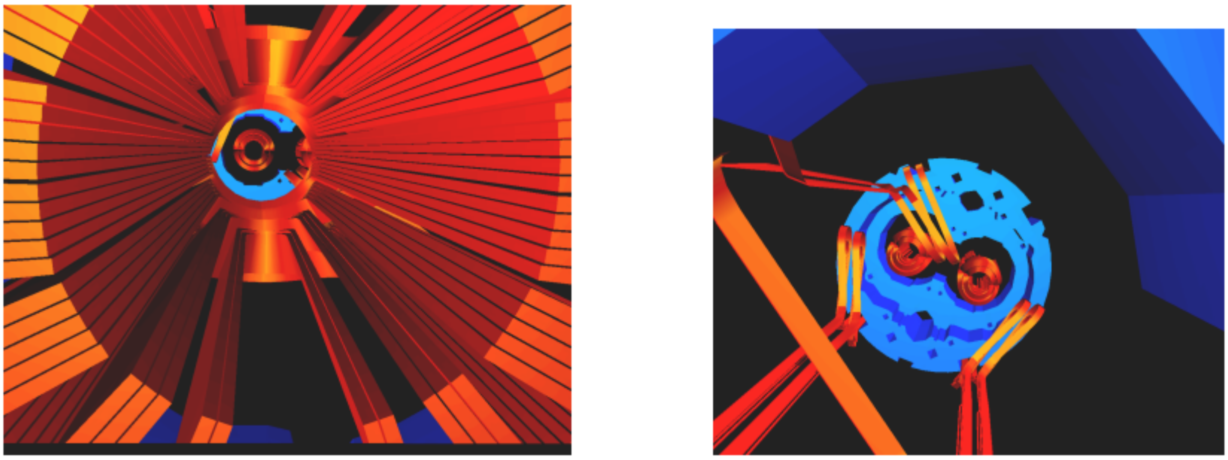


Fig 15.4: Views of a model of the interconnection region of two Main Dipoles in the LHC.

15.2.7 3-D field map in coil

The "3-D Field Map in Coil"-option produces a filename.map3-D-file. The "3-D Peak Field Calc."-option in the "Global Information 3-D" must be switched 'on'. The file contains five tables which describe the position of the line currents (filaments), the field in

x-, y-, and z-component, the the field in parallel-, perpendicular-, and longitudinal-component, the pressure on the conductors and the forces acting on the conductors.

```
      NFIL  NCUT  NCON      X         Y          Z
         1   1   1     68.5568      1.1522      0.0000
         1   2   1     68.5568      1.1522     36.6667
         1   3   1     68.5568      1.1522     73.3333
         1   4   1     68.5568      1.1522    110.0000
         1   5   1     68.5564      1.1565    116.3867
         1   6   1     68.5559      1.1699    122.7730
         1   7   1     68.5549      1.1924    129.1583
         1   8   1     68.5534      1.2242    135.5421
         1   9   1     68.5508      1.2653    141.9240
         1  10   1     68.5473      1.3374    148.3032
       ... ... ...         ...         ...         ...

      NFIL  NCUT  NCON      Bx        By        Bz        |B|
         1   1   1     -0.0136     -0.0929     -0.0001      0.0939
         1   2   1     -0.0164     -0.0986     -0.0002      0.0999
         1   3   1     -0.0173     -0.1122     -0.0003      0.1135
         1   4   1     -0.0152     -0.1300     -0.0010      0.1309
         1   5   1     -0.0127     -0.1353     -0.0005      0.1359
         1   6   1     -0.0091     -0.1376      0.0002      0.1379
         1   7   1     -0.0045     -0.1357      0.0012      0.1358
         1   8   1      0.0008     -0.1287      0.0024      0.1288
         1   9   1      0.0062     -0.1156      0.0040      0.1158
         1  10   1      0.0162     -0.0952      0.0080      0.0969
       ... ... ...         ...         ...         ...         ...

      NFIL  NCUT  NCON      B long.   B -|     B ||
         1   1   1     -0.0001      0.0939     -0.0144
         1   2   1     -0.0002      0.0999     -0.0173
         1   3   1     -0.0003      0.1135     -0.0182
         1   4   1     -0.0011      0.1309     -0.0163
         1   5   1     -0.0008      0.1359     -0.0153
         1   6   1     -0.0002      0.1379     -0.0162
         1   7   1      0.0005      0.1358     -0.0189
         1   8   1      0.0015      0.1287     -0.0226
         1   9   1      0.0026      0.1158     -0.0260
         1  10   1     -0.0005      0.0969     -0.0217
       ... ... ...         ...         ...         ...

      NCON  NCUT     P ||       P  -|       Px         Py         Pz
         1   1     -0.1018      0.0005     -0.1017     -0.0065      0.0000
         1   2     -0.1139      0.0006     -0.1138     -0.0080      0.0000
         1   3     -0.1057      0.0007     -0.1057     -0.0084      0.0000
         1   4     -0.0946      0.0006     -0.0945     -0.0075      0.0000
         1   5     -0.0905      0.0003     -0.0904     -0.0042      0.0000
         1   6     -0.0859     -0.0002     -0.0861      0.0013      0.0000
         1   7     -0.0808     -0.0008     -0.0821      0.0078     -0.0001
         1   8     -0.0747     -0.0014     -0.0786      0.0139     -0.0002
         1   9     -0.0672     -0.0018     -0.0753      0.0184     -0.0004
         1  10     -0.0566     -0.0023     -0.0708      0.0222     -0.0006
       ... ...         ...         ...         ...         ...         ...

      NCON  NCUT      Fr         Fphi       Fz
         1   1     -5.0024     -0.2598      0.0000
         1   2     -5.5976     -0.3265      0.0000
         1   3     -5.1962     -0.3507      0.0000
         1   4     -0.8139     -0.0543      0.0000
         1   5     -0.7810     -0.0255      0.0000
         1   6     -0.7528      0.0253     -0.0036
         1   7     -0.7308      0.0879     -0.0115
         1   8     -0.7153      0.1516     -0.0232
         1   9     -0.7044      0.2062     -0.0376
         1  10     -0.6915      0.2638     -0.0643
       ... ...         ...         ...         ...
```

15.2.8 3-D line currents

The "3-D Line Currents"-option creates a filename.fila3-D-file, which describes the positioning of line currents in 3-D coil models.

```
      NUMBER OF LINE CURRENTS *****
   12
   XS , YS , ZS
   XE , YE , ZE
   CURRENT
      12
          68.55680     1.15225     0.00000
          68.55680     1.15225    36.66667
          27.77778
      12
          68.55680     1.15225    36.66667
          68.55680     1.15225    73.33333
          27.77778
      12
          68.55680     1.15225    73.33333
          68.55680     1.15225   110.00000
```

```
        27.77778
    12
        68.55680     1.15225   110.00000
        68.55644     1.15654   116.38671
        27.77778
    12
        68.55644     1.15654   116.38671
        68.55587     1.16992   122.77296
        27.77778
```

16. ROXIE/BEM-FEM Transfer Files

16.1 The HMO-file

The .hmo-file contains mesh information. It is produced by either the HERMES 2-D parametric mesh generator or by the HyperMesh, 3-D mesh generator, using the `edyson` template file, edyson_tech_doc.

The .hmo-file consists of six blocks: The first block contains component information (material names, coils), the second block contains load collector data, the third block vector collector information, the fourth block specifies all nodes, the fifth one the elements, and the last one additional boundary conditions. With ROXIE we only make use of blocks one, four and five which we will describe in detail in the following tables. The .hmo-file is organized as follows:

```
`BEG_COMP_DATA`
`...`
`END_COMP_DATA`
`BEG_NODL_DATA`
`...`
`END_NODL_DATA`
`BEG_ELEM_DATA`
`...`
`END_ELEM_DATA`
```

16.1.1 The component data

The body of the component collector data block is structured as follows. One header record

Variable	Type	Description
`NCOLL`	I8	Total number of components

A sequence of records with the component numbers and names

Variable	Type	Description
`ICOLL`	I8	Number of the component
n/a	String	Component name

For numerical calculations the last component must have the name `SuperCoils`. It represents the coils modelled by line-currents.

16.1.2 The nodal data

The body of the component data block is structured as follows. One header record

Variable	Type	Description
`NNT`	I8	Total number of nodes

A sequence of records with the component numbers and names

Variable	Type	Description
`IN_HMO`	I8	Number of the node
XYZ(3)	1X,F12.8	Coordinates

For BEMFEM-calculations the node numbers have to be in ascending order. For EDYSON they are only required to be unique. The coordinates are given in mm. Axisymmetric problems are discretized in the xy-plane.

16.1.3 Element data

The body of the element data block is structured as follows. One header record

Type	Description
I8	Total number of all elements in file
1X,I8	Total number of L2 elements
1X,I8	Total number of L3 elements
1X,I8	Total number of T3 elements
1X,I8	Total number of T6 elements
1X,I8	Total number of Q4 elements
1X,I8	Total number of Q8 elements
1X,I8	Total number of TH4 elements
1X,I8	Total number of TH10 elements
1X,I8	Total number of P6 elements
1X,I8	Total number of P15 elements
1X,I8	Total number of H8 elements
1X,I8	Total number of H20 elements

A sequence of records which describe theelements

Variable	Type	Description
`IEL_HMO`	I8	Number of the element
`ICOLL`	1X,I4	Element component number
`ICONF`	1X,I3	Element config number
`KNE(1)`	1X,I8	Number of the first node
`KNE(2)`	1X,I8	Number of the second node
...	...	...

For BEMFEM-calculations the element numbers have to be in ascending order. For EDYSON they are only required to be unique. The element component number describes which material the element belongs to. The material names are given in the component data block. The element type number `ICONF` describes the element geometry as follows:

`ICONF`	Type	Description
60	L2	Line element with two nodes
63	L3	Line element with three nodes
103	T3	Triangular element with three nodes
106	T6	Triangular element with six nodes
104	Q4	Quadrilateral element with four nodes
108	Q8	Quadrilateral element with eight nodes
204	TH4	Tetrahedral element with four nodes
210	TH10	Tetrahedral element with ten nodes
206	P6	Pentahedral element with six nodes
215	P15	Pentahedral element with fifteen nodes
208	H8	Hexahedral element with eight nodes
220	H20	Hexahedral element with twenty nodes

With ROXIE we only use element types T6, Q8, P15 and H20. The element-wise node numbering of the respective types is depicted in Fig. 16.1.

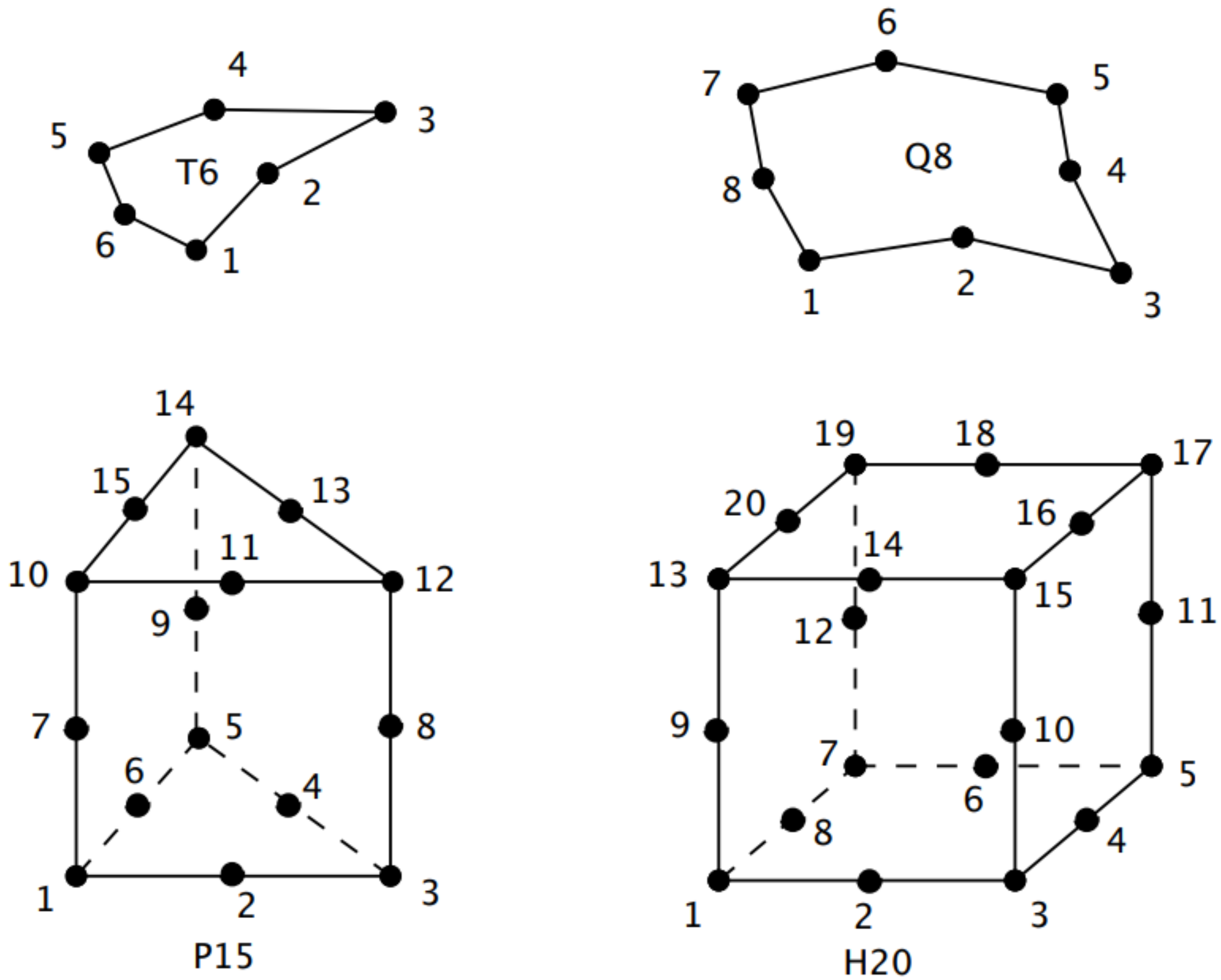


Fig. 16.1: sFinite-element types used with ROXIE. Element-wise node numbering in the .hmo-file.

16.2 The COR file

The .cor-file specifies the nodal coordinates for BEMFEM. It is basically a reference for the renumbering of the .hmo-file nodes. The first line is a header info line (version number, etc.). Then follows the header data line:

Variable	Type	Description
`NNT`	I8	Total number of nodes
`NDLN`	I7	Number of degrees of freedom per node
`NDIM`	I6	Dimension of the problem

Then comes a sequence of records of the form:

Variable	Type	Description
`IN`	Integer	Node number
`XYZ(3)`	Double	Nodal coordinates
`BSECT`	Integer	Boundary section (0:Interior FEM node, ><!-- -->0: BEM node on given boundary section)
`IDOF`	Integer	Number of degrees of freedom for current node

The last line is the closing line:

Variable	Type	Description
`FILEEND`	Integer	`FILEEND=-1` denotes the end of the file

The following table summarizes the different coordinate systems for the respective problem types:

Geometry	(x_1,x_2,x_3)
Plain 2-D	(x,y,0)
Axisymmetric	(r,0,z) (z,r,0)
3-D	(x,y,z)

16.3 The ELE file

The .ele-file contains elemental data. It has one header line (version number, etc.) and one data header line:

Variable	Type	Description
`IELEMS`	Integer	Total number of elements including boundary elements
`IMAXNOD`	Integer	Maximum number of nodes per element

It follows a sequence of element records:

Variable	Type	Description
`IEL`	Integer	Element number
`ITPE`	Integer	Element type number
`ICOLL`	Integer	Collector- (component-) number to which the element belongs
`INODS(21)`	Integer	A sequence of node numbers from .cor-file for the current element terminated by 0

A file closing line

Variable	Type	Description
`FILEEND`	Integer	`FILEEND = -1` denotes the end of the file

16.4 The BDR file

The boundary condition data is given in the .bdr-file. One file header info line (with version number, etc.) is followed by a sequence of records of the form

Variable	Type	Description
`INOD`	Integer	Node number (.cor-file) at which a boundary condition (BC) is specified
`IDOFTYP(10))`	0X,I1	Sequence of 10 flags each of which specifies a type of BC for each degree of freedom in the node; flag 0 means: no BC specified 1: homogeneous Dirichlet-condition 2: inhomogeneous Dirichlt-condition 4: pseudo-BEM-nodes for subsequent field calculation 5: inhomogeneity BEM-node 8: positive periodic condition 9: negative periodic condition
`VCOND(10)`	1X,12.5	Sequence of BC vallues for each degree of freedom

A file closing line

Variable	Type	Description
`FILEEND`	Integer	`FILEEND = -1` denotes the end of the file

ROXIE uses only the BC flag 1 for homogeneous Dirichlet-conditions.

16.5 The SOL file

The .sol-file contains the computed results of BEMFEM. It has one file header info line and a sequence of time steps. For ROXIE there is only one time step available. Each time step is composed of a header line:

Variable	Type	Description
`ITYP`	Integer	`ITYP = -1` marks the header line of a time step
`IPAS`	Integer	Number of the present time step
`TIME`	Double	Absolute time of the present time step

Then comes a sequence of subblocks containing problem dependent results; each subblock consists of a block header:

Variable	Type	Description
`ITYP`	Integer	`ITYP = -11` marks the block header line of the potential data block
`NCOL`	Integer	Maximum number of data columns (coordinates and/or reults)
`NROW`	Integer	Number of rows for the present block (0=not available)

The header is followed by a sequence of records:

Variable	Type	Description
`IN`	Integer	Node number
`XYZ(3)`	Double	Nodal Coordinates
`V(NCOL-3)`	Double	Results (vector and/or scalar potential)

The block is closed by a line

Variable	Type	Description
`BLOCKEND`	Integer	`BLOCKEND = -99` marks the block closing line.

And the time step is closed by

Variable	Type	Description
`TIMESTEPEND`	Integer	`TIMESTEPEND = -9` marks the end of the current time step.

16.6 The SRC file

BEM-FEM coupled problems can be driven by a source potential (φ_mathrm{S}, mathbf{A}_mathrm{S}) due to impressed charges or currents in the BEM domain. This potential should be given at the locations of the boundary nodes in the following structure. The first line yields

Variable	Type	Description
`BNODES`	I5	Number of nodes belonging to the boundary

Then follows a sequence of records with node numbers, nodal coordinates and prescribed potential values.

Variable	Type	Description
IN	I5	.cor-file node number
XYZ(3)	1X,E18.11	Coordinates
POT(3)	1X,E18.11	prescribed source potential, see below

The node numbers must be in ascending orders and the number of records must be equal `BNODES`. The degrees of freedom of the impressed source potential depend on the problem type as follows:

Problem Type	DOF1	DOF2	DOF3
2-D	A_z		
2-D Axi-symm.	rA_φ		
3-D vector Pot.	A_x	A_y	A_z
3-D scalar Pot.	φ		

16.7 The EVAL.LOC file

The BEM-FEM coupling allows the evaluation of the reduced potentials and fields at arbitrary points in the BEM domain once the problem has been solved. Such additional evaluation points are given in the eval.loc-file with the following structure. The header record yields

Variable	Type	Description
`NKSI`	I5	Number of additional evaluation points
`HFD`	1X,E12.5	Parameter h for finite differences

The header is followed by a sequence of records with the coordinates of the evaluation points:

Variable	Type	Description
`I`	I5	Number of evaluation point
`V(3)`	1X,E18.11	Coordinates

16.8 The EVALBFOUT.LOC file

On exit of a BEMFEM run an output file is written that yields the potential in the additional evaluation points specified in the eval.loc-file. The header record reads:

Variable	Type	Description
`NKSI`	I5	Number of additional evaluation points

Then follows a sequence of records with the results:

Variable	Type	Description
`I`	I6	Number of the evaluation point
`V(9)`	1X,E18.11	Coordinates and result DOF, see below

The degrees of freedom that appear depend on the problem type:

Problem type	DOF1	2	3	4	5	6
Magnetic mathbf{A} 2-D Axi 3-D	x	y	A_z	B_x	B_y	&
	Axi	z	r	rA_φ	B_z	B
	3-D	x	y	z	A_x	A
Magnetic φ 3-D	x	y	z	φ	B_x	B

The mathbf{B} field is computed from the potentials by means of finite differences with the parameter `HFD`.

16.9 The PLOTBF.OUT file

Some results from a computation for postprocessing are written to a textfile. In 2-D, this is the plotbf.out-file. It starts with a header record

Variable	Type	Description
`NELT`	Integer	Number of finite elements

Then come the finite-element headers, each one followed by a sequence of nodal records. The element header has

Variable	Type	Description
`IEL`	I5	Number of the element as specified in the .ele-file
`INEL`	I5	Number of nodes in the element
`IGPE`	I5	Properties group number as specified in the .ele-file
`MUR`	1X,E12.5	Average relative permeability of the element

The nodal records of each element read

Variable	Type	Description
`KNOD`	I5	Internal number of the considered node (not related to .cor-file)
`XY(2)`	1X,E12.5	x-, y-coordinate
`BXY(2)`	1X,E12.5	B_x-, B_y-component
`AZ`	1X,E12.5	A_z-component

The results are total fields (sum of reduced- and source fields). For Q8 quadrilateral elements a 9th line is added with empty `KNOD` entry. This record contains the field and potential values in the center of the element.

16.10 The PLOTBF3-D.OUT file

The postprocessing file for 3-D calculations is somewhat differently structured than the plotbf.out-file. There is one header record

Variable	Type	Description
`RELT`	Integer	Number of boundary elements

A sequence of records for each boundary element, each one followed by a sequence of nodal records.

Variable	Type	Description
`IEL`	I5	Consecutive number of the boundary element
`INEL`	I5	Number of nodes in the element

The nodal records read

Variable	Type	Description
`KNOD`	I5	Internal number of the considered node (not related to .cor-file)
`XYZ(3)`	1X,E12.5	x-, y-, z-coordinate
`A(3)`	1X,E12.5	A_x-, A_y-, A_z-component
`B(3)`	1X,E12.5	B_x-, B_y-, B_z-component

16.11 Additional files

The following files are not further detailed in this manual:

File	Description
`.DAPA`	Magnetization curves for BEMFEM
`.dyn`	Contains integral and mechanical result quantities for each time step
`.ght`	Binary file which contains the BEM matrices of a previous run
`.inp`	BEMFEM input file
`.out`	Collects messages from a BEMFEM run

17. Bibliography

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