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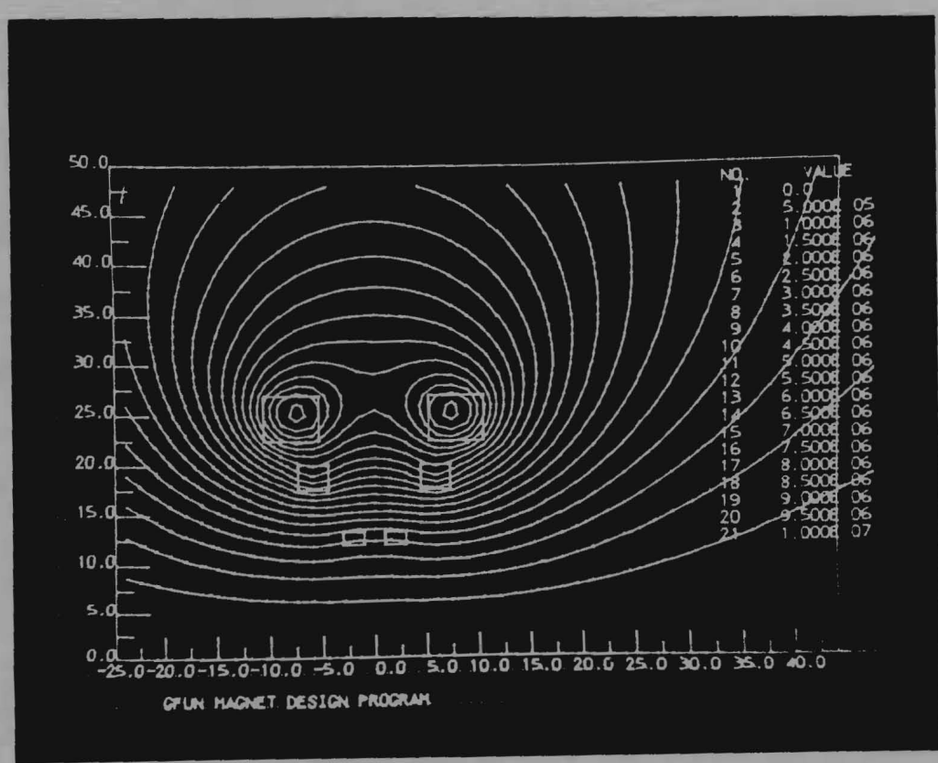
GFUN USERS' GUIDE–A User Guide to an Interactive Graphics Program for the Computer Aided Design of Magnets

M J Newman J Simkin
C W Trowbridge L R Turner

Science Research Council

Computer Applications Group
Rutherford High Energy Laboratory
Chilton Didcot Berkshire
1973



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GFUN USERS' GUIDE - A User Guide to an Interactive Graphics Program for the Computer Aided Design of Magnets.

M J Newman J Simkin C W Trowbridge L R Turner

Computing Applications Group
Applied Physics Division
Rutherford High Energy Laboratory
Chilton Didcot Berkshire
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1. INTRODUCTION

1.1 SCOPE OF THE PROGRAM

The GFUN[1] computer program is primarily an interactive graphics magnet design package. The core of the program is an algorithm for solving the magnetic field problem in the presence of current carrying regions and saturated iron regions. This manual covers the operation of the two dimensional program only, although the data structure and graphics facilities are similar in both the two and three dimensional versions of the program.

The general criteria that were used in deciding how to develop the program were as follows:

i. The program should be easy for the magnet designer to use. Most of the work of data input should be done by the computer. The input data should be displayed for checking. The results should be displayed in a way to make interpretation simpler.

ii. The program should be interactive. Calculating interactively saves the magnet designer time. His train of thought is not broken as it is when he must submit a job and wait minutes or days for the results. His ideas or doubts can be checked immediately. For example he can see from the picture if he has set up the problem incorrectly or awkwardly, or he can follow up anything interesting the graph of the field reveals. He can stop when a line of thought proves unprofitable, and he need not provide in advance for all possibilities.

For these reasons GFUN has been designed as an interactive package. However on-line facilities are not always available, and much of GFUN can be used in an off-line mode.

1,2 HARDWARE AND SOFTWARE

GFUN is used with the IBM 370/195 at the Rutherford Laboratory. The program is submitted to the central computer by the ELECTRIC[2] program and for normal production running will reside in a fenced region of core set at 160 K bytes. The on-line program can only be submitted at scheduled or pre-arranged times.

The graphics terminal consists of a Computek 400/15 storage display which is used for the input and output of text and the output of pictures. The terminal is connected to the central computer via a satellite computer (Honeywell DDP 224). The locally written software system DAEDALUS[3,4] allows programs in the central computer to send and receive information from the graphics terminal. DAEDALUS contains the following components:

a. MAST. This is the main on-line control program in the central computer and controls the flow of information both within the 370 and between the satellites and on-line programs.

b. L$ON. Special routines (added into the on-line package) which interface between the on-line programs(GFUN) and MAST

c. SATELLITE CONTROL PROGRAM resident in the 224 to control the flow of information to and from the central computer and to and from the terminal. (This is known as 'DAEDALUS' by the operating staff.)

The program called GFUN consists of the following software packages:

a. LDMPX.[5] INTERACTIVE GRAPHICS PACKAGE.
These routines handle the input and output of messages in and from GFUN program: provides routines for plotting points, changing vectors and writing text on the display; and controls the calls to L$ON.

b. LDACCESS.[5] DIRECT ACCESS PACKAGE.
These routines control a direct access filing system which allows data constructed by the GFUN program to be stored and retrieved.

c. MNDECODE.[6] MESSAGE DECODING PACKAGE.
These routines allow messages handled by DAEDALUS and LDMPX to be decoded into the form required by GFUN program and also checks validity of parameters and outputs error messages.

d. GFUN.[1] MAGNET DESIGN PROGRAM.
The application program contains the routines for defining and controlling the magnet data, and algorithms for computing the magnetisation, the magnetic field, contours of field and optimisation, etc.

1.3 HOW TO START AND STOP THE PROGRAM

The on-line program is intended for use by the magnet designers within Applied Physics Division at Rutherford Laboratory and must only be used during the scheduled time. There are no restrictions on the use of the off-line facilities, see Section 7.

The user must first log in to ELECTRIC[2] and then execute the file contained on the JOB FILE called GFUN32.

When the job comes on-line a message will appear in the top left hand corner of the display 'GFUN ON LINE'. Since the display will be allocated to ELECTRIC it must be re-allocated to GFUN by typing PEQU command to B the 224 command processor.

The user must allocate the display to ELECTRIC before 'logging out' and leaving.

For further information the ELECTRIC[2] AND DAEDALUS[4] Manuals should be consulted.

Examples

a. Getting started and normal end

```
==>LOGI ID=GF,ACCT=3400
++>USER  9 GF BL = 1287/ 1550 TL=499 NL=16 TG=37 NG=6  TL=6 84 NJ=10
==>EXEC JB=GFUN32
++>GFUN    SUBMITTED,JOB NUMBER=834
++>GFUN    QUEUED CLASS M POSN 001 PRI 008
++>GFUN    STARTED
==>++B PEQU GFUN
-B  OK
```

(After the message 'GFUN ON LINE' appears on the display the user may begin to send commands to the program.)

```
==>LIST  (Typical message)
++>OK
.
.
.
.
==>END    (To end program)
```

```
-ELEC   /GFUN   /STEPEND   0.1 SECS, 154K,0000
-ELEC   /GFUN   /ENDED
==>++B PEQU ELEC
-B      OK
==>LOGO
++>     OK  GF BL=1287/ 1500 TL=511 NL=17 TG=38 NG=6 TJ=6.84 NJ=12
```

b. Emergency stops.
Either the cancel command to ELECTRIC or KILL message to MAST will terminate the program.

```
==>CANCEL JOB=GFUN
++>GFUN    CANCELLED

==>++M WILL YOU PLEASE END GFUN
++>/GFUN   /  STEPEND  0.0 SECS, 148K,S222
++>/GFUN   /  ENDED
```

c. Commands to MAST to be used for checking if GFUN is
i) running, ii) on-line

```
i) ==>++M JOBS
   -MAST  JOBS  / MAST,HASP,FQGW,ELECTRIC,GFUN, IISHIFT,DEHASP30,GMAAA

ii)==>++M NAME
   -MAST  NAME  0/HASP  0/ELEC  1/FQGW  0/GFUN  0/MAST
```

1.4 UNITS

For historical reasons,and because local users prefer it,a mixed system of units has been adopted for this program.

All dimensions must be specified in centimetres, currents in Amps and results are quoted in gauss or kilogauss. BH tables must be specified in gauss/oersted. Angles with respect to x axis and specified in degrees.

At a later stage it is intended to provide the user with a choice of units which will include SI.

2. COMMANDS AND PARAMETERS

In this section each command is discussed in turn and some simple examples of their use are given. Detailed definitions and parameters are given in the associated tables.

2.1 FILE MANAGEMENT

A magnet design can be stored on a permanently mounted disc under a file name and generation number. A set of such magnet files are contained in a named data set which can be accessed by the user by the following commands.

i. LIST DSN = GFUN4

This causes the data set named GFUN4 to be accessed and the program will list the GFUN4 directory. All subsequent magnet file management commands will refer to the GFUN4 directory.

ii. ROOM

To be used for determining the space left on the accessed directory.

The number of unused files and unused data blocks is printed on the display. Each block consists of 500 characters.

iii. WRITE FL = GFTOPIC

To be used for writing a magnet file.

This causes the current magnet geometry including BH data and magnetisation results to be stored on the disc under the name GFTOPIC, NGEN, where NGEN is an automatically generated number indicating that the name GFTOPIC has been used before (NGEN - 1) times.

iv. READ FL = GFTOPIC,5

To be used for reading into the current storage magnet file named GFTOPIC with generation number 5.

The contents of this file are printed in the following order:

Magnet File Name and Symmetry

Conductor Geometry

Iron Geometry

BH Data

Magnetisation Results

When this display is full the next page is accessed by typing sub command CONT (or C). Subsequent pages can be skipped by typing SKIP (or S). After printing, the magnet picture is drawn on the display.

v. PRINT

To be used for printing the contents of the current magnet file on the display as in the READ command.

vi. DELETE FL = GFTOPIC,5

Causes the magnet file named GFTOPIC with generation number 5 to be deleted from the disc data set previously defined by the LIST command. The space released is printed on the screen.

2.2 INITIALISATION AND TERMINATION

i. RESTART

Causes the program to restart with initialisation to default values for all parameters. (See Appendix i)

ii. FRAME XMAX = 10, YMAX = 10

$$

Can be used when setting up a new problem. The scales of the frame are entered as parameters. The whole rectangular space is used but to a scale in which (YMAX - YMIN) and (XMAX - XMIN) are mapped on to a square region of size 800 RU.

iii. END

Causes the program to terminate.

Command	Function	Parameters/Sub Commands
READ	Reads magnet data file Prints magnet data on the screen Prints B-H data Prints magnetisation results if previously computed Draws magnet picture	FL = NAME, N NAME is file name N is generation number Type C to continue to next frame Type S to skip to geometry picture display
WRITE	Creates named magnet data file	FL = NAME, N The default value for N is the next generation number
DELETE	Deletes named file	FL = NAME, N No defaults
LIST	Lists directory of stored magnets	DS = NAME, Name is directory name. The default value is GFUN4
ROOM	Prints space left on directory	
PRINT	Prints current contents of magnet stored data values	Type C for continue Type S for skip
FRAME	Sets scales To be used when initializing a new problem	XMIN, XMAX YMIN, YMAX Default sets XMIN = 0 YMIN = 0 YMAX = XMAX $$ Terminator required
RESTART	Restarts program	
END	Terminates program	

2.3 ENTERING BH DATA

The Table of Flux Density values versus Magnetisation Field values can be entered in free format in gauss/oersteds. (See Section 1.3)

```
eg.        BH
           0.0        0.0
        1000          1.0
       20000       1000.0
          $$
```

The entered values are printed and displayed graphically on the screen. The last entry can be cancelled by sub command C.

An alternative method is to read from the data set a named file which only contains a standard BH table.

```
eg.        READ  FL = BHDATA
```

This is a magnet file containing only a BH table.

A third method is to read an existing magnet file and then delete the magnet geometry.

```
eg.        READ  FL = EPPEM, 17
           SKIP
           ERASE MATE = 1, E1 = 1, E2 = NC
           ERASE MATE = 2, E1 = 1, E2 = NF
```

When NC is the number of current elements in EPPEM, 17 and NF is the number of iron elements in EPPEM, 17.

Command	Function	Parameters/Sub Commands
BH	Enables data value of B-H to be entered in free format. Type B value followed by space followed by H value. B and H are in gauss, oersteds.	C Cancels last entry $$ Terminates data

2.4 ELEMENT SPECIFICATION

i. The DRAW command is used for entering element data. The type of element as to material, shape and symmetry has to be specified. In a particular magnet system two types of material are allowed, conductor and iron, but only one type of symmetry. However, the system can contain elements of many different shapes. The choice of symmetry includes plane 2D, axisymmetric and multipole. The detailed lists of codes and parameters are given in the next section. It is usual to set the symmetry then define the material and shape. The symmetry will be set once for a magnet but the material and shape can be changed as required,

a) DRAW SYMM = -3, MATE = 0, SHAPE = 0
J = 1000
X1 = 2, Y1 = 5, A = 2, B = 3, ANGLE = 45
$$

Causes a rectangle, with BLHC located at position (2, 5) of dimensions 2 cm x 3 cm rotated by 45° for X axis to be drawn and stored. The rectangle has current density of 1000 Amps/cm^2.

The symmetry of code of -3 means that the element is in fact axisymmetric about the X axis and reflected in the Y axis.

If a further element with the same current density is to be entered it is sufficient to specify the geometry.

eg. DRAW X1 = 10, Y1 = 15, A = 4
$$

Causes a second conductor element to be drawn and stored at position (10, 15) with dimension 4 cm x 3 cm. The value of B, ANGLE and J remain the same as specified for the first element.

b) DRAW SYMM = 2, MATE = 3, SHAPE = 8
X1 = 3, Y1 = 0, X2 = 4, Y2 = 5, X3 = 10, Y3 = 15
X4 = 20, Y4 = 5, NX = 4, NY = 2
$$

Causes 32 triangular iron elements to be mapped into the defined quadrilateral as shown in figure.

c) DRAW SYMM = 2, MATE = 3, SHAPE = 5
R = 8.0, DR = 6.0, NR = 2, PHI = 0.0, DPHI = 22.5, NPHI = 4
$$

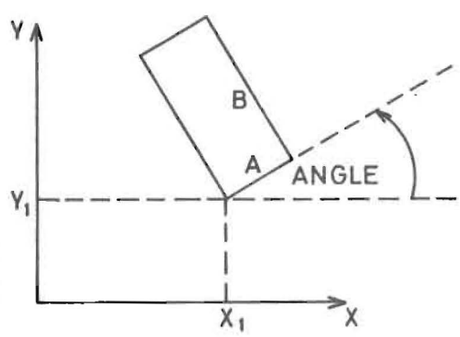
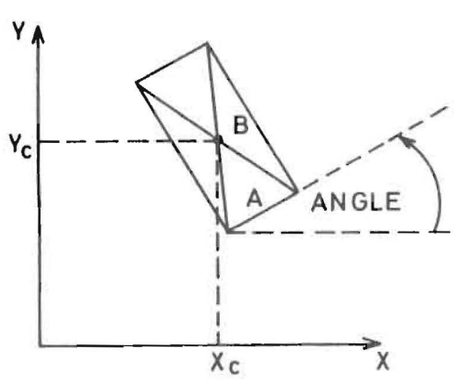
Causes 32 triangular iron elements to be mapped into one quadrant of an annular region of inside radius 8.0 cm and outside radius 20.0 cm. The symmetry code 2 means that the magnet is a symmetric dipole.

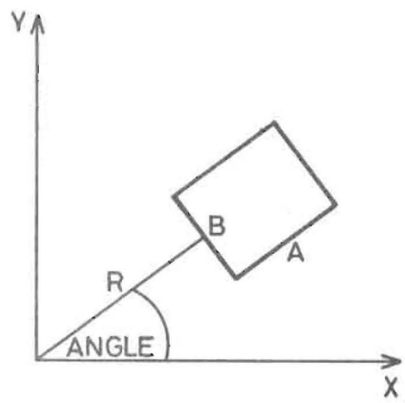
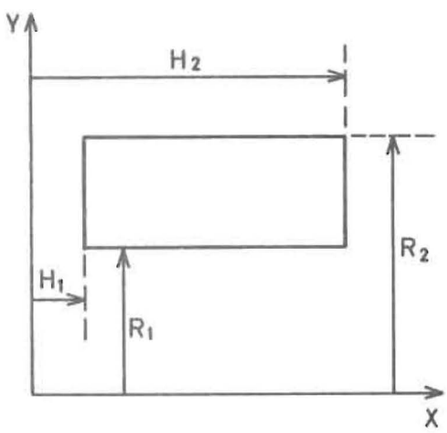
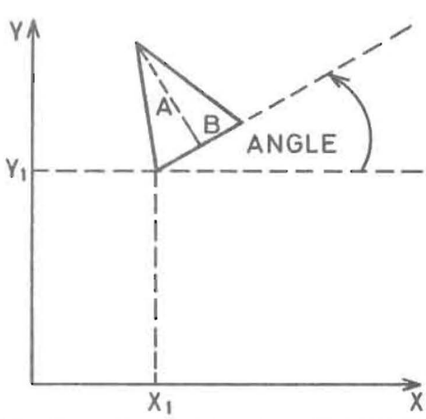
d) DRAW SYMM = 4, SHAPE = 0, MATE = 1
R = 5.0, ANGLE = 20, A = 2, B = 1, I = 1000.0

Causes 1 symmetric rectangular quadrupole current element at an angle of 20° radius 5 cm to be drawn.

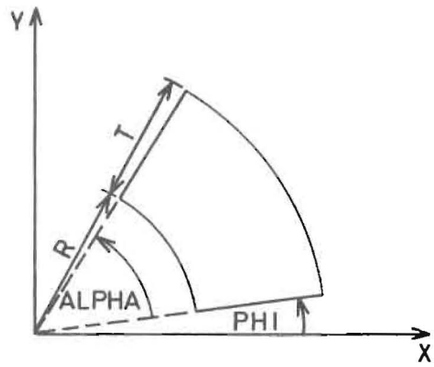
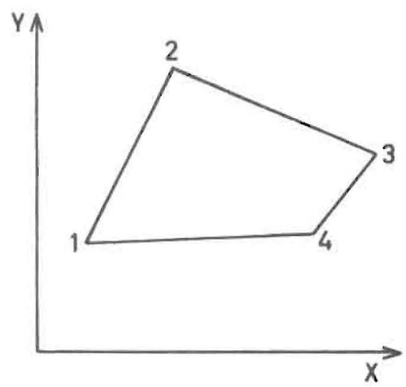
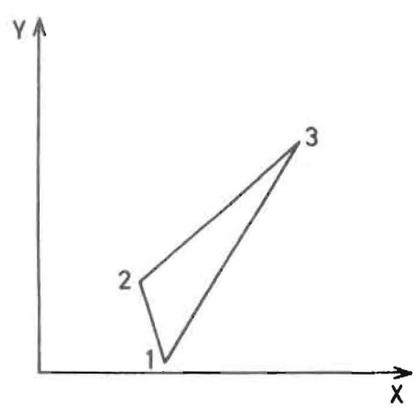
For a complete worked example see Section 6.

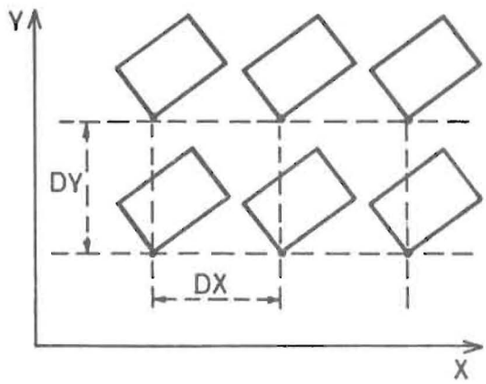
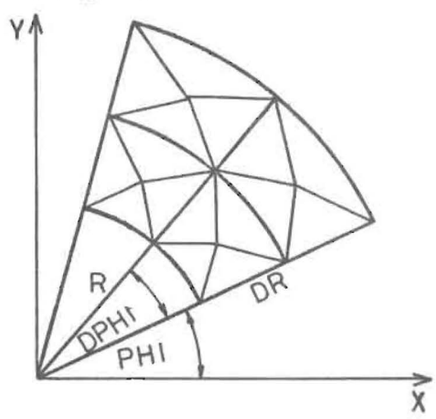
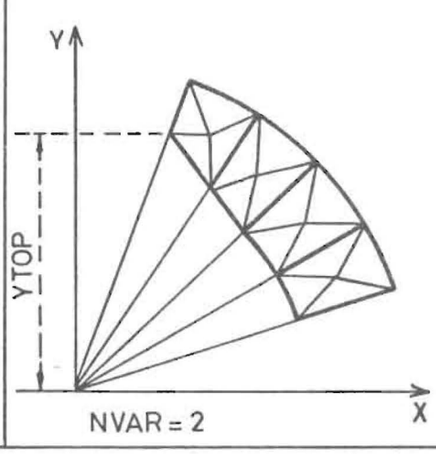
Command	Function	Parameters/Sub Commands
DRAW	Enables elements to be drawn and stored of various shapes to represent both the conductor and iron parts of a magnet. Material type is specified by a material code. Element shape is specified by a shape code and symmetry type is specified by a symmetry code for entire geometry.	Material Codes MATE 0 Conductor J specified 1 Conductor I specified 2 Iron μ constant 3 Iron μ variable
	Symmetry Codes (See Section 3)	Symmetry Codes SYMM 0 or 3 = Axi Symmetry - rotation about X-axis 1 No symmetry 2 Dipole 4 Quadrupole N N Pole -2 Dipole with reflection in x axis -3 Axi Symmetric with reflection in y axis
	Other DRAW parameters	J Current density (MATE = 0) I Current (MATE = 1) MU Permeability (MATE = 2) continued

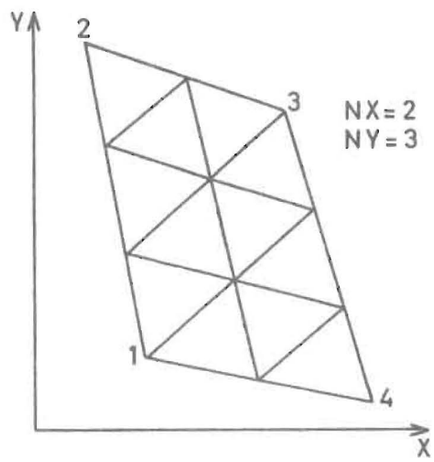
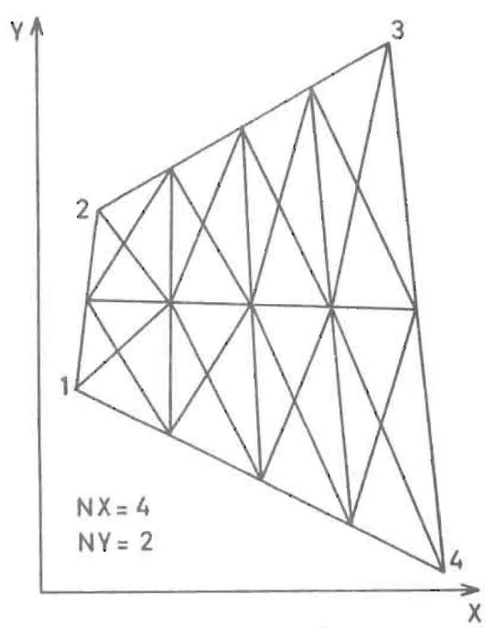
Command	Function	Parameters/Sub Commands
DRAW (cont'd)	Dimensions in centimetres Currents in amperes Current density in Amps/cm^2 Angles in degrees Regularly spaced elements may be generated by the number and increment parameters (see examples later).	Shape code SHAPE 0 RECTANGLE 1 ISOCELES TRIANGLE 2 SECTOR 3 QUADRILATERAL 4 TRIANGLE 5 Maps annular region with isoceles triangles 6 Maps quadrilateral region with triangles 2 per cell 7 Maps quadrilateral region with triangles 4 per cell 8 Maps truncated annular region with rectangles
	SHAPE = 0 Rectangle  (a) BLHC (Bottom Left-hand Corner)	A Width = dimension in x-direction when angle = 0 B length = dimension in y-direction when angle = 0 ANGLE rotation degrees (XI (YI Coordinates of BLHC
	 (b) Centre	A Width B Length ANGLE rotation in degrees (XC (YC Coordinates of centroid cont'd

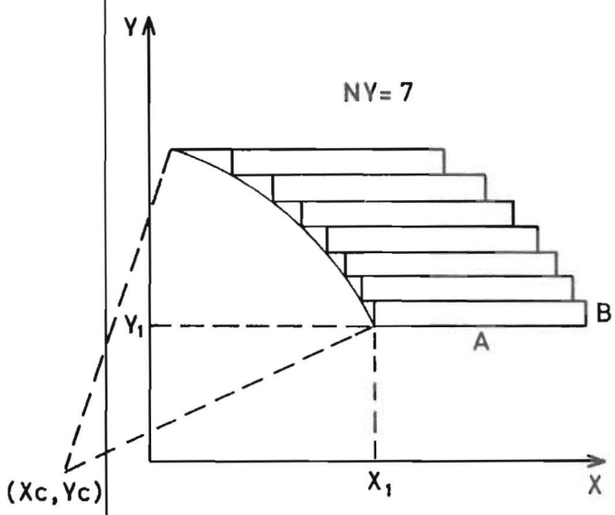
Command	Function	Parameters/Sub Commands
DRAW (cont'd)	 (c) Polar	A width B length R) Polar coordinates of mid point ANGLE) of inner edge
	 (d) Alternative when ANGLE = 0	R1 inner) R2 outer) H1 lower) H2 upper) Also valid in Cartesian coordinates
	<u>SHAPE = 1</u> Isoceles triangle 	A Altitude B Base ANGLE Rotation degrees (X1 (Y1 Coordinates of BLHC

cont'd

Command	Function	Parameters/Sub Commands
DRAW (cont'd)	SHAPE = 2 Sector  	R inner radius T radial thickness PHI angle of lower edge, degrees ALPHA angular length, degrees
	SHAPE = 3 Quadrilateral  Corners numbered clockwise, consecutively	X1,Y1) X2,Y2) Coordinates of X3,Y3) Vertices X4,Y4)
	SHAPE = 4 Triangle  To generate groups of regularly spaced elements additional parameters can be used. These are available for SHAPE = 0 to 4 inclusive.	X1,Y1) X2,Y2) Coordinates of X3,Y3) Vertices

Command	Function	Parameters/Sub Commands
DRAW (Cont'd)	eg. SHAPE = 0, NX = 3, NY = 2  	DX X increment DY Y increment NX Number in x direction NY Number in y direction For SHAPE = 2 only use DR radial increment DPHI angular increment NR Number in r direction NPHI Number in PHI direction
	To map regions SHAPE = 5, 6, 7, 8 can be used. <u>SHAPE = 5</u> Mapping Sector/Annular region with isoceles triangles.  	R inside radius DR radial increment PHI lower angle DPHI angular increment NR number in radial direction NPHI number in Phi direction
	Option for straight line as inner boundary  	Extra parameters required YTOP = Y coordinate of the end of the inner boundary NVAR = Number of elements to be drawn with inner boundary circular

Command	Function	Parameters/Sub Commands
DRAW (contd)	<u>SHAPE = 6</u> Mapping quadrilateral region with triangles 2 per cell  Diagonals can be given other sense by starting corner numbering one place round <u>SHAPE = 7</u> Mapping quadrilateral region 4 per cell  (Often gives better results than SHAPE = 6)	X1, Y1,) X2, Y2) X3, Y3) X4, Y4) Coordinates of Vertices NX Number of intervals in X NY Number of intervals in Y cont'd

Command	Function	Parameters/Sub Commands
DRAW (cont'd)	SHAPE = 8 Mapping a truncated annular region with rectangles  Terminator required	XI) YI) Coordinates of BLHC A Width B Length XC) YC) Coordinates of centre of generating circles NY Number of rectangles $$ Terminator

(ii) RECO causes the picture to be reconstructed with additional facilities for changing certain parameters. These parameters include the X and Y limits and symmetry codes. Also the magnet can be scaled.

a) RECO

Picture reconstructed from current stored values.

b) RECO SYMM = 1, XMAX = 20.

Picture reconstructed with XMAX = 20 and restored with symmetry Code 1.

c) RECO NFLG = 0, SC = 0.5.

Picture reconstructed without element numbering and scaled down geometrically by factor 2 with twice the current density.

(iii) ERASE causes elements to be erased from the currently stored geometry. (NOT the file).

Examples:

a) ERASE MATE = 0, E1 = 1, E2 = 10

Erases the first 10 conductor elements.

b) ERASE MATE = 3, E1 = 3, E2 = 5.

Erases Iron elements of numbers 3 to 5 inclusive.

(iv) MODI causes elements to be modified.

This modification command can be used in two ways.

a) To modify all element parameters of a set of elements keeping their position constant.

b) To shift one particular element to a new position.

Example:

a) MODI MATE = 0, E1 = 3, E2 = 7, ANGLE = 30, B = 2, J = 1000

Conductor element numbers 3 to 7 inclusive redrawn and stored with angle = 30°, B = 2.0 cm, current density of 1000 Amps/cm^2.

b) MODI MATE = 3, E1 = 4, X1 = 3, Y1 = 2

Iron element number 4 shifted to a new position (3, 2).

(v) MOVE. Causes either all the conducting elements or all the iron elements to be moved and/or rotated.

Example:

MOVE MATE = 3, E1 = 5, X1 = 2, Y1 = 3, ANGLE = 45

Moves the entire iron structure to a new position with element number 5 at point (2, 3) and then causes the structure to be rotated through 45°.

Command	Function	Parameters/Sub Commands
RECO	Reconstructs picture	XMIN - default = 0 if XMAX specified) XMAX) Scales YMIN - default = 0 if YMAX specified) YMAX) SYMM - Symmetry code (see below) SC - Scale factor Default = 1 NFLG - Element numbering flag If no subparameters, reconstructs last picture.
ERASE	Erases elements E1 to E2 inclusive	MATE Material Code E1, E2 Element Numbers
MODI	Enables elements to be modified a) Multi element modification Modifies elements E1 to E2 inclusive b) Single element modification Modifies element E1 to new position Terminator required	MATE Material code E1, E2 Element numbers IC Coordinate code IC SHAPE PARAMETERS 1 0, 1 A,B,ANGLE,I,J,MU 1 2 T,ALPHA,I,J,MU 3 0 A,B,ANGLE,R,I,J,MU 1 0, 1 X1, Y1 1 2 R, PHI 3 0 R,ANGLE $$
MOVE	Moves and rotates all elements of given material code to a new position defined by the coordinates of BLHC of a specified element.	MATE Material Code E1 Element Number X1 New coordinates of Y1 Element E1 ANGLE Rotation of angle degrees

2.5 MAGNETISATION

The GETM command is used for calling the routines for solving the magnetisation equations for the iron. The process is iterative and the number of iterations required must be specified. The command can also be used for continuing a previous solution by specifying the number of iterations done before. There is no default value for this parameter so for a new problem it must be given set to zero. Other parameters include initial permeability, external field (if any) and various control parameters for printing.

Examples:

a) GETM NITD = 0, NIT = 20, IMU = 1000

Starts solution of current magnet file for magnetisation with an initial permeability of 1000. The final results are stored in common storage.

b) GETM NITD = 20, NIT = 40

Here the solution is continued up to 40 iterations. At this point if the user is satisfied about convergence he may write the file up to disk which will now contain the new values of magnetisation.

If the display becomes full with iteration information or other printing the process stops. To continue it is necessary to type CONT (C). To interrupt the calculation and return program to the wait state the sub command STOP (S) may be used.

Command	Function	Parameters/Sub Commands
GETM	Solves for magnetisation of the iron elements. Results are stored and can be transferred to the data set on disk by command WRITE. The number of iterations completed and convergence information is also stored.	NITD Number of iterations done before NIT Number of iterations IMU Initial value of permeability HEXT External field value CHIC Convergence accelerator MPRI = 0 No printing 1 On screen each iteration 2 Matrix on LP output 3 Both RECA = 0 Matrix stored on disk 1 Recalculate each iteration Default values NITD provides value NIT 1 IMU 11.0 MPRI 0 HEXT 0.0 RECA 1.0 CHIC 1.0 Type C or CONT to continue when display is full. Type S or STOP to terminate iterations.

2.6 MAGNETIC FIELDS

(i) The GETB command is used for calling the routines for performing the field integrations. The field of specified type can be computed at defined points, along lines or over a defined grid. The computed values along lines are displayed graphically. The computed value at a point can be printed on the display. The computed values can also be displayed in tabular form on the screen or line printer.

Examples:

a) GETB x = 10, y = 3
The field components at the point (10, 3) are printed on the display.

b) GETB NX = 21, DX = .2, TYPE = 0. The homogeneity is displayed along a line in the x direction at y = 0.0 starting at x = 0 to x = 4.0 in steps of .2.

c) GETB NX = 21, DX = .2, NY = 21, DY = .2, TYPE = 3, PRINT = 1.
The total field over the defined rectangular grid is tabulated on the screen and stored. Then stored values can be used later as data for the continuing routines initiated by the MAP command.

(ii) The MAP command is used for calling the routines for drawing contours. The user should have previously used the GETB command for storing the field of the required type over a rectangular region.

Examples:

a) MAP LINES = 10
Draw 10 contours distributed linearly between maximum and minimum values.

b) MAP START = 0.0, INCR = .1, FINI = 2.0, draw set of contours starting at 0.0, finishing at 2.0 with interval .1.

<u>NB</u>. Units for fields are kilogauss.

Command	Function	Parameters/Sub Commands
GETB	Computed magnetic field of specified TYPE along a line or over a regularly spaced mesh. a) Field at a single point can be printed on screen. b) Fields of a specified TYPE along a line can be printed on the screen. c) Fields of a specified TYPE over a regularly spaced mesh can be printed on the screen	TYPE Field Type TYPE = 0 DH/H % 1 HY 2 HX 3 HT 4 VECTOR POTENTIAL 5 HARMONIC ANALYSIS (See Section 4) 6 SCALAR POTENTIAL Default TYPE = 1 SAME = 1 Reconstructs picture SAME = 0 Same picture Default SAME = 1 SCALE LIMITS HMIN Fields in kilogauss or HMAX homogeneity in per cent. HMIN = 0) Program chooses HMAX = 0) scale limits Default HMIN=0, HMAX=0 PRINT = 0 no printing = 1 Screen printing, Type C to continue = 2 Line printer Default PRINT = 0 CHARACTERS FOR PLOTTING CHAR = 43 (+) CHAR = 46 (.) CHAR = 42 (*) Default CHAR = 43 FOR AXI SYMM COILS DD Deletion distance Default DD = 1.0 TOL Field tolerance Default TOL = 100.0 FOR SECTOR CURRENTS (SHAPE = 2) INMAX = Number of terms in the series Default INMAX = 10
	a) <u>Field at a point</u>	X) Y) point coordinates Default X = 0, Y = 0.
	b) (i) <u>Field along a line in x direction</u>	X) Y) starting point coordinates DX increment NX number of points <50
	(ii) <u>Field along a line in y direction</u>	X) Y) starting point coordinates DY increment NY number of points <50

cont'd

Command	Function	Parameters/Sub Commands
GETB (cont'd)	c) <u>Field over a mesh</u> Printing only. This option is usually followed by COMMAND MAP to obtain contour maps of fields of the specified type. d) <u>Field harmonics</u> Assumes that the field about the origin can be described by a Fourier Cosine series Calculates the harmonics from the fields at points in a cylinder defined by the parameters.	X) starting point of mesh Y) BLHC NX) size of mesh NY) < 50 x 50 R inside radius of the cylinder PHI coords. of BLHC of cylinder NR number of radial field points NPHI number of azimuthal " " DR radial increment DPHI azimuthal increment RN normalising radius N highest order coefficient NN type of field, 1 dipole (Max NRxDR = 50, max N = 40) S(TOP) To terminate field output
MAP (only available after GETB on 2D mesh)	Draws map of contours	LINES = Min. number of lines required or (START starting value of first time (INCREM increment between lines (FINISH finishing value of last line GRID = <u>NO</u>/YES (whether grid of points needed) BOX = <u>NO</u>/YES (whether box surrounding area needed) ERASE = <u>YES</u>/NO (existing picture should be erased before map is drawn) FORBID= YES/<u>NO</u> (whether option of excluding part of area is to be used) XCENTRE) Coordinates of centre of YCENTRE) forbidden annular area INNER) Inner and outer radii of OUTER) annulus

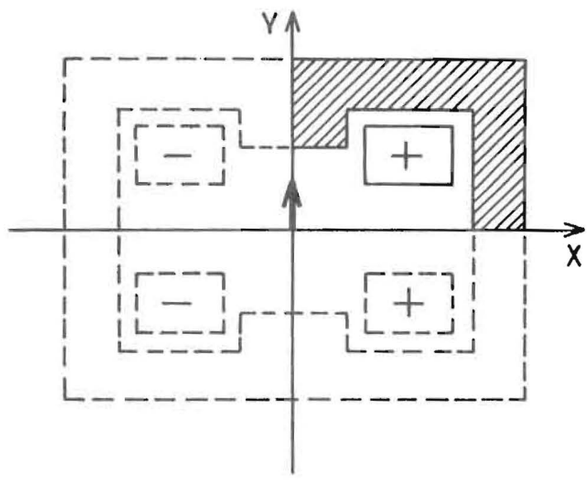
3. SYMMETRY CODES

The problem symmetry is specified by the SYMM parameter when using the DRAW or RECO command. (See Section 2.4.)

(a) SYMM = 1 NO SYMMETRY
Complete magnet must be specified

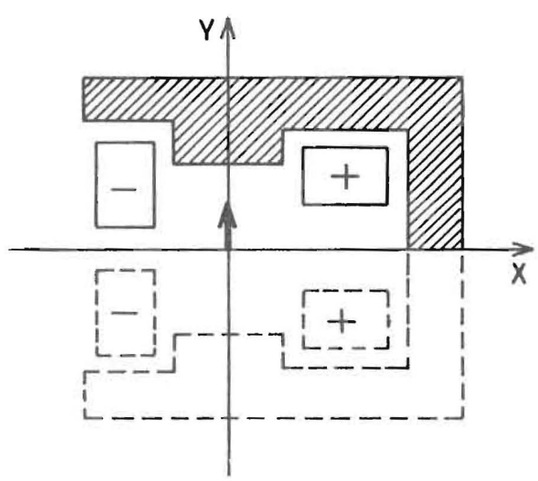
(b) SYMM = 2 SYMMETRIC DIPOLE Field in y direction
Iron geometry symmetric in x and y axes
Current symmetric in x axis
antisymmetric in y axis

e.g.



(c) SYMM = -2 ASYMMETRIC DIPOLE. Field in y direction
Iron geometry symmetric in x axis
Current symmetric in x axis

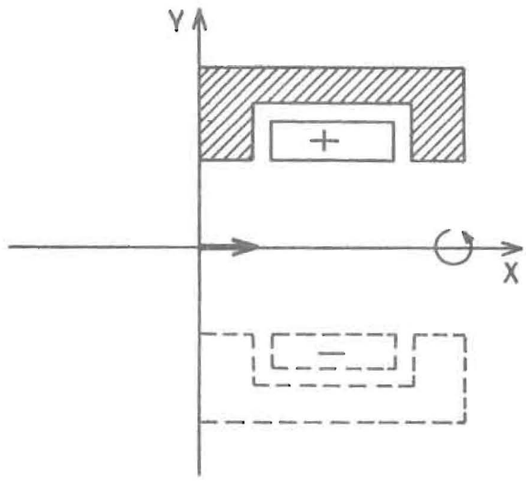
e.g.



(d) SYMM = 3 AXISYMMETRIC about the x axis

Field in x direction

e.g.



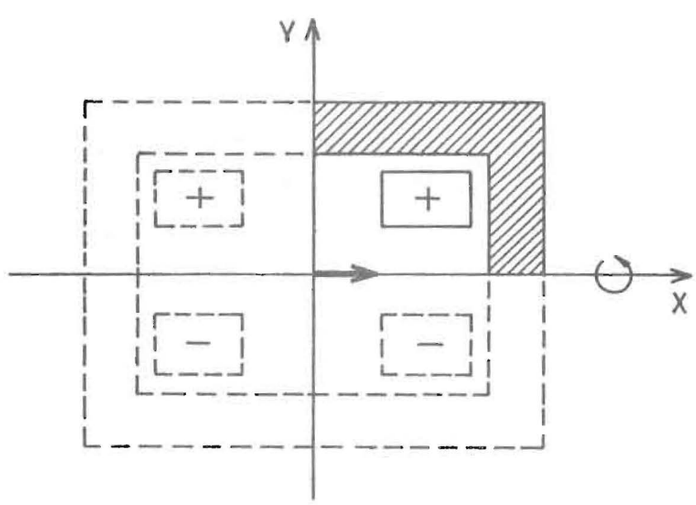
(e) SYMM = -3 AXISYMMETRIC about x axis

Field in x direction

Iron geometry and current reflected in y axis

in split pair symmetry

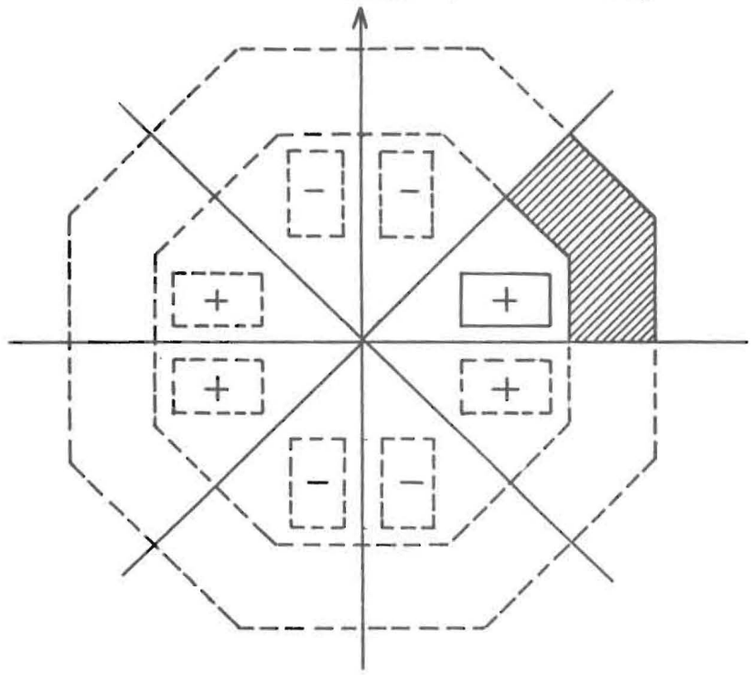
e.g.



(f) SYMM = 4 SYMMETRIC QUADRUPOLE

Geometry has 8 fold multiplicity

Currents alternate as shown and geometry to be specified in the first $\pi/4$ sector only



(g) SYMM = 6 HIGHER ORDER SYMMETRIC MULTIPOLES

Geometry has 2 x NSYM multiplicity

Currents alternate as before and geometry to be specified in first π/NSYM sector only

4. HARMONIC ANALYSIS

For high energy physics applications, ie. beam optics, it is frequently desirable to describe a magnetic field by its harmonic components. Over a given region, if the field can be described by a fourier series of the type:

$$\begin{matrix} B(\theta) \\ (r) \end{matrix} = \sum_{n=1}^{\infty} B_n r^{n-1} \begin{matrix} (\cos\theta) \\ (\sin\theta) \end{matrix}$$

the command HARM will cause the program to calculate the values of Bn - the harmonic coefficients.

HARM initiates a GETB command at a series of field points on a regular cylindrical mesh and the resulting field values are analysed - using a least-squares method - to determine the harmonic coefficients. At present the command is only implemented for dipole fields which contain no even harmonic terms.

Example:

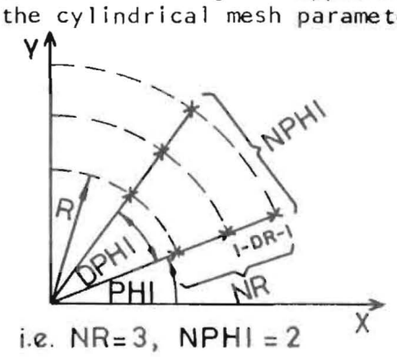
HARM R=3, DR=0.5, NR=3, PHI=0, NPHI=15, DPHI=6, NN=1, N=30, RN=5

The results are presented as:

N B(N) C(N)

where C(N) is the normalised coefficient

$$C(N) = \frac{B(N)}{B(1)} \times RN^{N-1}$$

Command	Function	Parameters		Default
HARM	Performs harmonic analysis of the field over a region mapped out by the cylindrical mesh parameters.  i.e. NR=3, NPHI = 2	R DR NR PHI DPHI NPHI N RN NN	radius radial increment No. of radial steps starting angle azimuthal increment No.of azimuthal steps highest order term to be calculated normalising radius not used at present but will be used to define the series fitted, ie. dipole, quadrupole	3.0cm 0.3cm 3 0° 6° 15 30 5.0cm 1

5. OPTIMISATION

Parameters defining current elements can be optimised to minimise the field variation over a prescribed region. The user can specify a number of field points spanning either a rectangular or elliptical region. The program then attempts to optimise selected parameters for a specified range of elements. The parameter minimised is the RMS value of the quantity (Hp - Ho)/Ho, where Hp is the field at a point and Ho the field at the origin for all of the selected field points. In certain cases it may be necessary to impose limiting values for the selected parameters to prevent impractical solutions. The function is unconstrained unless parameter MAX1 is supplied. The maximum change in a variable per iteration is controlled by the parameter ESCAL and the convergence tolerance by the parameter ERROR.

The contribution to the field for any magnetised iron elements will be added into the function but it must be remembered,that in varying the conductor elements,magnetisation changes so that the command 'OPTI' must be followed by a command 'GETM'. To ensure a converged solution the process must be repeated as many times as is necessary to achieve the desired tolerance.

Example:

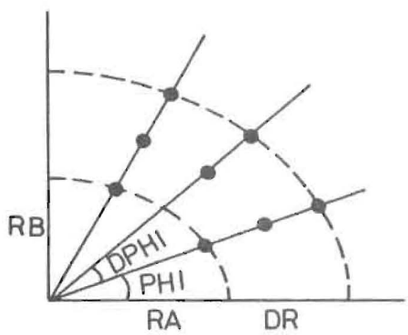
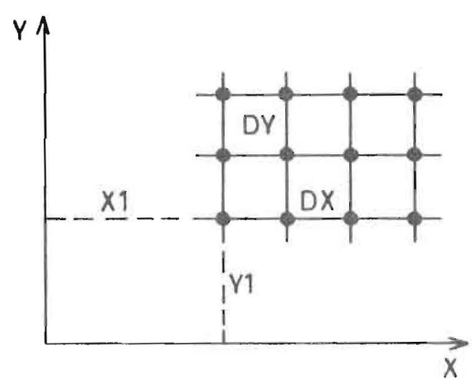
a) OPTI VAR1 = ALPH

This will optimise the angular arcs of a set of sector conductors for the field homogeneity over a circular region of radius 4.0 cm.

b) OPTI VAR1 = ANGLE, VAR2 = B, E1 = 1, E2 = 4, IC = 3
RA = 4.5, RB = 4.5, NR = 2, DR = 1.0, MAX1 = 90, MAX2 = 2

The first 4 (polar coord. type) elements are optimised. The parameter angle is constrained between 0 and 90° and the length of element B is constrained between 0 and 2 cm. The field region is annular, of inside radius 4.5 and thickness 1.0 cm.

A complete worked example is given in Section 6.

Command	Function	Parameters/Sub Command
OPTI	Optimises conductor elements E1 to E2 inclusive with respect to homogeneity over a rectangular or elliptical region. Either one or two variables may be selected for optimisation. The same selected variable will be applied to each of the elements to be varied.	E1 lowest element No. — Defaults 1 E2 highest element — Max.number ERROR accuracy tolerance — .1 ESCALE error scaling parameter — 100.0 VAR1 1st selected variable — - MAX1 maximum value — 90.0 MIN1 minimum value — 0.0 VAR2 2nd selected variable — - MAX2 maximum value — 90.0 MIN2 minimum value — 0.0 IC coordinate code — 1
	a) Allowed variables. VAR1 is a compulsory parameter A maximum of 10 variables allowed.	IC SHAPE VARIABLES 1 0,1 A,B,ANGLE,X1,Y1,I,J 3 2 T,ALPHA,R,PHI,I,J 4 0 A,B,Right hand edge of rectangle remains fixed in position.
	b) Elliptical homogeneity region  NR = 3 NPHI = 2	Default RA Major radius — 4.0 RB Minor radius — 4.0 DR Radial increments — 0 NR Number of radial points — 1 PHI Initial angle — 0 DPHI Angular increments — 22.5° NPHI No. of angular increments — 4 This option is the default option.
	c) Rectangular homogeneity region  	Default X1) BLHC of region — 0.0 Y1) — 0.0 DX X increment — 1.0 DY Y increment — 1.0 NX Number of X points — 2.0 NY Number of Y points — 2.0 This option is obtained by specifying NX, NY or both.
	Maximum of 50 field points allowed	cont'd

Command	Function	Parameters/Sub Command
OPTI (Cont'd)	d) Display printing and calculation interruption	PRINT = 0 No printing PRINT = 2 Printing at the end of last iteration TYPE C(ONT) to continue TYPE S(TOP) to terminate optimisation.

6. EXAMPLE PROBLEMS

6.1 SOLENOIDS

In this example a split pair of solenoids is analysed. The cross section dimensions and radii of both coils are fixed. The problem is to determine the separation between the coils to minimise the magnetic field variation over a square region.

After the program sends message 'GFUN ON-LINE' the commands are 'typed in' as follows:

```
FRAM  XMAX=20, YMAX=20 [Sets scales]
$$
DRAW  MATE=0, SHAP=0, SYMM=-3, R1=5, R2=6, H1=.25, H2=2.25, J=10000
$$
```

[Sets material to conductor, shape to rectangle, symmetry to axisymmetric with reflection in y axis (see 3.2), and draws section of coil at an initial separation of 0.5 cm. See Figure 6.1.]

```
GETB  NX=21, DX=.1, TYPE=0
```

[Computes and displays the field homogeneity along the x axis (axis of rotation). The region of interest is a square region 4 cm x 4 cm centred at the origin. Note the field has homogeneity >10%. See Figure 6.2]

```
RECO  XMAX=2.5, YMAX=2.5.
```

[Change scale to enlarge central region.]

```
GETB  NX=41, NY=41, DX=.05, DY=.05
```

[Computes field on a mesh over region.]

```
MAP   LINES=5
```

[Draws contours of homogeneity, see Figure 6.3.]

RECO

[Reconstructs picture.]

OPTI VAR1=X1, IC=1, NX=4, NY=4, DX=.5, DY=.5, PRINT=0

[Optimises X1 the ½ separation, displays field points and resulting homogeneity. Figure 6.4.]

GETB NX=41, NY=41

MAP LINES=5

[Draws contours of homogeneity after optimisation, homogeneity now <1%. Figure 6.5.]

RECO XMAX=10, YMAX=10

[Reconstructs picture on new scales. Note that the coil moved further out to approximately Helmholtz condition $2X_1$ =(R1+R2)/2. (See Figure 6.6)]

GETB NX=41, NY=41, DX=.25, DY=.25, TYPE=3, TOL=10, DD=0.1

[Total field computed at each point of a grid 10 x 10 cm. For points inside the coil DD* set at 0.1 and tolerance set at 10 gauss.]

MAP LINES=10

[Contours of total field in kg over the whole system. See Figure 6.6.]

* Deletion distance to force convergence for points inside coil only applicable to axisymmetric currents.

6.2 C-MAGNET

Extensive use of the data filing system is illustrated in this example. It is less frustrating to write a data file at frequent intervals than to lose all the data following a program or system failure. This example is divided into three parts; the second part shows the use of the off-line GETM facility (see Section 7.1).

(a) Data entry On-line program

```
LIST DS=GFUN4          [Lists files on Directory GFUN4]
RECO SYMM=-2,XMAX=50,YMAX=50
DRAW MATE=0,SHAPE=0,ANGLE=0,J=400,X1=21.5,Y1=5.5,A=5,B=10
$$
DRAW MATE=0,X1=27.0
$$
WRITE FL=EPERGNE
DRAW MATE=0,J=-400,X1=48.0
$$
DRAW MATE=0,X1=53.5
$$                    [Conductor data entered]
WRITE FL=EPERGNE
DELE FL=EPERGNE,1
DRAW MATE=3,SHAPE=7,NX=1,NY=2,X1=0,X2=0,X3=10,X4=10
Y1=0,Y2=31,Y3=31,Y4=0  [8 iron elements for the yoke, see Figure 6.7]
$$
DRAW MATE=3,SHAPE=7,NX=1,NY=2,X1=10,X2=10,X3=21,X4=21
Y1=0,Y2=16,Y3=16,Y4=0
$$                       [16 iron elements, see Figure 6.8]
WRITE FL=EPERGNE
DELE FL=EPERGNE,2
DRAW MATE=3,SHAPE=7,NX=1,NY=1,X1=32.5,X2=32.5,X3=34.4,X4=34.4
Y1=4.5,Y2=16,Y3=16,Y4=4.5
$$                       [1st pole shim, see Figure 6.9]
DRAW MATE=3,SHAPE=7,NX=1,NY=1,X1=45.6,X2=45.6,X3=47.5,X4=47.5
Y1=4.5,Y2=16,Y3=16,Y4=4.5
$$                       [2nd pole shim, see Figure 6.10]
WRITE FL=EPERGNE
DELE FL=EPERGNE,3
DRAW MATE=3,SHAPE=7,NX=2,NY=2,X1=34,4,X2=34.4,X3=45.6,X4=45.6
Y1=5, Y2=16,Y3=16,Y4=5
$$                       [Pole tip, see Figure 6.11]
```


cont'd..

```
DRAW MATE=3,SHAPE=7,NX=4,NY=1,X1=10,X2=10,X3=47.5,X4=47.5
Y1=16,Y2=26,Y3=26,Y4=16
$$                  [Pole limb]
WRITE FL=EPERGNE
DELE FL=EPERGNE,4
DRAW MATE=3,SHAPE=7,NX=1,NY=1,X1=10,X2=10,X3=47.5,X4=47.5
Y1=26,Y2=31,Y3=31,Y4=26
$$                  [Complete iron data entered, see Figure 6.12]
WRITE FL=EPERGNE
DELE FL=EPERGNE,5
BH
500    0.556
1000   0.8
1500   0.91
2000   1.06
3000   1.2
4000   1.38
5000   1.54
6000   1.71
7000   1.92
8000   2.14
9000   2.4
10000  2.78
$$
WRITE FL=EPERGNE
DELE FL=EPERGNE,6
BH
11000  3.28
12000  4.0
13000  5.2
14000  7.3
15000  11.7
16000  24.6
17000  56.7
18000  108
19000  181
20000  300
21000  525
22000  1050
$$
```

[BH data, see Section 2.3]

[BH data continued]

cont'd..

```
WRITE FL=EPERGNE                [Complete data file]
DELE  FL=EPERGNE,7
END
```

b) Magnetisation Computation. Off-line Program

To calculate the iron magnetisation in this case the off-line GETM program must be used because there are more than 32 iron elements. Following the rules given in Section 7.1 the user should submit the off-line job by use of ELECTRIC.

```
PARM NAME=EPERGNE,NGEN=10,NITD=0,NIT=30,IMU=1000 *
EXEC JB=GETM64
```

After executing 30 iterations the program writes a new magnet file on to the data set containing the magnet geometry and the new magnetisation data. This file is named EPERGNE,11.

* Files EPERGNE, 8 and 9 were used for other purposes.

c) Field Computation. On-line Program

The on-line program is now used to compute fields etc.

```
LIST                [Lists files on directory]
READ FL=EPERGNE,11  [The new file, current data displayed, see Fig. 6.13]
C                   [Iron data, Fig. 6.13]
C
C
C                   [Magnetisation data, Fig. 6.14]
C
C                   [Complete file read into program]
BH
$$                  [BH data plotted, see Fig. 6.15]
RECO XMAX=100,YMAX=100,NFLG=0
GETB X=35,Y=0,DX=.5,NX=21,HMIN=0,HMAX=10,PRINT=1,TYPE=3
C                   [Print out of field, Fig.6.16; plot of field Fig. 6.17]
GETB NX=41,HMIN=8.8,HMAX=9.05,DX=.25 [Enlarged scale, see Fig. 6.18]
GETB NX=41,HMIN=0,HMAX=10,DX=1       [Fringe field, see Fig. 6.19]
RECO XMAX=50,YMAX=50
GETB NX=21,NY=21,DX=.5,DY=.2,TYPE=3,CHAR=46,X=35[Field over rectangular mesh,
                                        field points displayed, see Fig. 6.20]
RECO XMIN=33,XMAX=43,YMAX=10 [Enlarged scale]
MAP  LINES=10       [Contour map of field, see Fig. 6.21]
MAP  STAR=9,FINI=9.1,INCR=.005,LABE=NO[Contour map, see Fig. 6.22]
MAP  STAR=9,FINI=9.02,INCR=.001  [Contour map, see Fig. 6.23]
END
```

6.3 OPTIMISATION OF A DIPOLE

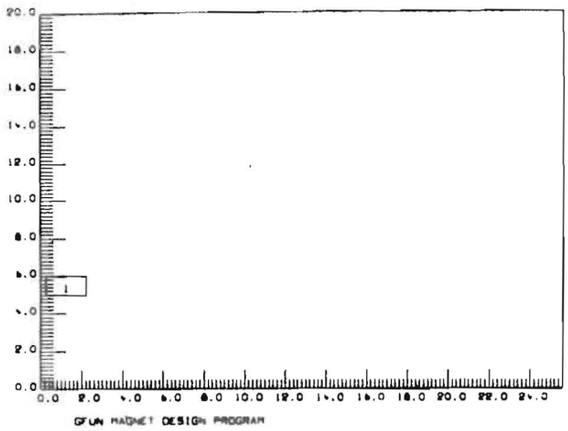
The problem here is to determine the angular arc lengths of an array of current sectors which minimise the field variation over a circular region. Initially the arcs are optimised without the iron yoke, and subsequently with the iron yoke, by alternating the OPTI and GETM commands until a desired convergence is achieved.

```
FRAME XMAX=30,YMAX=30
$$
RECO
DRAW SHAPE=2,MATE=0,J=4000,R=5,DR=0.9389,NR=4,T=0.8534
PHI=0,ALPHA=30,SYMM=2
$$  [Sector type elements, initial angle 30°, see Fig. 6.24]
GETB NX=21,DX=.2,TYPE=0  [Initial check on the field]
RECO
OPTI VARI=ALPHA,RA=4,RB=4,NR=1,PRINT=0  [Field points for optimisation
                                          and optimised angles, see Fig. 6.25]
RECO [Picture reconstructed with new angles, see Fig. 6.26]
BH
0.0 0.0
2675.0 0.975
5350.0 1.950
7500.0 2.8
10000.0 3.5
13500.0 5.0
14000.0 6.8
14500.0 8.6
14800.0 10.2
15200.0 12.9
15600.0 17.0
16000.0 25.4
16850.0 53.0
17800.0 104.0
18550.0 150.0
20000.0 2900.0
24000.0 4600.0
25000.0 5500.0
27000.0 7200.0
29000.0 9050.0
31000.0 10850.0
33000.0 12750.0
```

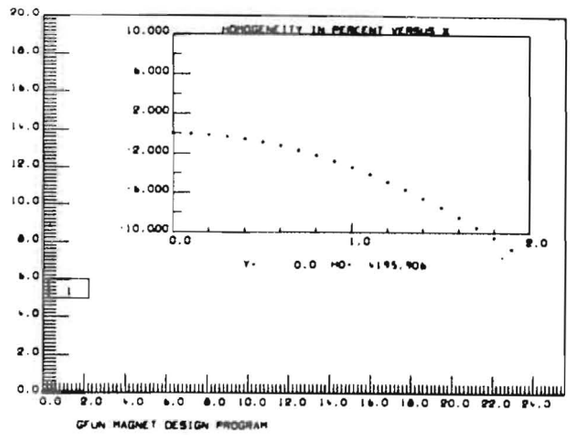
[BH Data, Fig. 6.27]

cont'd..

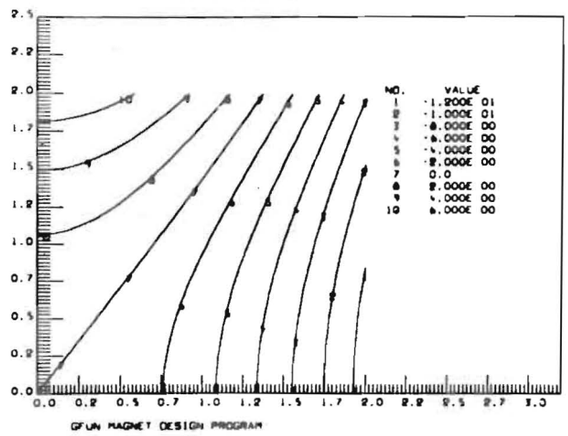
```
36000.0 15800.0
40000.0 20000.0
60000.0 40000.0
$$
RECO
DRAW SHAPE=5,MATE=3,R=9.67, DR=7.6,NR=2,PHI=0,NPHI=4, DPHI=22.5
$$   [One quadrant of iron yoke, see Fig. 6.28]
GETM NIT=30,NITD=0,IMU=1000 [Magnetisation iterations showing
                                 convergence, Fig. 6.29]
GETB NX=21,DX=.2,TYPE=0,SAME=1,INMAX=30
GETB NY=21,DY=.2,SAME=0  [Field variation in central region, see Fig.6.30]
OPTI VARI=ALPHA
GETM NIT=30,NITD=1
GETB NX=21,SAME=1
GETB NY=21,SAME=0  [Fig. 6.31]
OPTI VARI=ALPHA
GETM NIT=30,NITD=1
GETB NX=21,SAME=1
GETB NY=21,SAME=0  [Final field variation after optimisation taking
                     account of yoke, Fig. 6.32]
GETB TYPE=5,R=3,DR=.5,NR=3,PHI=0,NPHI=15,DPHI=6,NN=1,N=30,RN=5
                   [Harmonic analysis, Fig. 6.33]
RECO XMAX=5,YMAX=5
GETB NX=21,NY=21,DX=.175,DY=.175,TYPE=0
MAP  [Contour lines of homogeneity, see Fig. 6.34]
RECO YMIN=4,YMAX=6,XMAX=2
GETB DX=.1,DY=.1,NX=21,NY=21,Y=4,INMAX=50
           [Search for peak fields, for sector type elements only,
            INMAX set to 50 to ensure good accuracy]
MAP        [Contour map of field in conductor, see Fig. 6.35]
END
```



6.1 The split pair of solenoids defined by entering data for one coil only.

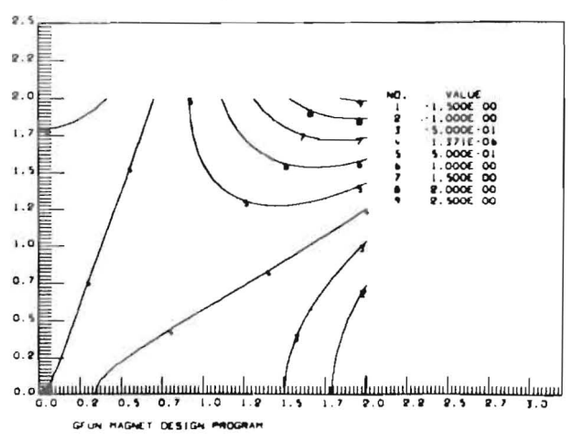


6.2 Field along the axis before optimisation.

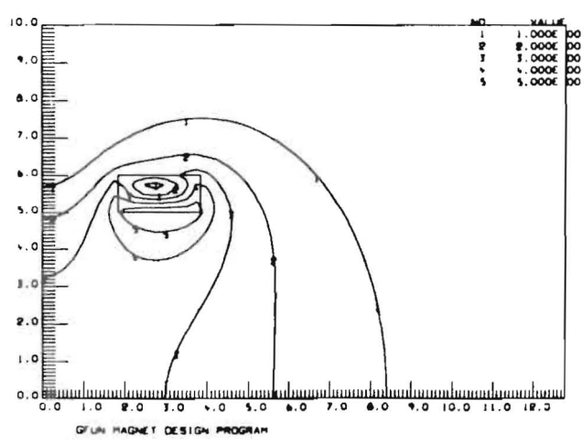


6.3 Field map over central region before optimisation.

6.4 Optimisation results, half gap changed from 0.5cm to 1.842cm.

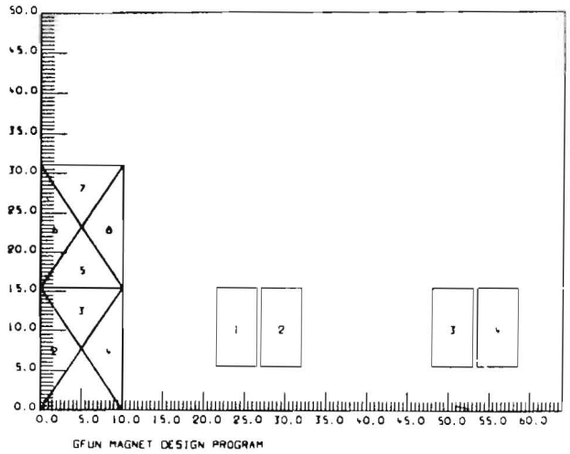


6.5 Field map after optimisation.

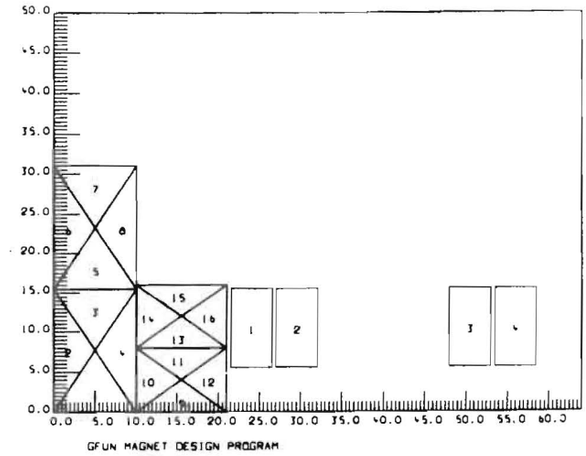


6.6 General contour map of fringe field.

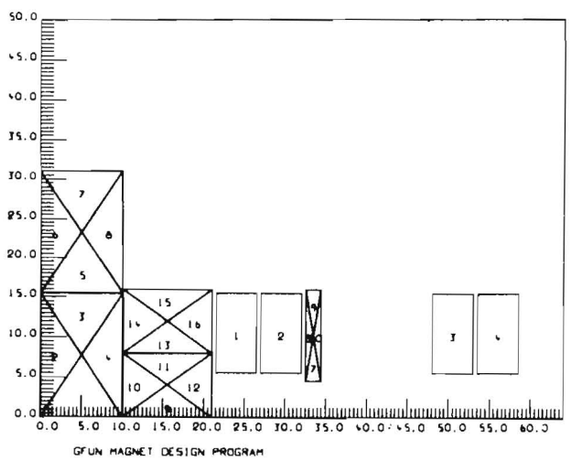
FIGURES 6.1 to 6.6 - SPLIT PAIR SOLENOIDS



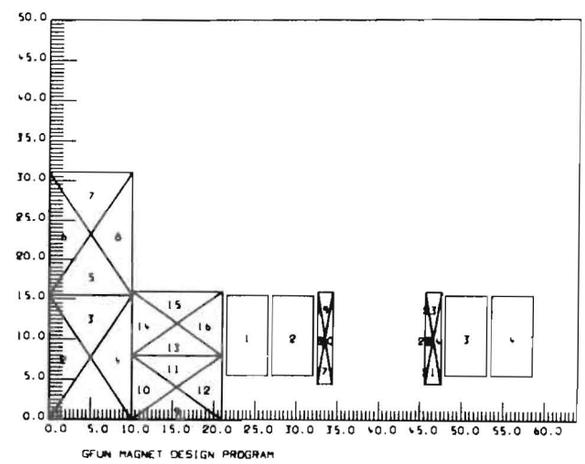
6.7 Data for 4 conductor elements and 8 iron elements of yoke entered.



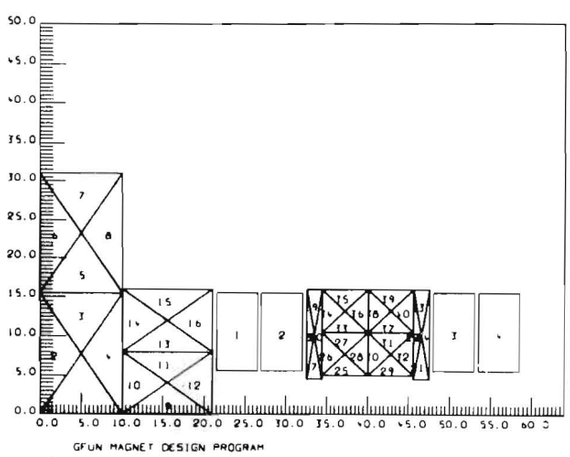
6.8 Yoke completed.



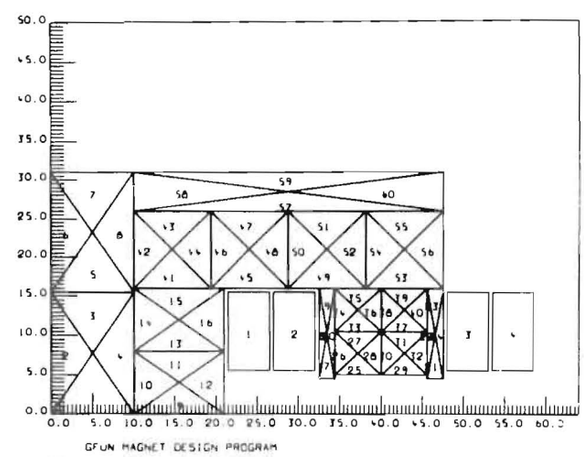
6.9 Pole shim.



6.10 Pole shims completed.



6.11 Pole tip.



6.12 Pole limb, geometry data completed.

FIGURES 6.7 - 6.12 - C-MAGNET GEOMETRY

```
[PERGNE 1]                    DATE  4/  3/ 78 TIME 14. 7.23
                    ELEMENT CONFIGURATION
                  -2 POLE SYMMETRY
                CONDUCTOR ELEMENTS
N    X1      Y1      X2      Y2      X3      Y3      X4      Y4      CUR.DEN
1   21.50    5.50   21.50   15.50   26.50   15.50   26.50    5.50  4.000E 02
2   27.00    5.50   27.00   15.50   32.00   15.50   32.00    5.50  4.000E 02
3   48.00    5.50   48.00   15.50   53.00   15.50   53.00    5.50  4.000E 02
4   53.50    5.50   53.50   15.50   58.50   15.50   58.50    5.50  4.000E 02
```

6.13a Conductor data

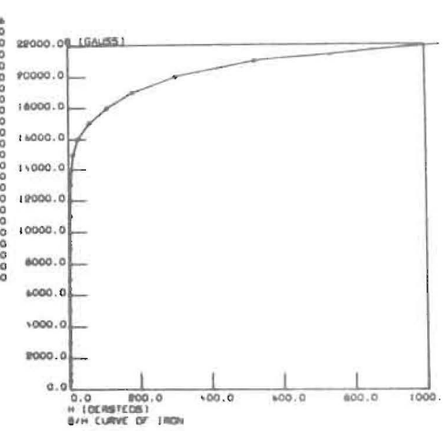
```
MAGNETISATION AFTER   39 ITERATIONS CONVERGED TO**********GAUSS
          MX          MY
  1  1.944E 02  1.584E 04
  2  5.598E 00  1.360E 04
  3  3.988E 02  1.611E 04
  4  1.645E 02  1.689E 04
  5  4.650E 03  1.820E 04
  6  8.029E 01  9.009E 03
  7  5.857E 03  3.182E 02
  8  1.016E 04  8.714E 03
  9  1.588E 04  4.918E 03
 10  1.485E 02  1.597E 04
 11  1.355E 04  6.089E 03
 12  1.647E 03  5.307E 03
 13  1.877E 04  6.044E 03
 14  5.469E 01  3.455E 03
 15  1.488E 04  7.007E 03
 16  1.168E 03  1.617E 04
 17  5.149E 03  1.970E 04
 18  2.513E 03  2.065E 04
 19  1.882E 03  1.908E 04
 20  4.331E 03  2.458E 02
 21  4.881E 03  1.954E 04
 22  3.482E 03  1.994E 03
 23  1.390E 03  1.831E 04
 24  2.537E 03  2.076E 04
 25  5.908E 02  9.053E 03
 26  7.100E 03  1.739E 04
 27  6.450E 03  1.699E 04
 28  1.089E 03  9.454E 03
 29  7.448E 02  9.083E 03
 30  1.056E 03  7.851E 03
 31  8.897E 03  1.499E 04
 32  7.066E 03  1.761E 04
 33  3.186E 03  1.708E 04
 34  7.558E 02  2.055E 04
 35  1.481E 04  9.954E 03
 36  7.588E 03  6.881E 03
 37  5.786E 03  1.503E 04
 38  7.090E 03  1.646E 04
 39  2.530E 03  1.999E 04
 40  1.542E 03  1.957E 04
 41  1.440E 04  7.167E 03
 42  1.001E 04  2.685E 03
 43  1.276E 04  6.674E 02
 44  1.733E 04  4.211E 03
 45  1.885E 04  3.602E 02
 46  1.752E 04  4.654E 02
 47  1.797E 04  1.185E 03
 48  1.908E 04  2.182E 02
 49  1.946E 04  6.606E 03
 50  1.919E 04  4.520E 03
 51  1.687E 04  2.172E 03
 52  1.557E 04  3.461E 03
 53  3.100E 03  1.952E 04
 54  1.557E 04  6.128E 03
 55  1.890E 04  2.486E 03
 56  4.057E 02  1.569E 04
 57  1.867E 04  1.689E 03
 58  1.850E 04  1.746E 03
 59  1.938E 03  6.432E 01
 60  6.565E 02  9.331E 01
```

6.14 Magnetisation results

```
IRON ELEMENTS
N    X1      Y1      X2      Y2      X3      Y3      X4      Y4      MU
1    0.0     0.0     5.00    7.75   10.00    0.0     0.0     0.0   6.958E 02
2    0.0    15.50    5.00    7.75    0.0     0.0     0.0     0.0   7.910E 02
3   10.00   15.50    5.00    7.75    0.0    15.50    0.0     0.0   5.360E 02
4   10.00    0.0     5.00    7.75   10.00   15.50    0.0     0.0   4.669E 02
5    0.0    15.50    5.00   23.25   10.00   15.50    0.0     0.0   3.195E 02
6    0.0    31.00    5.00   23.25    0.0    15.50    0.0     0.0   3.741E 03
7   10.00   31.00    5.00   23.25    0.0    31.00    0.0     0.0   3.503E 03
8   10.00   15.50    5.00   23.25   10.00   31.00    0.0     0.0   2.362E 03
9   10.00    0.0    15.50    4.00   21.00    0.0     0.0     0.0   5.470E 02
10  10.00    8.00   15.50    4.00   10.00    0.0     0.0     0.0   6.359E 02
11  21.00    8.00   15.50    4.00   10.00    8.00    0.0     0.0   1.346E 03
12  21.00    0.0    15.50    4.00   21.00    8.00    0.0     0.0   3.347E 03
13  10.00    8.00   15.50   12.00   21.00    8.00    0.0     0.0   1.659E 03
14  10.00   16.00   15.50   12.00   10.00    8.00    0.0     0.0   1.816E 03
15  21.00   16.00   15.50   12.00   10.00   16.00    0.0     0.0   6.133E 02
16  21.00    8.00   15.50   12.00   21.00   16.00    0.0     0.0   4.541E 02
17  32.50    4.50   33.45   10.25   34.40    4.50    0.0     0.0   4.144E 01
18  32.50   16.00   33.45   10.25   32.50    4.50    0.0     0.0   2.365E 01
19  34.40   16.00   33.45   10.25   32.50   16.00    0.0     0.0   2.896E 03
20  34.40    4.50   33.45   10.25   34.40   16.00    0.0     0.0   2.861E 03
21  45.60    4.50   46.55   10.25   47.50    4.50    0.0     0.0   4.713E 01
22  45.60   16.00   46.55   10.25   45.60    4.50    0.0     0.0   2.460E 03
23  47.50   16.00   46.55   10.25   45.60   16.00    0.0     0.0   1.271E 02
24  47.50    4.50   46.55   10.25   47.50   16.00    0.0     0.0   1.792E 01
25  34.40    5.00   37.20    7.75   40.00    5.00    0.0     0.0   3.736E 03
26  34.40   10.50   37.20    7.75   34.40    5.00    0.0     0.0   1.055E 02
27  40.00   10.50   37.20    7.75   34.40   10.50    0.0     0.0   1.149E 02
28  40.00    5.00   37.20    7.75   40.00   10.50    0.0     0.0   3.665E 03
29  40.00    5.00   42.80    7.75   45.60    5.00    0.0     0.0   3.729E 03
30  40.00   10.50   42.80    7.75   40.00    5.00    0.0     0.0   3.677E 03
31  45.60   10.50   42.80    7.75   40.00   10.50    0.0     0.0   2.057E 02
32  45.60    5.00   42.80    7.75   45.60   10.50    0.0     0.0   9.442E 01
33  34.40   10.50   37.20   13.25   40.00   10.50    0.0     0.0   2.154E 02
34  34.40   16.00   37.20   13.25   34.40   10.50    0.0     0.0   3.429E 01
35  40.00   16.00   37.20   13.25   34.40   16.00    0.0     0.0   1.618E 02
36  40.00   10.50   37.20   13.25   40.00   16.00    0.0     0.0   3.510E 03
37  40.00   10.50   42.80   13.25   45.60   10.50    0.0     0.0   5.213E 02
38  40.00   16.00   42.80   13.25   40.00   10.50    0.0     0.0   1.670E 02
39  45.60   16.00   42.80   13.25   40.00   16.00    0.0     0.0   5.044E 01
40  45.60   10.50   42.80   13.25   45.60   16.00    0.0     0.0   6.843E 01
41  10.00   16.00   14.69   21.00   19.38   16.00    0.0     0.0   5.673E 02
42  10.00   26.00   14.69   21.00   10.00   16.00    0.0     0.0   3.499E 03
43  19.38   26.00   14.69   21.00   10.00   26.00    0.0     0.0   2.575E 03
44  19.38   16.00   14.69   21.00   19.38   26.00    0.0     0.0   1.712E 02
45  19.38   16.00   24.06   21.00   28.75   16.00    0.0     0.0   1.027E 02
46  19.38   26.00   24.06   21.00   19.38   16.00    0.0     0.0   1.966E 02
47  28.75   26.00   24.06   21.00   19.38   26.00    0.0     0.0   1.564E 02
48  28.75   16.00   24.06   21.00   28.75   26.00    0.0     0.0   8.937E 01
49  28.75   16.00   33.44   21.00   38.13   16.00    0.0     0.0   3.430E 01
50  28.75   26.00   33.44   21.00   28.75   16.00    0.0     0.0   6.195E 01
51  38.13   26.00   33.44   21.00   28.75   26.00    0.0     0.0   2.934E 02
52  38.13   16.00   33.44   21.00   38.13   26.00    0.0     0.0   5.429E 02
53  38.13   16.00   42.81   21.00   47.50   16.00    0.0     0.0   6.144E 01
54  38.13   26.00   42.81   21.00   38.13   16.00    0.0     0.0   3.186E 02
55  47.50   26.00   42.81   21.00   38.13   26.00    0.0     0.0   2.804E 03
56  47.50   16.00   42.81   21.00   47.50   26.00    0.0     0.0   6.570E 02
57  10.00   26.00   28.75   28.50   47.50   26.00    0.0     0.0   1.044E 02
58  10.00   31.00   28.75   28.50   10.00   26.00    0.0     0.0   2.662E 03
59  47.50   31.00   28.75   28.50   10.00   31.00    0.0     0.0   9.149E 02
60  47.50   26.00   28.75   28.50   47.50   31.00    0.0     0.0   9.661E 02
```

6.13b Iron data

```
B          H
500.000    0.556
1000.000   0.800
1500.000   0.910
2000.000   1.060
3000.000   1.200
4000.000   1.380
5000.000   1.540
6000.000   1.710
7000.000   1.980
8000.000   2.140
9000.000   2.400
10000.000  2.780
11000.000  3.280
12000.000  4.000
13000.000  5.200
14000.000  7.100
15000.000  11.700
16000.000  24.600
17000.000  56.700
18000.000  108.000
19000.000  181.000
20000.000  300.000
21000.000  525.000
22000.000  1050.000
```

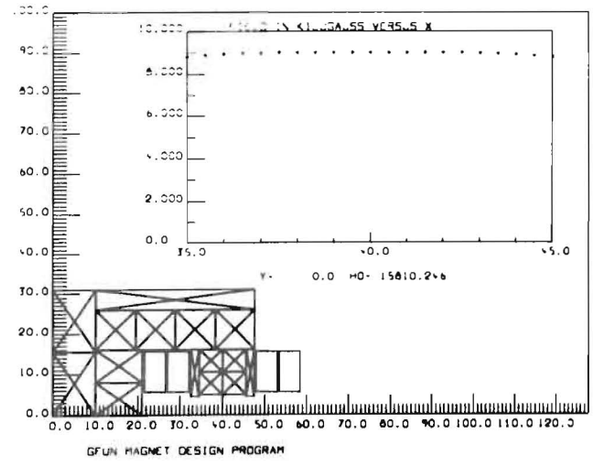


6.15 B-H data.

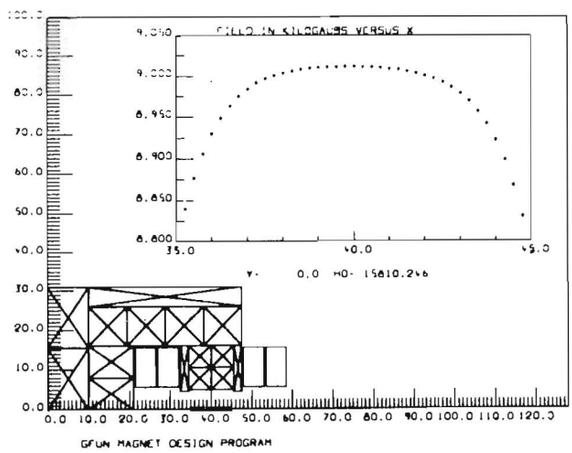
FIGURES 6.13 - 6.15 - C-MAGNET

X	Y	HX	HY	HT	DH/HO	PHI(I,J)
3.5000E 01	0.0	-3.0013E-12	8.7928E 03	8.7928E 03	-4.3865E 01	8.7928E 00
3.5500E 01	0.0	-5.9193E-13	8.8763E 03	8.8763E 03	-4.3858E 01	8.8763E 00
3.6000E 01	0.0	1.0674E-12	8.9301E 03	8.9301E 03	-4.3517E 01	8.9301E 00
3.6500E 01	0.0	1.2543E-12	8.9617E 03	8.9617E 03	-4.3305E 01	8.9617E 00
3.7000E 01	0.0	5.2118E-12	8.9841E 03	8.9841E 03	-4.3176E 01	8.9841E 00
3.7500E 01	0.0	-1.2679E-12	8.9963E 03	8.9963E 03	-4.3098E 01	8.9963E 00
3.8000E 01	0.0	-1.2276E-12	9.0036E 03	9.0036E 03	-4.3052E 01	9.0036E 00
3.8500E 01	0.0	-1.7950E-12	9.0078E 03	9.0078E 03	-4.3026E 01	9.0078E 00
3.9000E 01	0.0	2.7442E-12	9.0101E 03	9.0101E 03	-4.3011E 01	9.0101E 00
3.9500E 01	0.0	4.1797E-13	9.0112E 03	9.0112E 03	-4.3004E 01	9.0112E 00
4.0000E 01	0.0	-3.8626E-13	9.0113E 03	9.0113E 03	-4.3003E 01	9.0113E 00
4.0500E 01	0.0	1.1326E-12	9.0106E 03	9.0106E 03	-4.3008E 01	9.0106E 00
4.1000E 01	0.0	6.8622E-13	9.0089E 03	9.0089E 03	-4.3019E 01	9.0089E 00
4.1500E 01	0.0	1.8554E-12	9.0058E 03	9.0058E 03	-4.3038E 01	9.0058E 00
4.2000E 01	0.0	5.3436E-13	9.0007E 03	9.0007E 03	-4.3070E 01	9.0007E 00
4.2500E 01	0.0	4.7916E-13	8.9924E 03	8.9924E 03	-4.3123E 01	8.9924E 00
4.3000E 01	0.0	-1.3628E-12	8.9789E 03	8.9789E 03	-4.3208E 01	8.9789E 00
4.3500E 01	0.0	-1.4214E-12	8.9572E 03	8.9572E 03	-4.3346E 01	8.9572E 00
4.4000E 01	0.0	1.0927E-12	8.9224E 03	8.9224E 03	-4.3566E 01	8.9224E 00
4.4500E 01	0.0	-4.5134E-12	8.8677E 03	8.8677E 03	-4.3911E 01	8.8677E 00
4.5000E 01	0.0	-1.5518E-13	8.7841E 03	8.7841E 03	-4.4440E 01	8.7841E 00

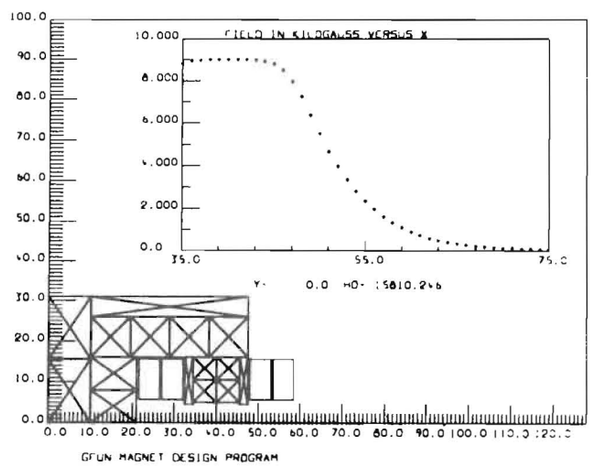
6.16 Print out of fields.



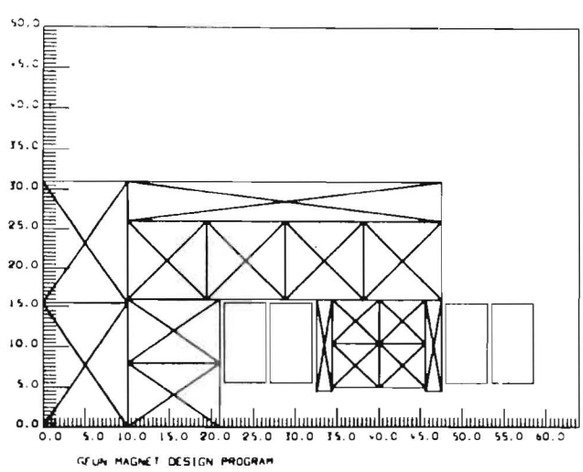
6.17 Plot of fields in mid plane.



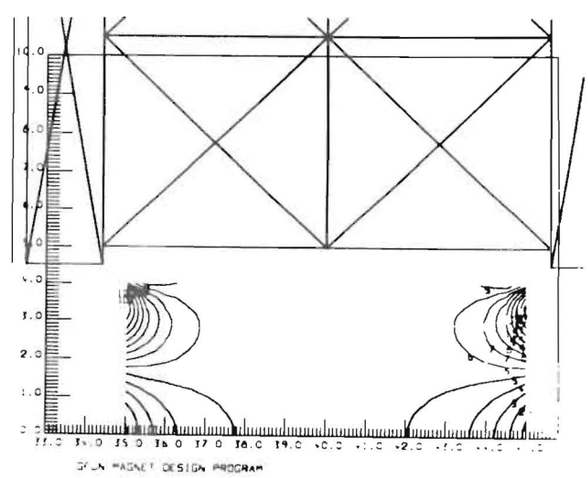
6.18 Enlarged scale - plot of fields in mid plane.



6.19 Plot of fringe fields.

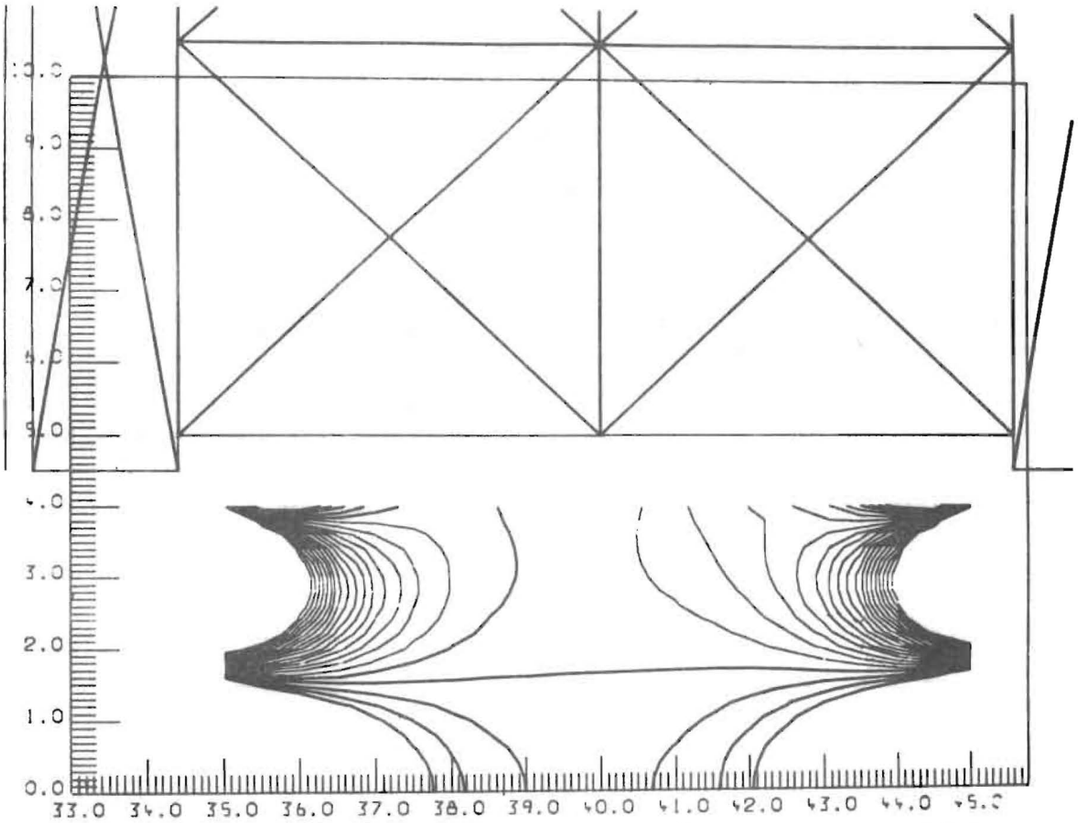


6.20 Field points for contour map.



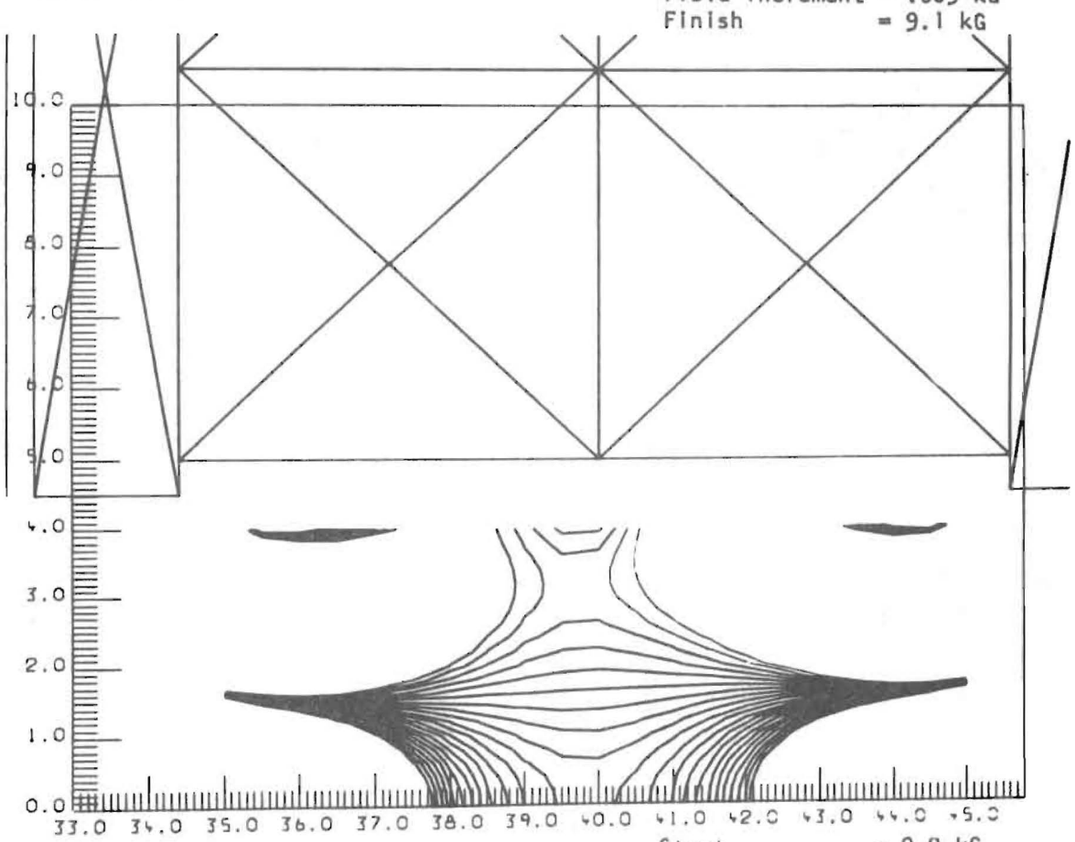
6.21 Contour map of fields.

FIGURES 6.16 - 6.21 - C-MAGNET FIELDS



6.22 GFUN MAGNET DESIGN PROGRAM CONTOUR MAP

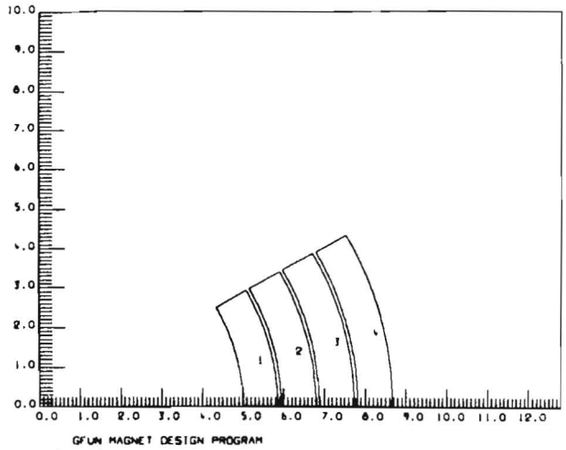
Start = 9.0 kG
Field increment = .005 kG
Finish = 9.1 kG



6.23 GFUN MAGNET DESIGN PROGRAM CONTOUR MAP

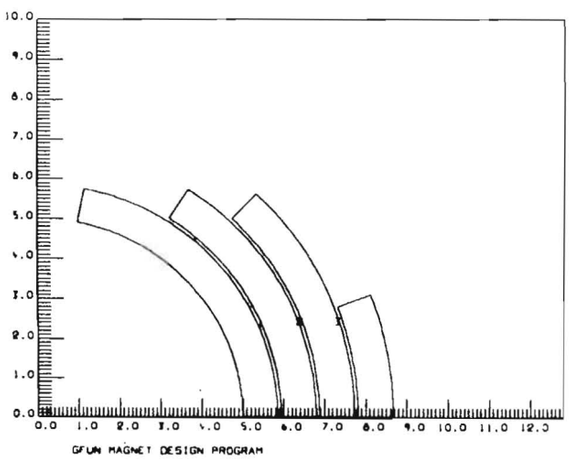
Start = 9.0 kG
Field increment = .001 kG
Finish = 9.02 kG

FIGURES 6.22 - 6.23 - C-MAGNET

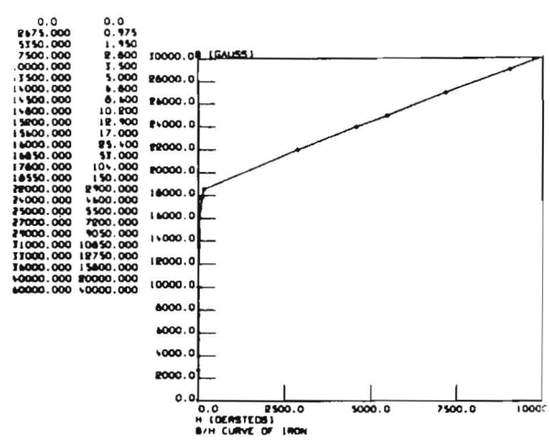


6.24 One quadrant of sector conductor elements at initial angle of 30°.

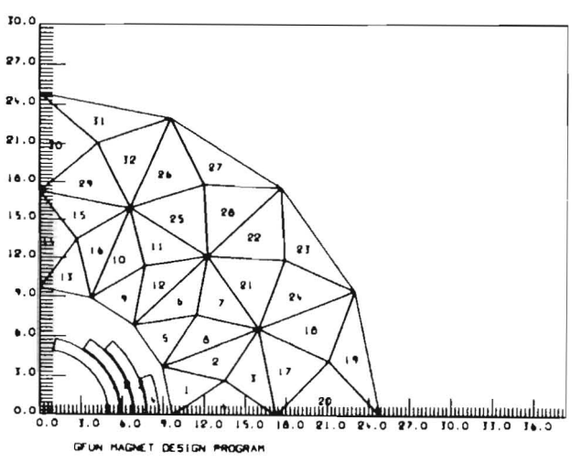
6.25 Optimised angles and field points.



6.26 Optimised conductors.



6.27 B-H data.

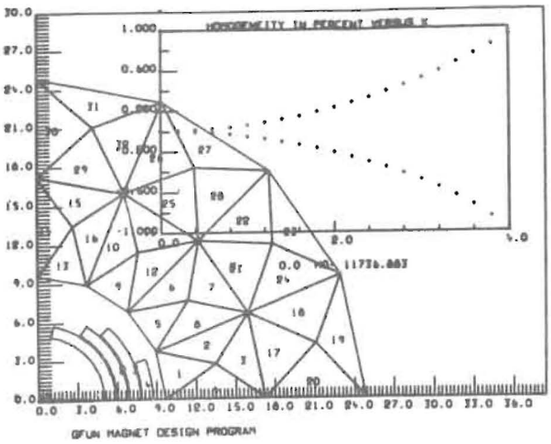


6.28 Iron yoke data entered.

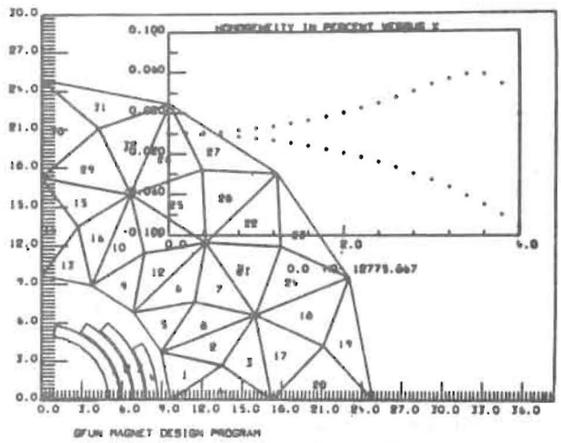
```
          0 ITERATIONS COMPLETED****EXTERNAL FIELD-      0.0
(CHI USED IS CHI CALCULATED
    1 ITERATIONS.  ELEMENT    1 CHANGED BY  15.39039
    2 ITERATIONS.  ELEMENT   13 CHANGED BY   3.49230
    3 ITERATIONS.  ELEMENT    9 CHANGED BY   1.25438
    4 ITERATIONS.  ELEMENT    1 CHANGED BY   0.77155
    5 ITERATIONS.  ELEMENT    1 CHANGED BY   0.70444
    6 ITERATIONS.  ELEMENT    1 CHANGED BY   0.63734
    7 ITERATIONS.  ELEMENT    1 CHANGED BY   0.57100
    8 ITERATIONS.  ELEMENT    1 CHANGED BY   0.51031
    9 ITERATIONS.  ELEMENT    1 CHANGED BY   0.45911
   10 ITERATIONS.  ELEMENT    1 CHANGED BY   0.40921
   11 ITERATIONS.  ELEMENT    1 CHANGED BY   0.36490
   12 ITERATIONS.  ELEMENT    1 CHANGED BY   0.32654
   13 ITERATIONS.  ELEMENT    1 CHANGED BY   0.29337
   14 ITERATIONS.  ELEMENT    1 CHANGED BY   0.26448
   15 ITERATIONS.  ELEMENT    1 CHANGED BY   0.23920
   16 ITERATIONS.  ELEMENT    1 CHANGED BY   0.21689
   17 ITERATIONS.  ELEMENT    1 CHANGED BY   0.19708
   18 ITERATIONS.  ELEMENT    1 CHANGED BY   0.17946
   19 ITERATIONS.  ELEMENT    1 CHANGED BY   0.16367
   20 ITERATIONS.  ELEMENT    1 CHANGED BY   0.14946
   21 ITERATIONS.  ELEMENT    1 CHANGED BY   0.13666
   22 ITERATIONS.  ELEMENT    1 CHANGED BY   0.12512
   23 ITERATIONS.  ELEMENT    1 CHANGED BY   0.11461
   24 ITERATIONS.  ELEMENT    1 CHANGED BY   0.10512
   25 ITERATIONS.  ELEMENT    1 CHANGED BY   0.09647
   26 ITERATIONS.  ELEMENT    1 CHANGED BY   0.08858
   27 ITERATIONS.  ELEMENT    1 CHANGED BY   0.08141
   28 ITERATIONS.  ELEMENT    1 CHANGED BY   0.07484
   29 ITERATIONS.  ELEMENT    1 CHANGED BY   0.06886
   30 ITERATIONS.  ELEMENT    1 CHANGED BY   0.06337
(EAS        1          DATA SET STORED
```

6.29 Magnetisation iterations.

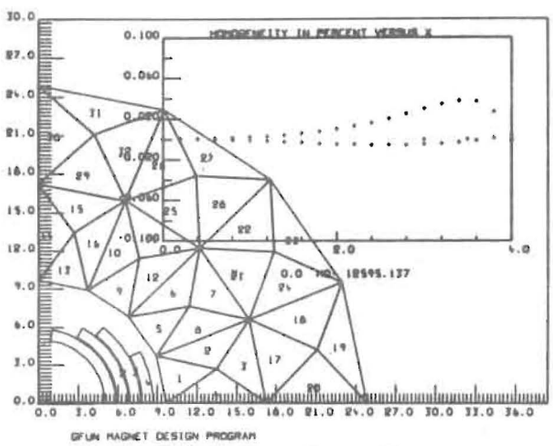
FIGURES 6.24 to 6.29 - OPTIMISED DIPOLE



6.30 Homogeneity plot before optimisation.



6.31 Homogeneity plot after initial optimisation.

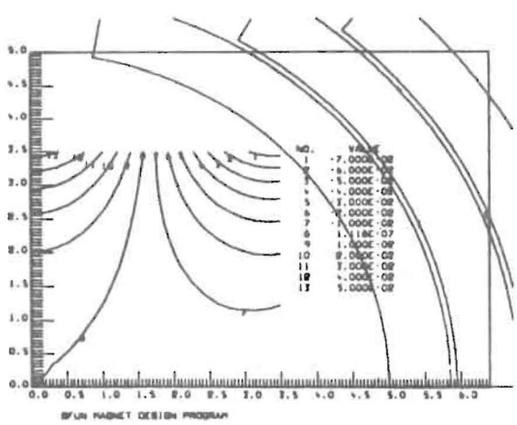


6.32 Homogeneity plot after final optimisation

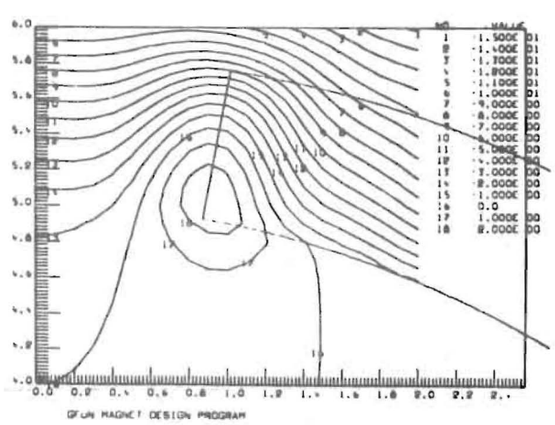
DDD HARMONICS ONLY,SERIES FITTED IS
BTHETA=A(N)*R/B**(N-U)*COS(N*THETA),B= 5.000

N	A(N) UNNORMALISED	A(N)
1	-12595.121094	1.000000
3	0.223149	-0.000443
5	-0.019921	0.000989
7	0.000494	-0.000613
9	-0.000008	0.000235
11	-0.000002	0.001657
13	0.000000	-0.003974
15	-0.000000	0.004923
17	0.000000	-0.004679
19	-0.000000	0.003761
21	0.000000	-0.002617
23	-0.000000	0.001532
25	0.000000	-0.000647
27	0.000000	-0.000064
29	-0.000000	0.000487

6.33 Table of Harmonic Structure of the final magnet.



6.34 Contours of homogeneity



6.35 Contours of fields in the conductors.

FIGURES 6.30 - 6.35 - OPTIMISED DIPOLE

7. OFF-LINE FACILITIES

7.1 MAGNETISATION - GETM

The maximum number of iron elements that can be processed by the on-line program is 32. For many problems 32 elements are not sufficient either to represent the geometry adequately or to attain high accuracy.

The number of elements can be extended up to a maximum of 100 by use of the off-line GETM facility. After constructing a named magnet data set by use of the on-line program the user can launch a batch job which will read the data set, compute the magnetisation, and rewrite the data set which now contains the values of the magnetisation. The on-line program can then be used to obtain the field values and graphs as before.

There are two versions of the off-line program available on the ELECTRIC JOB FILE:

a. GETM64 for up to 64 elements

b. GETM100 for up to 100 elements

i. To execute.

Type EXEC JB = GETM64 / GETM100 } parameters

ii. Parameters

ID		Default = Logged in ID
ACCT		No default
TIME		Default = 1-30, one minute thirty seconds
LINES	=	Thousands of Lines. Default = 5
USER	=	User name. Default = A.N.Other
CL	=	Class. Default = C (GETM64), = E(GETM100)
NAME	=	File name for which M is to be calculated. No default.
NGEN	=	Generation number of file. No default. For example, if you want to find the magnetisation for the problem stored on YOURFILE, 3 set NAME = YOURFILE, NGEN = 3
MPRI	=	Printing code. Default = 1

MPRI = 0 No printing

MPRI = 1 Print H in elements last three steps

MPRI = 2 Print matrix information

MPRI = 3 Print both

NIT = Number of iterations desired. Default = 1

NITD = Number of iterations done so far. Default = 0

IMU = Value of permeability to be used first iteration
Default = 10,000

HEXT = Magnitude of applied external field. Default = 0

iii. Operation

Reads data from the file (eg. YOURFILE,3), calculates the magnetisation for as many iterations as are specified, and creates an updated file on the disk data set, (eg. YOURFILE,4).

7.2 GFUNWUMP - OFF-LINE MUGWUMP VERSION

In some circumstances it may be desirable to run the entire program off-line. The package called GFUNWUMP combines the GFUN program with the facilities offered by the graphics retrieval system known as 'MUGWUMP'.[2] The user prepares a file in his directory containing the GFUN commands for his problem. The program is available on the ELECTRIC JOB FILE under the name GFUNWUMP(D2).

i. Example of command file for a simple split pair solenoid:

```
==>ENTE FL=SOLEN
==>FRAM XMAX=100, YMAX=100
==>QQ    (TEMPORARY,$$ EDITED IN LATER)
==>DRAW MATE=0,SHAP=0, SYMM=-3, R1=20, R2=40, H1=10, H2=50
==>J=1000
==>QQ    (TEMPORARY,$$ EDITED IN LATER)
==>GETB TYPE=3, NX=21, DX=1
==>END
==>$$
++>OK
==>MODI FL=SOLEN
==>$L:QQ
++>   2:QQ
==>$U   //
++>FIELD TXT  1, 2 :QQ
==>$E:$$
==>$L:QQ
++>   5:QQ
==>$E:$$
==>$$
++>OK
```

ii. To execute

EXEC JB = GFUNWUMP(D2), CO=SOLEN

iii. To retrieve

The standard MUGWUMP[2] procedure is used so the reults will be stored on the users ELECTRIC file under the name 'IDUNWUMP' where ID is the logged in identifler.

8. THEORETICAL BASIS OF THE MAGNETIC FIELD ALGORITHMS

8.1 GENERAL REMARKS

In GFUN, the fields from the currents and from the iron are both found by direct calculation. The magnetisation of the iron is first found by solving the integral equations it obeys. Then the field at any point, line, or region is calculated from the known currents and previously determined magnetisation. Because the magnetisation is found through an integral equation, only the regions occupied by iron enter the calculation. As a consequence, the method has two significant advantages over other methods, such as relaxation or finite-element techniques, which require the solution of partial-differential equations. First, as the direct calculation is performed only over the iron, fewer elements are required Second, problems with boundary conditions do not arise. The following paragraphs give first a description of how the field $\vec{H}$ is calculated when the currents and magnetisation are known, and then a description of how the magnetisation is found. The methods for obtaining the contribution to field from the current alone are well known and are adequately described elsewhere.

8.2 FINDING $\vec{H}$ FROM $\vec{M}$

In the presence of current-carrying conductors and magnetic materials, the magnetic field $\vec{H}$ can be written as the sum of a field $\vec{H}_c$ due to the currents and a field $\vec{H}_m$ due to the magnetisation of the iron. In SI units, the field due to the current is given by the volume integral:

$$\vec{H}_c = \frac{1}{4\pi} \int \frac{\vec{J} \times \vec{r}}{r^3} \, dV \qquad (1)$$

where $\vec{r}$ is the vector from the source point to the field point. In practice the current density $\vec{J}$ is specified, and the evaluation of $\vec{H}_c$ is straightforward. In two dimensions, the calculation is facilitated by using complex variables and the techniques described by R A Beth.[7]

The field $\vec{H}_m$ can be found from the scalar potential V_m:

$$H_m = -\text{grad } V_m$$

The scalar potential V_m is given by the volume integral:

$$V_m = \frac{1}{4\pi} \int \frac{\vec{M} \cdot \vec{r}}{r^3} \, dV \tag{2}$$

and thus $$H_m = \frac{-1}{4\pi} \text{grad} \int \frac{\vec{M} \cdot \vec{r}}{r^3} \, dV \tag{3}$$

Let the field point have coordinates (x, y, z); and the source point (x', y', z'), Then Equation (3) has x component

$$H_{mx} = -\frac{1}{4\pi} \frac{\partial}{\partial x} \iiint \frac{M'_x(x-x') + M'_y(y-y') + M'_z(z-z') \, dx' \, dy' \, dz'}{r^3} \tag{4}$$

with similar expressions for H_{my} and H_{mz}. In Equation (4)

$$r^2 = (x-x')^2 + (y-y')^2 + (z-z')^2.$$

When the differentiation shown in Equation (4) is carried out, and also the integration over z, the resulting equations are:

$$H_{mx} = \frac{1}{2\pi} \iint \{M'_x \, [(x-x')^2 - (y-y')^2] + 2M'_y \, (x-x')(y-y')\}/r^4 \, dx' \, dy'$$

$$\text{and } H_{my} = \frac{1}{2\pi} \iint \{2M'_x \, (x-x')(y-y') + M'_y[(y-y')^2 - (x-x')^2]\}/r^4 \, dx' \, dy' \tag{5}$$

where the integration is carried out over the iron region. Consider this region divided into N elements, over each of which the magnetisation is taken as constant. Also denote the field point by a. Then Equation (5) yields:

$$H_{mx}(a) = \sum_{b=1}^{N} C_{ax,bx} \, M_x(b) + C_{ax,by} \, M_y(b)$$

$$H_{my}(a) = \sum_{b=1}^{N} C_{ay,bx} \, M_x(b) + C_{ay,by} \, M_y(b) \tag{6}$$

where

$$C_{ax,bx} = \frac{1}{2\pi} \iint_{A_b} [(x-x')^2 - (y-y')^2]/r^4 \, dx' \, dy' \tag{7a}$$

$$C_{ax,by} = \frac{1}{2\pi} \iint_{A_b} 2(x-x') \, (y-y')/r^4 \, dx' \, dy' \tag{7b}$$

$$C_{ay,bx} = C_{ax,by} \tag{7c}$$

$$C_{ay,by} = -C_{ax,bx} \tag{7d}$$

The integrals in Equation (7) are performed by techniques analogous to those described by Beth, and the summation in Equation (6) can then be carried out.

8.3 DETERMINATION OF $\vec{M}$

Before Equation (6) can be evaluated, the magnetisation of each element must be known. However Equation (6) suggests a way it can be determined.

Consider the field point a to be the centroid of the element a. The total field at a is the sum of $\vec{H}_{ca}$ and $\vec{H}_{ma}$. Also the magnetisation is related to the field H through the magnetic susceptibility.

$\vec{M} = \chi\vec{H}$ with $\chi\ (H) = \mu(H)/\mu_o - 1$.

Combining these considerations yields:

$$H_x\ (a) = H_{cx}\ (a) + \sum_{b=1}^{N} C_{ax,bx}\chi_b H_x(b) + C_{ax,by}\chi_b\ H_y\ (b)$$

which can be rearranged to read

$$\sum_{b=1}^{N} (C_{ax,bx}\chi_b - \delta_{ab})\ H_x(b) + C_{ax,by}\chi_b H_y(b) = -\ H_{cx}(a) \tag{8a}$$

Similarly:

$$\sum_{b=1}^{N} C_{ay,bx}\chi_b H_x(b) + (C_{ay,by}\chi_b - \delta_{ab}) H_y(b) = - H_{cy}(a) \qquad (8b)$$

If the χ_b were known Equations (8) would be a system of 2N simultaneous linear equations, which could be solved for the H_{bx} and H_{by}. In practice Equations (8) are solved using some initial value of χ_b; then the values of H_{bx} and H_{by} are used to re-evaluate χ_b. The process is iterated until it converges.

8.4 SYMMETRY CONSIDERATIONS

If the magnet being calculated has a plane of symmetry, then only half the current and iron elements need enter the calculation. Likewise, if the magnet has two planes of symmetry, the calculation need include only the elements in one quadrant. The coefficients are calculated by Equation (7) for both the direct and reflected elements, and the results added or subtracted depending on whether the magnetisation component of the reflected element has the same or opposite sign as the component of the direct element.

Because the x and y components will have opposite reflection behaviour, the combined coefficients will not obey Equation (7c) and 7(d).

9. ACKNOWLEDGEMENTS

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