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# Ernest O. Lawrence Radiation Laboratory

MAGNETOSTATIC COMPUTER PROGRAM TRIM
OPERATIONS MANUAL

Of limited interest

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# MAGNETOSTATIC COMPUTER PROGRAM TRIM OPERATIONS MANUAL


John S. Colonias


December 28, 1965

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## ABSTRACT

This paper describes the capabilities and limitations of the magnetostatic computer program TRIM, with particular emphasis on the usage of this program, preparation of input data, and general utilization. The program is a general two-dimensional magnetostatic code capable of solving mathematical models of two-dimensional magnets.

## I. INTRODUCTION

This paper describes in detail the information required to operate TRIM, a magnetostatic computer program. The program is written in machine language "FAP" and it is operational for the IBM 7094 computer system, under the 7094 monitor system.

Our purpose is to furnish detailed information on the capabilities and limitations of this program, on preparation of input data, and on operating characteristics that will ensure the proper use of this versatile code. Parts of this paper have been taken from an unpublished paper by F. Andrews of LRL, Livermore with his permission.

## II. PROGRAM CAPABILITIES

TRIM is a general two-dimensional magnetostatic code capable of solving mathematical models of two-dimensional magnets.

It uses a mesh composed of irregular triangles in which the mesh lines may be distorted to conform to irregular interfaces and boundaries. Additional features include

(a) Variable triangular mesh of about 1600 points is used; may have many regions.

(b) Conductor sides and all points at the interface lie on mesh lines.

(c) No geometrical restriction is imposed. Any shape of magnet may be considered.

(d) Symmetry about the median plane is not required. Therefore both symmetric and asymmetric magnets may be investigated.

(e) Any current distribution may be considered.

(f) Several different kinds of iron may be used in the same magnet; voids or currents within the iron may be used.

## III. PROGRAM DESCRIPTION

The program is divided into two major parts, the mesh generator, GENMON, and the proper trim code, TRIMON. Both these parts will be examined with sufficient detail to ensure proper understanding.

### A. GENMON

The purpose of the generator is to construct the irregular triangle mesh.[1,2] It does this by interpolating on specified (by input) boundary points, locating the internal mesh points of each region by a pseudo-equipotential method, and by assigning regional properties to each triangle.

The generator performs these functions by using four subroutines--INPT, HSTAR, SETTLE, and GENOR--in a manner described in Ref. 1. This part of the code has been written in machine language, and it is operational under the IBM 7094 monitor system.

### B. TRIMON

Once the irregular triangular mesh has been generated, TRIMON[3] takes over and calculates the vector potentials and magnetic induction in any plane arrangement of iron, air, and conductors. From these quantities the gradient, flux density, and energy are derived and printed.

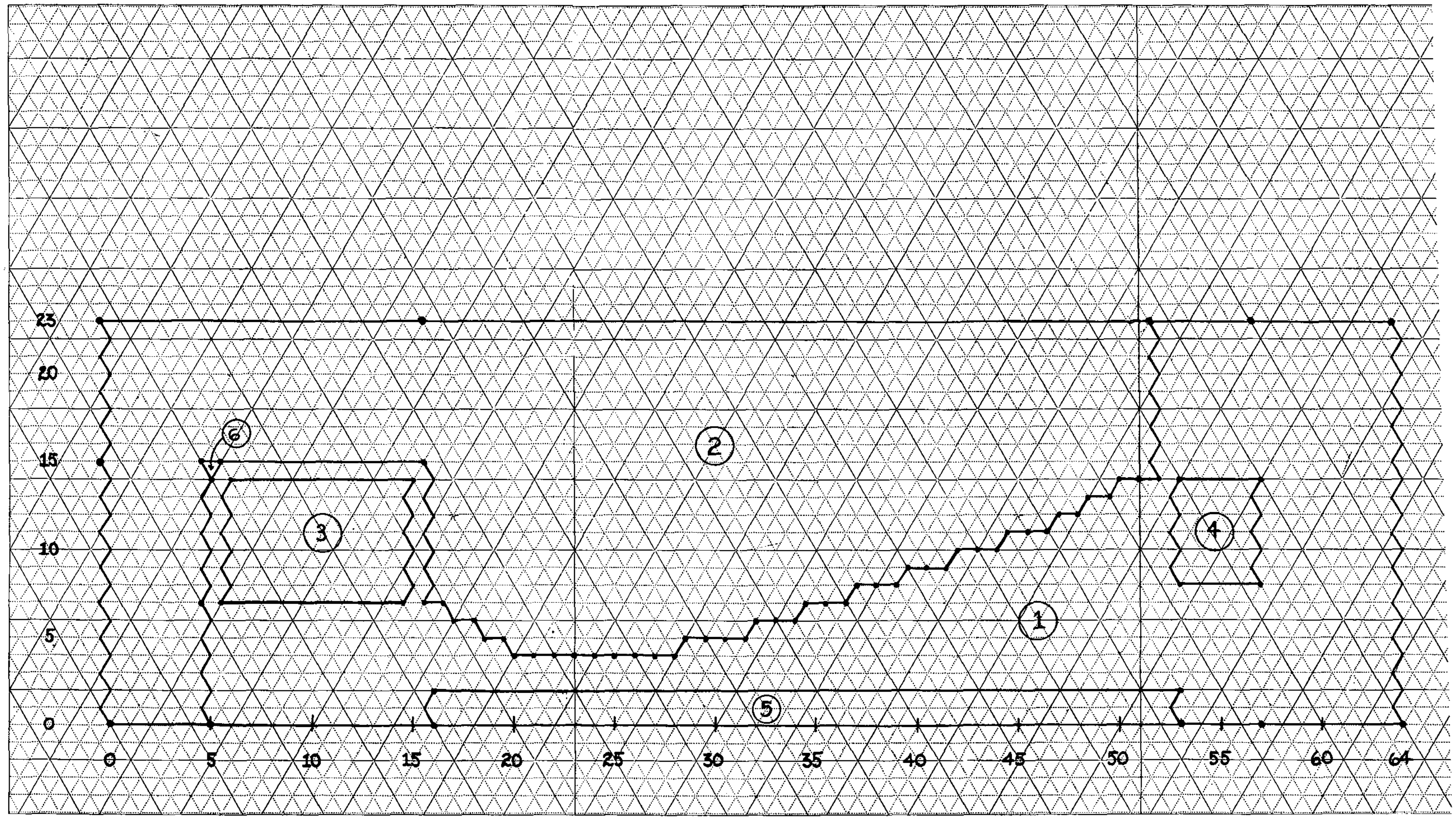
TRIMON has been written in machine language and is operated under the IBM 7094 monitor system. Instructions for operation are given in Appendix II.[4]

## IV. PREPARATION OF INPUT DATA

The preparation of data requires considerable effort and attention. It is suggested that the instructions given below, as well as the sample input data included, be studied carefully before any attempt is made to prepare input data.

As a first step, draw a diagram which shows the problem as pictured in terms of mesh coordinates. We call this a "logical diagram" because the rows are those followed by the program in performing the relaxation process. Figures 1, 2, 3, and 4 show such logical diagrams for various magnet configurations. The physical dimensions for these magnets are shown in Figs. 5, 6, 7, and 8. For purposes of illustation, Fig. 1 will be used as an example to show the process required in accurately recording input data.

Now since the logical diagram is nothing but a transformation between the mesh indices and physical space, the next logical step is to transform the mesh indices to the corresponding geometrical coordinates of the magnet and record them as input. However, since the magnet consists of




MUB-11612

Fig. 1. Logical diagram for CERN C magnet.

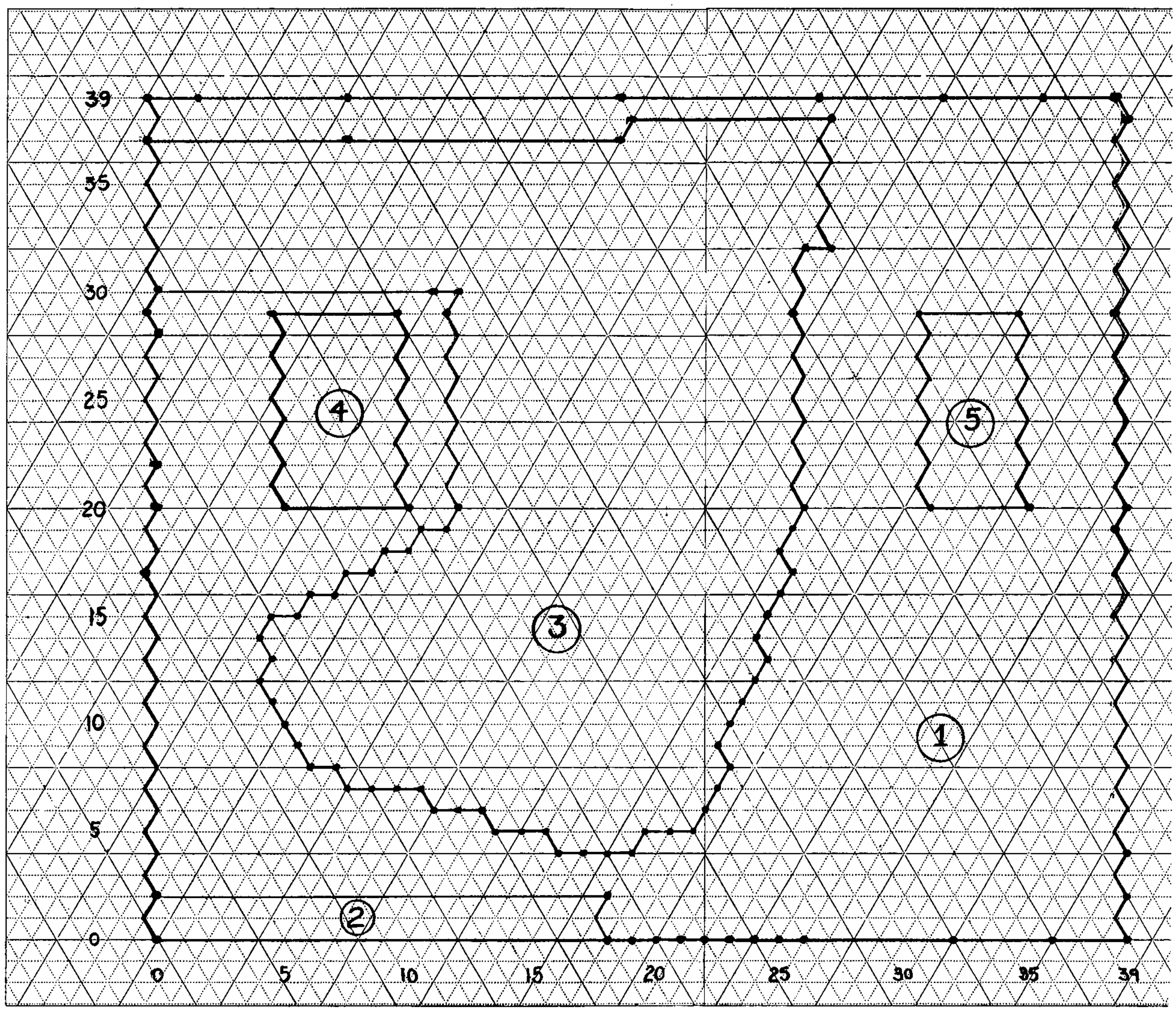
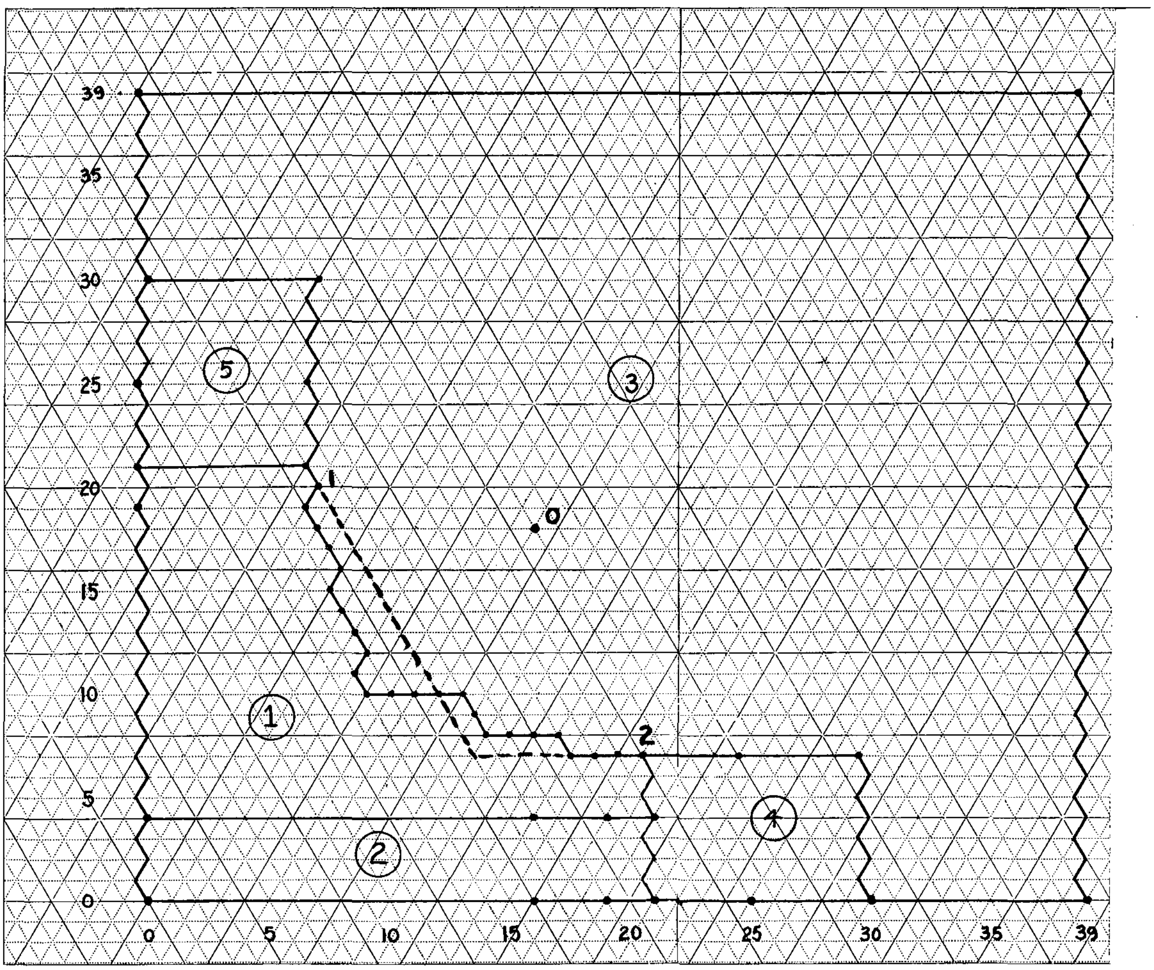
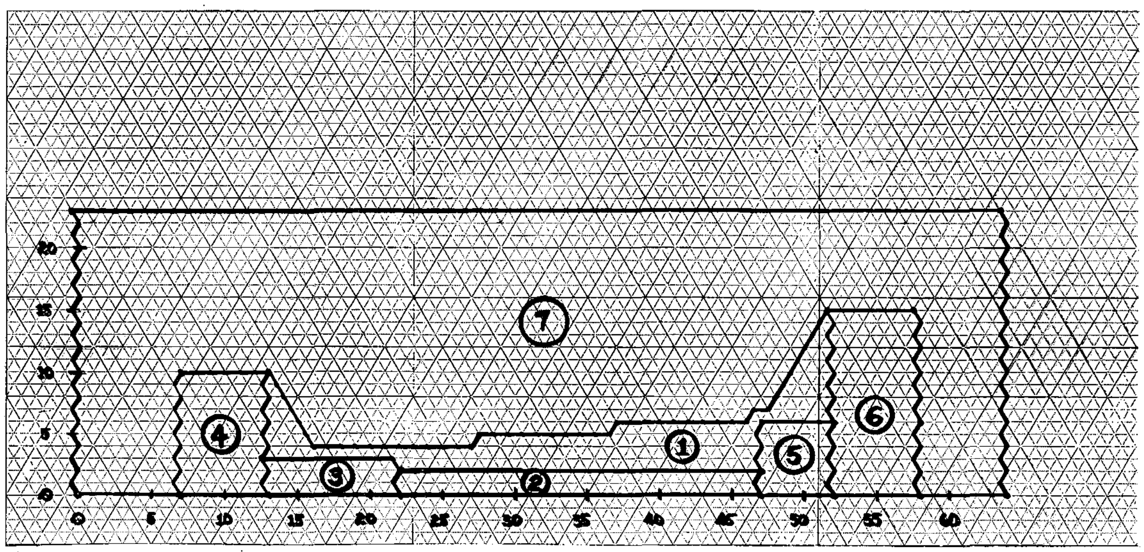



Fig. 2. Logical diagram for COLLINS quadrupole.



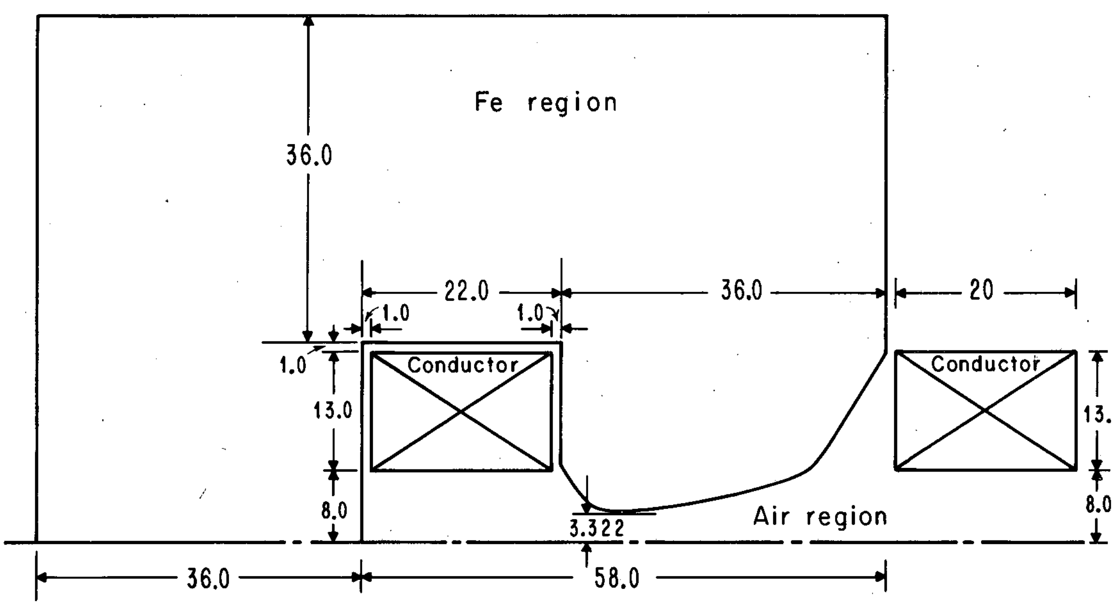

MUB 11533

Fig. 3. Logical diagram for quadrupole magnet.



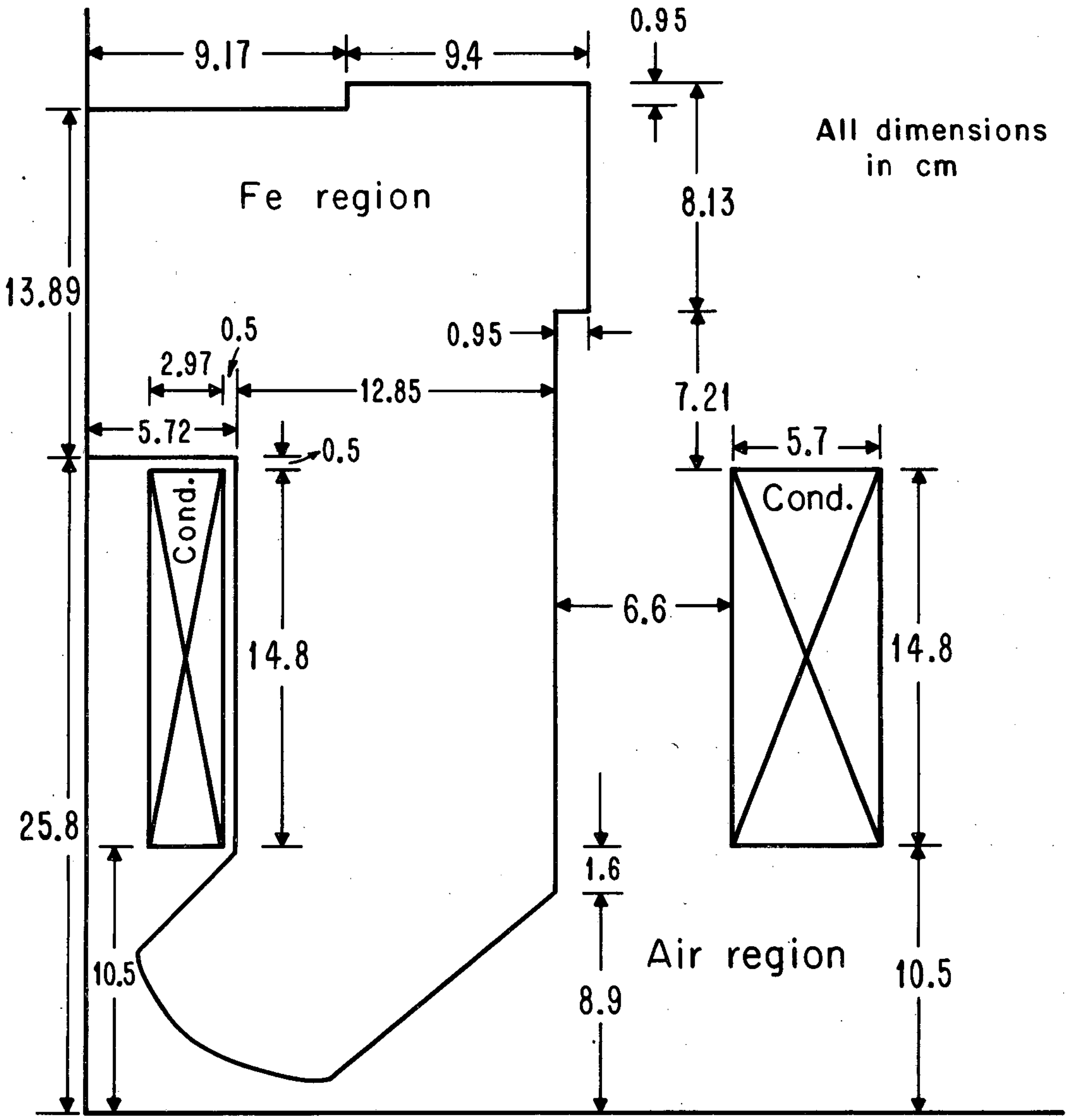

MUB-11534

Fig. 4. Logical diagram for a conformal "H" magnet.




MUB 11921

Fig. 5. CERN PS magnet. Dimensions are in centimeters.

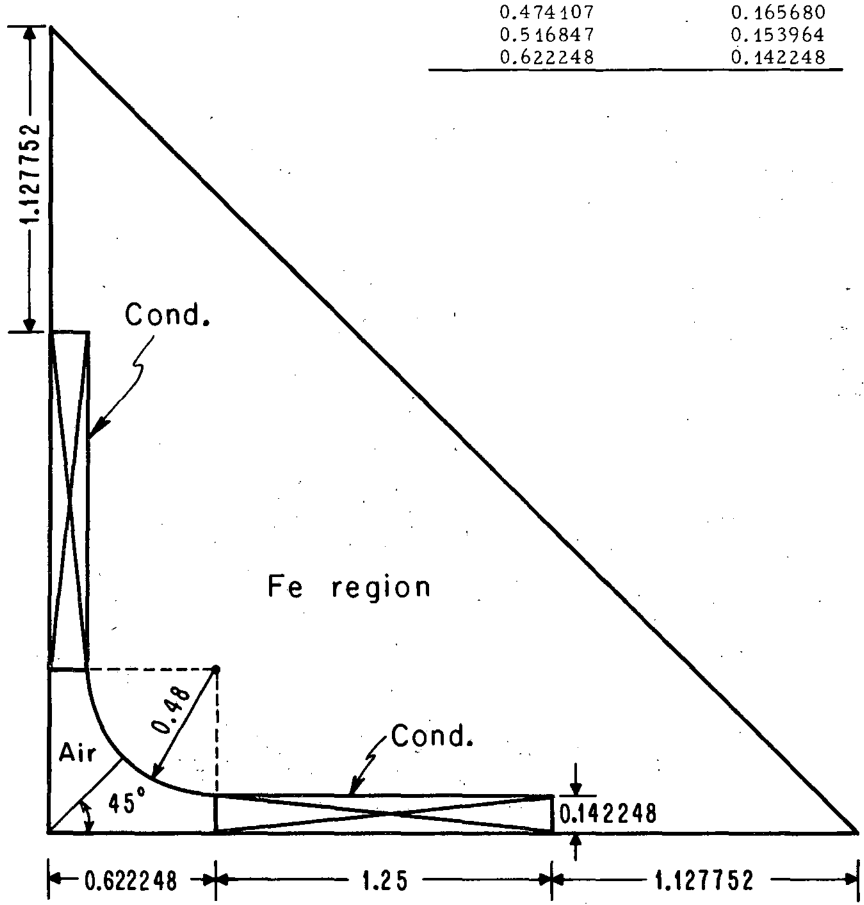



MUB-11919

Fig. 6 "COLLINS" quadrupole profile. Dimensions in centimeters.

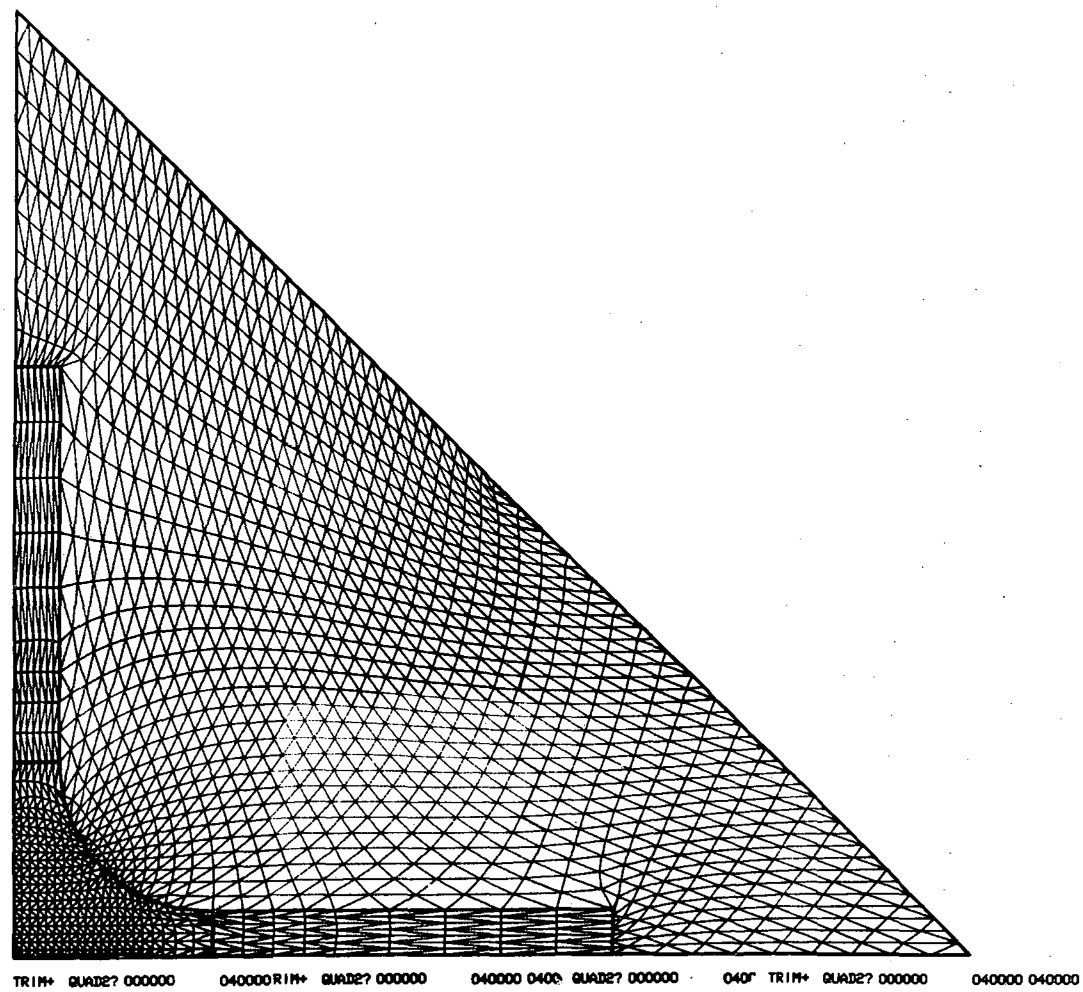
Pole face coordinates

| X (inches) | Y (inches) | X (inches) | Y (inches) |
|---|---|---|---|
| 0.142248 | 0.622248 | 0.259408 | 0.308006 |
| 0.153964 | 0.516847 | 0.282843 | 0.282843 |
| 0.165680 | 0.474107 | 0.294968 | 0.271124 |
| 0.177396 | 0.441950 | 0.308006 | 0.259408 |
| 0.189112 | 0.415386 | 0.322068 | 0.247692 |
| 0.200828 | 0.392451 | 0.337302 | 0.235976 |
| 0.212544 | 0.372165 | 0.353911 | 0.224260 |
| 0.224260 | 0.353911 | 0.372165 | 0.212544 |
| 0.235976 | 0.337302 | 0.392451 | 0.200828 |
| 0.247692 | 0.322068 | 0.415386 | 0.189112 |
| | | 0.441950 | 0.177396 |
| | | 0.474107 | 0.165680 |
| | | 0.516847 | 0.153964 |
| | | 0.622248 | 0.142248 |




MUB-11920

Fig. 7(a) Quadrupole magnet layout. Dimensions are in inches.




MUB-11958

Fig. 7(b) Generated mesh of the quadrupole magnet shown in Fig. 7.

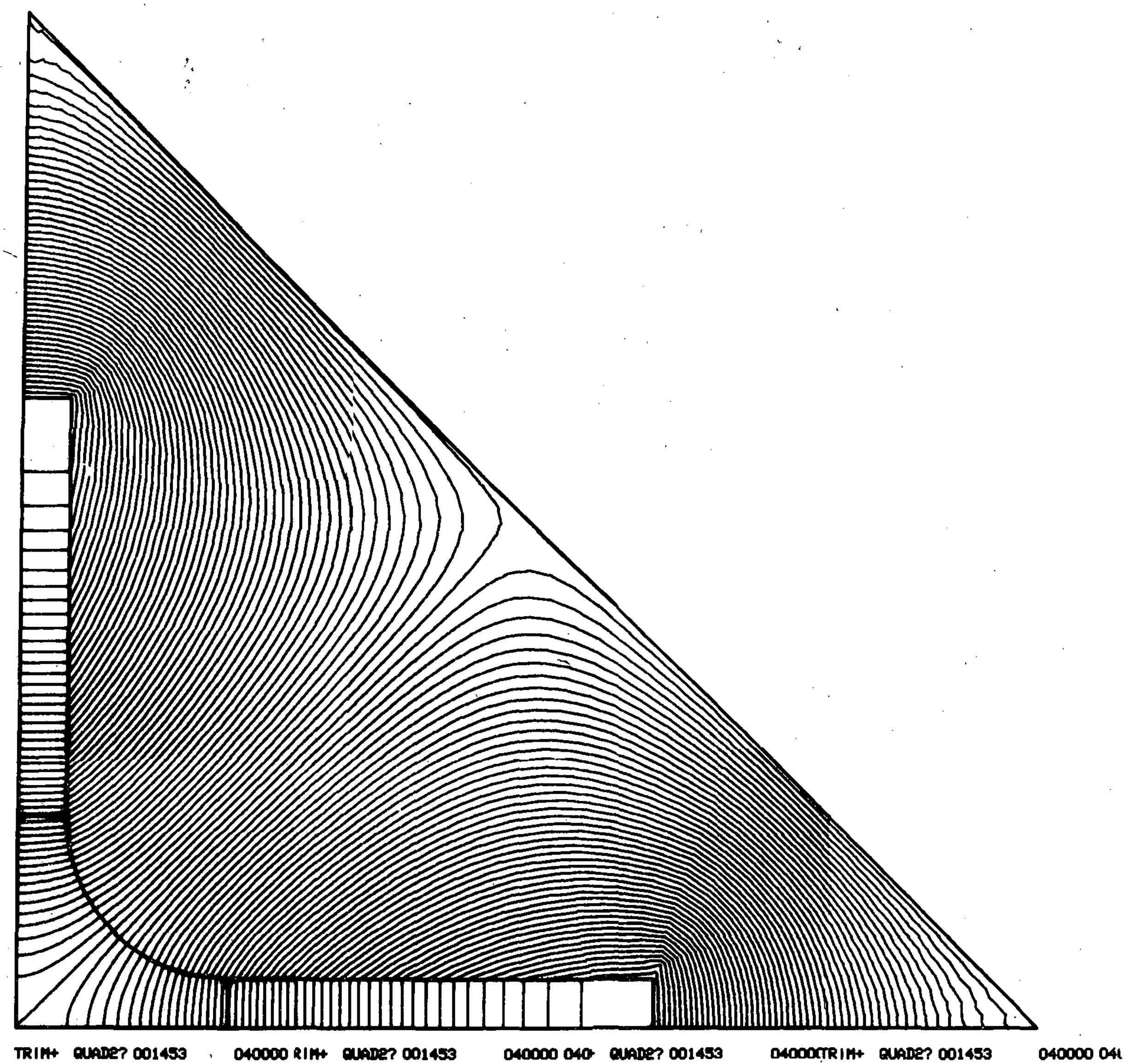
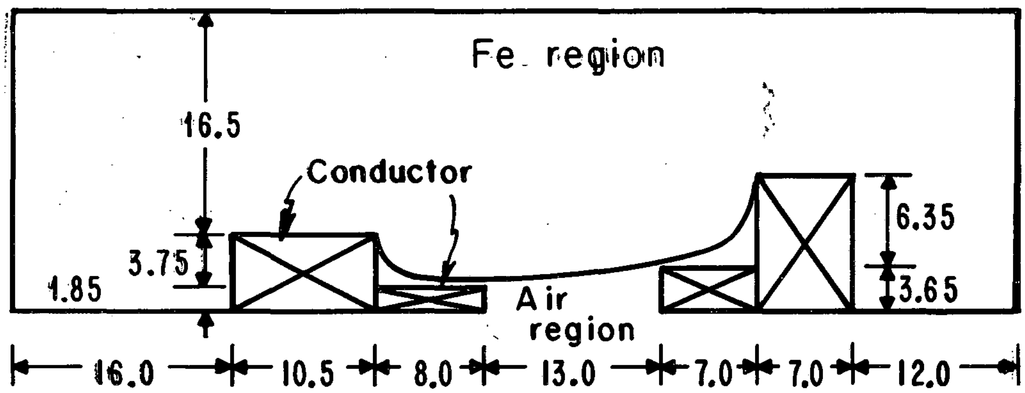



Fig. 7(c) CRT plot of flux distribution for the quadrupole magnet shown in Fig. 7.




Pole face coordinates

| X (cm) | Y (cm) | X (cm) | Y (cm) | X (cm) | Y (cm) |
|---|---|---|---|---|---|
| 26.5 | 5.5 | 37.0 | 2.47637 | 44.5 | 3.23410 |
| 26.72 | 4.36 | 37.5 | 2.51567 | 45.0 | 3.30029 |
| 27.02 | 3.76 | 38.0 | 2.55622 | 45.5 | 3.37166 |
| 27.32 | 3.36 | 38.5 | 2.59811 | 46.0 | 3.444916 |
| 27.72 | 2.95 | 39.0 | 2.6414 | 46.5 | 3.52143 |
| 28.72 | 2.33 | 39.5 | 2.68615 | 47.0 | 3.60142 |
| 29.22 | 2.07 | 40.0 | 2.73245 | 48.0 | 3.77283 |
| 30.42 | 2.055 | 40.5 | 2.78037 | 49.0 | 3.96136 |
| 31.00 | 2.08548 | 41.0 | 2.83 | 50.0 | 4.16973 |
| 32.0 | 2.14183 | 41.5 | 2.88143 | 51.42 | 4.54 |
| 33.0 | 2.20130 | 42.0 | 2.93477 | 52.42 | 5.06 |
| 34.5 | 2.29698 | 42.25 | 2.96298 | 53.12 | 5.77 |
| 35.0 | 2.33075 | 42.5 | 2.99012 | 53.57 | 6.56 |
| 35.5 | 2.36553 | 43.0 | 3.04759 | 54.03 | 8.28 |
| 36.0 | 2.4136 | 43.5 | 3.10732 | 54.4 | 10.00 |
| 36.5 | 2.43829 | 44.0 | 3.16944 | | |

MUB 11922

Fig. 8. Conformal "H" magnet. Dimensions are in cm.

different materials (i. e., iron, conductors, and air), the concept of "regions" is introduced, which besides its usefulness in separating various materials, also serves as an agent in forcing regular or otherwise special zoning in any part of the problem. Figures 1 and 2 show these distinct regions.

GENMON superposes the regions in the order they are given in the input. Thus, all or part of a region which has once been specified may be respecified later in the input. This can save a great deal of writing in the input. It can also lead to trouble, since one may easily force mesh lines to cross one another in impossible ways, producing triangles of negative area. Such crossing can be avoided by twice recording points that belong in the boundary of two regions with a common border. This will become more obvious as the input data for the test problems are analyzed.

To recapitulate the procedure involved in preparing input data:

1. Draw a logical diagram of the problem.
2. Separate it into regions.
3. Record geometrical coordinates to correspond with each mesh line specified.

Note that the limited number of points available necessitates the careful distribution of mesh lines throughout the mesh. Namely, the experimenter should decide a priori which regions are most important and where the most accuracy is desired, and disperse the available points accordingly.

In magnet calculations for accelerator design, one is interested in the magnetic field and its gradient on the median plane, particularly within the limits of the vacuum chamber; therefore, one expects that the zoning in this region is very important. With this in mind, Figs. 1, 2, 3, and 4 were zoned.

Now we may proceed to the actual recording of the mesh coordinates and their corresponding physical dimensions.

For each geometrical point the data are recorded in the following sequence:

a. IY - index for vertical mesh line
b. IX - index for horizontal mesh line
c. Y - coordinate of physical dimension for this point
d. X - coordinate of physical dimension for this point.

Therefore, referring to Fig. 1 for the logical diagram and to Fig. 5 for the actual dimensions, we see that the coordinates of the four points of region 3 are:

| Point | IY-mesh | IX-mesh | Y-dimension (cm) | X-dimension (cm) |
|---|---|---|---|---|
| 1st | 7 | 6 | 8 | 37 |
| 2nd | 14 | 6 | 21 | 37 |
| 3rd | 14 | 15 | 21 | 57 |
| 4th | 7 | 15 | 8 | 57 |

Here it was assumed that the points were taken clockwise; however, the direction is immaterial. Also notice that in closing the region the first point need not be specified again.

The points shown above are entered in a data sheet as shown below:

```
LOD 7A 6+ 8+37
  D 7A15+ 8+57
  D14A15+21+57
  D14A 6+21+37
```

where LO = Indicator that this is the first point in this region. As used here, A and D are peculiar to the card-reading routine on the IBM 7094 and indicate numbers to be placed in the address and decrement parts of words, respectively.

After the region points have been specified, they are accompanied by two more cards--one having region constants, as will be shown, and one having -OM, which is a sentinel indicating the end of the region boundary points.

Information necessary for the region card is the following:

1. Region number
2. Flag describing the material of the region as follows:
   1 = air
   2 = iron
   or
   3 = iron of specified permeability, different from the preceding
3. Region current in ampere-turns (NI)
4. Region current density in ampere-turns/cm$^2$
5. Sentinel indicating the type of triangles into which the region should be zoned, as follows:
   1 = equilateral triangles
   2 = right triangles

Note: If region NI is specified, insert zero for $NI/CM^2$, and vice versa. The region information is recorded in the following manner.

LOA3D1-40250+OA2

1 2 3 4 5

Circled numbers identify the region constants as shown above. LO is the same indicator specifying the beginning of a new region. The completed region, therefore, will appear as shown below.

```
LOA3D1-40250+OA2          Region Card
LOD 7A 6+ 8+37
   D14A 6+21+37           Region boundary points
   D14A15+21+57
   D 7A15+ 8+57
   -OM                    Region termination card
```

In the same fashion all regions are recorded and punched on IBM cards. Any column may be used from 1 to 72. The X and Y dimension coordinates need not be integers; they may be entered as floating point numbers (i. e., 3.0, 4.375, etc.) or with exponents (i. e., 3. E10, 4.6E-3 etc.).

In problems where the pole face is described by circular arc, use may be made of the special arc routine incorporated in the program. This routine allows the user to specify only the end points and the center of the arc; the other points are interpolated equally in the program.

Use of this routine may be made as follows

1. Prepare the logical diagram as before for purposes of illustration, Fig. 3 may be used with the logical figure modified as shown by the dotted line. This modification is necessary since a circular arc must be described logically by two straight lines.
2. Next enter the data for arc as follows:

   For point 1 (Fig. 3) enter

   D20A7 + 0.622248+0.142248.

   For point 2

   D7A2ϕ+0.142248+0.622248.

   For point O (the logical center of the arc)

   D 18 A 16.

The last quantity necessary is the logical angle $\theta$, which is the ratio of the triangle sides along logical slant to the sum of triangles of arc, or

$$\theta = \frac{\text{No. of triangles in slant line}}{\Sigma \text{ triangles in arc}}$$

For this example $\theta = \frac{13}{20} = 0.65$.

3. These data are recorded as follows:

$$\underbrace{\odot\ 100000}_{\text{Flag}}\underbrace{\text{D20A7+0.622248+0.142248}}_{\text{First point}}\ \underbrace{\text{D18A 16}}_{\text{Logical center}} +\ \underbrace{0.65}_{\theta}\ \underbrace{\text{+D7A21+0.142248+0.622248}}_{\text{second point}}$$

The final assembled data deck will consist of the following cards:

1. Problem constants (for details see next paragraph)
2. Region card
3. Subsequent region boundary points (any number of cards)
4. End of region card
5. Region card (for next region)
6. Subsequent region boundary points, etc., until all regions have been exhausted (any number of cards).

Z

Z End of problem cards

Z

End of file card.

A complete listing for the sample problems shown in Figs. 1 and 2 appears in Appendices I. a and I. b.

## V. DESCRIPTION OF PROGRAM CONSTANTS

It was mentioned in the previous paragraph that the first card of the assembled deck consists of program constants. A detailed description of these parameters is shown in Table I. These constants give the experimenter additional flexibility with which to process a variety of problems, including symmetric and asymmetric magnets.

Table I. Program constants (see also Ref. 5).

| Code no. | Description | Standard values of program constants |
|---|---|---|
| L0 | Mesh parity. Provisions have been made in the program so that rows can run in either the X or the Y direction. Here -1 parity indicates where the rows run in the X direction and +1 parity the Y direction. | |
| L1 | N, number of regions to be specified in input (integer in address). Any number of regions may be specified. | |
| L2 | L, maximum value of row index, i. e., number of rows of triangles (integer in address). | |
| L3 | K, maximum value of "column" index (integer in address). | |
| L4 | Mode: if<br>L4 = -2, air solution only<br>L4 = 0, all points<br>L4 = -1, air solution followed by iron solution<br>If set is equal to -1, it will be changed to zero after convergence in air and relaxation continued to converge over all points. | |
| L5 | $\rho_{air}$: Over-convergence factor for points surrounded entirely by air (floating point). | 1.94 |
| L6 | $\rho_{Fe}$: Fraction of new couplings to use in Fe (floating point). | 0.0625 |
| L7 | Convergence criterion: value of residual at which the problem has converged sufficiently (floating point) | $10^{-6}$ |
| L8 | Dimension conversion factor. If dimension in cm, insert 0 or 1. If in inches, insert 2.54 cm/in. etc. (floating point) | 0 |

Table 1 (cont.)

| Code No. | Description | Standard values of program constants |
|---|---|---|
| L9 | Interval between monitor prints (integer in address) | 20 |
| L10 | Interval between dumps (integer in address) | 10,000 |
| L11, L12, L13 | Not used | |
| L14 $\eta_{max}$ | Constants having to do with recalculation of over-convergence factor | 1 |
| L15 $\beta$ | | 0.5 |
| L16 $\omega_0$ | | 0.005 |
| L17 $r_{max}$ | | 15 |
| L18 | Reciprocal of laminations stacking factor: Factor by which to multiply B in order to correct for presence of nonferrous material between laminations of magnet (floating point). | 1 |
| L19 | Asymmetry sentinel; for problems without median plane symmetry, equals the value 1 which corresponds to the median plane (integer in address). | 0 |
| L20 | Boundary condition sentinel for K=0, L=0. When L20 $\neq$ 0, the logical boundaries K = 0 and L = 0 will both be treated as reflecting surfaces. Note that this input has the effect opposite to that of L19. | |

This completes the program constants that may be changed at the discretion of the experimenter. In the absence of specific input of any of the program constants specified above, the program will assume that the standard values prevail.

The complete listing of the input data for the logical diagrams appearing in Figs. 1 and 2 includes some of the program constants mentioned above (see Appendix I).

FORTRAN MONITOR

| PLOTRL | 4289-01 | J.S. COLONIAS | 5408 | | A |
|---|---|---|---|---|---|
| PROBLEM NAME | ACCOUNT NUMBER | NAME OF PROGRAMMER | EXTENSION | DATE & TIME SUBMITTED | MACHINE |

MAX. RUN TIME IN MINUTES 5

COMPILE (CIRCLE) EXECUTE ASSEMBLE

MAX. OUTPUT ON TAPE A3: ~ 100 lines

CRT Print 1 Copies/Frame ID JC

COMMENTS &/OR OTHER INSTRUCTIONS:

| EXTRA TAPE USAGE | CHANNEL B | UNIT 7 | | CHANNEL | UNIT | | CHANNEL | UNIT | | CHANNEL | UNIT | | CHANNEL | UNIT | | CHANNEL | UNIT | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (CIRCLE) Input Output (X)utility | I | O | X | I | O | X | I | O | X | I | O | X | I | O | X | I | O | X |
| DENSITY (circle) | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 |
| IDENTIFICATION | CERN I NI=40,250 DEC. 10,1965 | | | | | | | | | | | | | | | | | |
| Print (CIRCLE) Save | P | S | | P | S | | P | S | | P | S | | P | S | | P | S | |

IBM L56216 RL-2868 (REV. 9/62)

FORTRAN MONITOR

| GENMON | 4289-01 | J.S. COLONIAS | 5408 | | |
|---|---|---|---|---|---|
| PROBLEM NAME | ACCOUNT NUMBER | NAME OF PROGRAMMER | EXTENSION | DATE & TIME SUBMITTED | MACHINE |

MAX. RUN TIME IN MINUTES 5

COMPILE (CIRCLE) EXECUTE ASSEMBLE

MAX. OUTPUT ON TAPE A3: ~ 100 lines

CRT Print Copies/Frame ID

COMMENTS &/OR OTHER INSTRUCTIONS:

| EXTRA TAPE USAGE | CHANNEL B | UNIT 7 | | CHANNEL | UNIT | | CHANNEL | UNIT | | CHANNEL | UNIT | | CHANNEL | UNIT | | CHANNEL | UNIT | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (CIRCLE) Input Output (X)utility | I | O | X | I | O | X | I | O | X | I | O | X | I | O | X | I | O | X |
| DENSITY (circle) | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 | 200 | 556 | 800 |
| IDENTIFICATION | CERN I NI=40,250 DEC. 10,1965 | | | | | | | | | | | | | | | | | |
| Print (CIRCLE) Save | P | S | | P | S | | P | S | | P | S | | P | S | | P | S | |

IBM L56216 RL-2868 (REV. 9/62)

Fig. 9. Sample instruction card.

Fig. 10. Sample job card

## VI. OPERATING INSTRUCTIONS

The versatility of this program in handling various types of problems is not simple. In this paragraph we list operating instructions for a variety of situations that might arise during the course of experimenting with this program.[4] Remember that there are two sets of distinct mesh sizes - one with dimensions 39 by 39 or less, and the other with dimensions 23 by 64 or less. The first number denotes the maximum Y-mesh size and the second the maximum X-mesh size. It is assumed that once the experimenter has chosen the proper mesh size, the following instructions are applicable:

a. Prepare input data as specified in the previous paragraphs.

b. Once all data cards have been punched, assemble the decks and submit them to computer room.

The final assembled deck should consist of the following:

1. Instruction card (see sample in Fig. 9)
2. ID card
3. GENMON deck (mesh generator program cards)
4. One card with * DATA
5. Data ID card (see sample in Fig. 10)
6. End of file card.

c. If the mesh generation was completed successfully, you will receive a tape B7 which constitutes the input to TRIMON. If generation was not successful, correct errors and resubmit.

d. Once you have received a B7 tape you may run TRIMON, following the instructions described in the attached supplementary note.[5] See also Appendix II.

One of the important features of TRIM is the ability of the program which causes the resulting triangular mesh to be displayed on a CRT, thus allowing the experimenter to observe the quality of the triangles and modify the distribution of mesh, if necessary.

To obtain a CRT plot, one must have generated the problem and obtained a B7 tape as described in Sec. V. The necessary information that the plot cards must contain and the order in which they appear on a data card are:

a. Y-axis scale

b. X-axis scale

c. Y origin

d. X origin (the lower left corner of the plot)

e. Zero (not used at this time)

f. The number of contours to plot (integer)

g. The number of dumps to skip

h. A flag to denote whether mesh lines are desired or not

If flag = 0, no mesh lines

If flag = 1, mesh lines

i. Flag indicating end of plot card

As an example,

```
L0 + 10 + 10 + 5 + 7 + 0A40A2A1Y
     a    b    c   d   ef  g h i
```

Here the scale would be 10 cm in both directions; the Y origin would be 5 cm, the X origin would be 7 cm, 40 contour lines would be plotted, plotting will begin from dump No. 2, and mesh lines are desired. These data may be punched anywhere from columns 1 through 72 of a standard IBM card. (Blank spaces will be ignored.)

There is no limit to the number of plot cards that may be used. All cards will be read and plotted sequentially. The deck of plot cards must be ended with a card containing a Z.

Once the cards have been prepared, the final deck to be submitted to the computer must include the following:

1. Job card (see sample on Fig. 11)
2. Monitor CRT deck (binary deck). Be careful to choose the proper deck with your choice depending on whether the maximum dimensions of your problem are 39 by 39 or 23 by 64.
   This deck will begin with *PLEASE HANG. Continue by specifying the name of the problem tape, i.e., *PLEASE HANG CERN1.
3. One card with *DATA
4. CRT plot cards (as specified in the preceding paragraph)
5. End-of-file card.
6. Submit this deck for execution accompanied with the B7 input tape (obtained from GENMON).

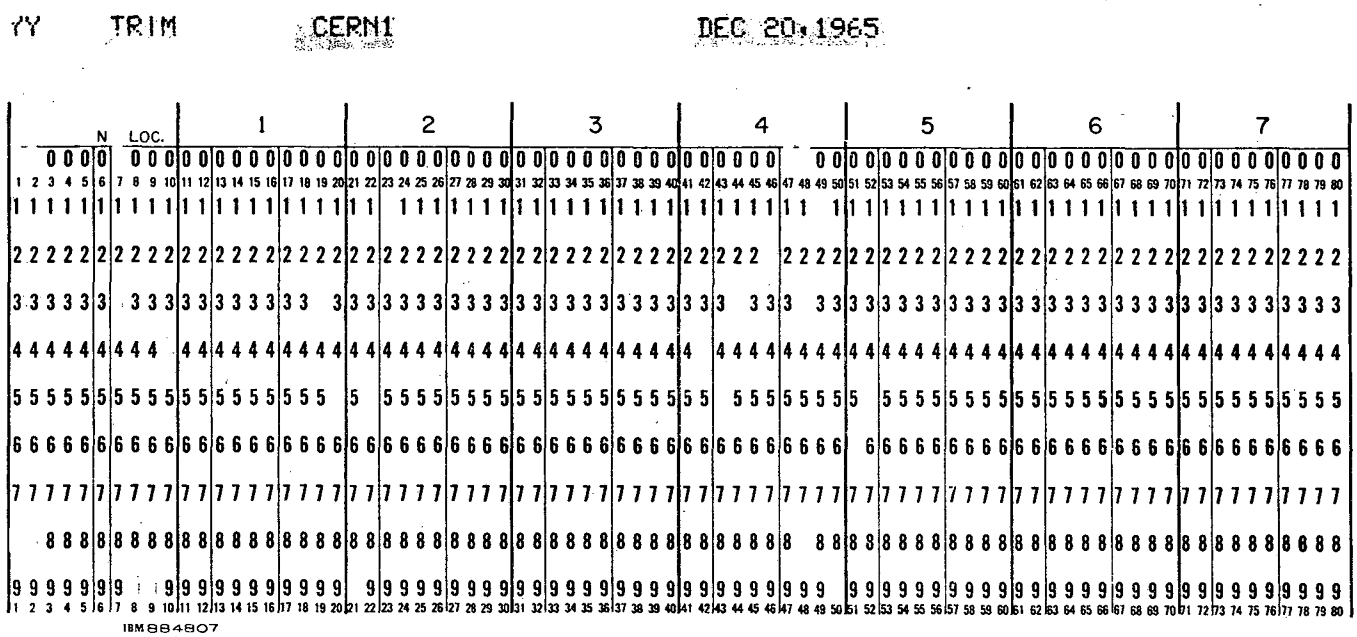



Fig. 11. Sample job card for CRT plot.

# VII. OUTPUT DESCRIPTION

## A. GENMON

A sample of a successful GENMON output is shown in Appendix IV. a. It is self explanatory in the sense that it describes all regions as they are processed, the material, and the type of triangles.

The QF and PF show respectively the number of iterations and the times that they converged in sequence. Five sequential convergences constitute successful generation, which is indicated by GENERATION COMPLETED.

Appendix IV. b shows an unsuccessful generation. Even though it ends with GENERATION COMPLETED, the appearance of negative triangles necessitates checking the input data at the location specified and correcting the error. However, if input data seem to be correct, obtain CRT plots which will reveal the error.

## B. TRIMON

All printing is done OFF LINE. Observe that both GENMON and TRIMON use numbers which are in excess -50 exponential notation (i. e., 52.15 = 2.15, 54.3765 = 3,765. 49.3 = 0.03). A sample of this output is shown in Appendix V.

The four-line monitoring printout consists of:

1. $\rho_{air}$ (under the word TRIM)
2. The cycle count (under the problem name)
3. The minimum and maximum values of the vector potential "A" in the mesh, and the maximum change that has occurred in A on the last cycle.
4. The maximum value of B in the iron
5. The "length" of the vector
6. The ratio of residuals from the last two cycles
7. The residual from the last cycle
8. The residual divided by the length
9. The value of p of the couplings.

If the Fe points are being skipped, i. e., mode < 0, there will appear next to TRIM the word AIR, and likewise if AIR points are being skipped, the word FE will appear.

When the convergence criterion is satisfied, the cycle counter Q and the number of successive times it has been satisfied P are printed out. After P reaches 5, a dump is made onto the B7, the dump number is printed out, a current print and a monitor print are forced, and finally an edited version of the median plane quantities is printed. The five columns to this printout are:

1. (labelled XB) These are the average X positions of successive pairs of mesh points, viz., the location at which the first difference of A is evaluated.
2. (labelled B) The Y component of the magnetic flux density.
3. (labelled XBX) The X positions of the mesh points, at which A and its second difference are evaluated.
4. (labelled A) The value of A
5. (labelled BX) The second X derivate of A (gradient).

In the asymmetrical version of the code, a column between A and the second derivative gives the X component of the field, naturally evaluated at the mesh points.

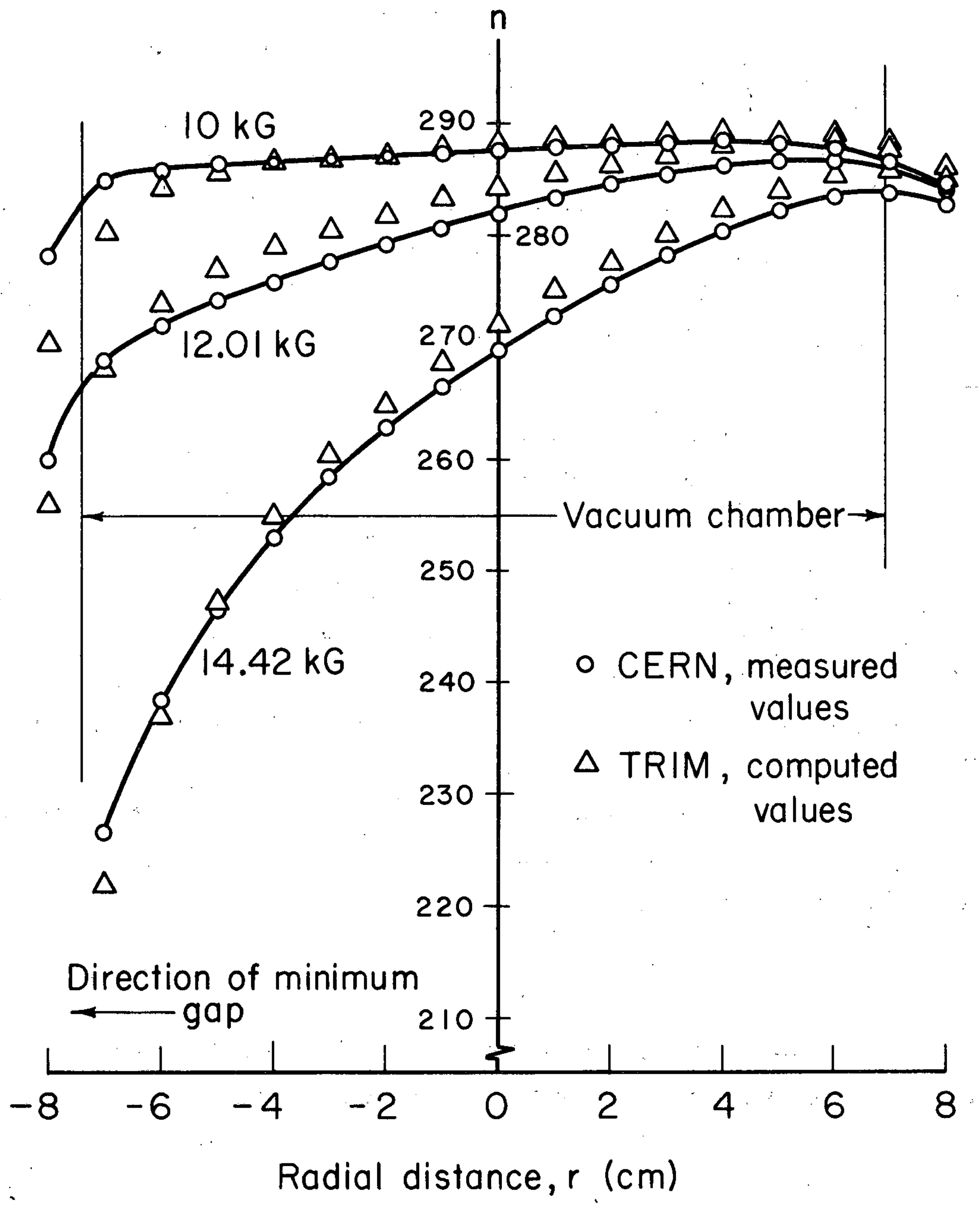
## VIII. GENERAL REMARKS

The information presented in this paper should enable an experimenter to profitably exploit the potentialities of this program. Some experimentation with CRT plots of generated problems will convince the user that TRIM is definitely zone dependent, that is, zoning plays a very important role in the quality of the obtained results. The ability to predict a priori the quality of the generated mesh depends on the experience of the user.

Our experience[6] with this program has shown that, for most geometries, right triangles in air and equilateral triangles in iron give the best results. Also to obtain the best accuracy, it is essential to force regular zoning in the region of the median plane under the pole tip.

Finally, remember that the whole mesh consists of only 1,600 points, and do not expect to obtain results better than about 1% within the useful region of the vacuum chamber.

Figure 12 shows the percent deviation from measured data obtained from the CERN magnet which has been used as an example throughout this paper. As can be seen, the maximum error is ≈ 1% within the limits of the vacuum chamber.




MUB-7472

Fig. 12. Computed and measured gradients for the CERN PS magnet.

The approximate time required to run a problem utilizing the full mesh is about 30 minutes on the IBM 7094. This includes mesh generation, air, and iron solutions.

## IX. AUXILIARY PROGRAMS

### A. BEDIT

This program is used to print out the absolute value of flux density (B) at each upper and lower triangle of the generated mesh (B7 output tape).

Sample input data for the CERN magnet are shown in Appendix III. In Columns 1 and 2 of a standard IBM card, put the value of the beginning X-coordinate. In Columns 3 and 4, put the value of the beginning Y-coordinate.

The printout consists of a flux-density map. The flux-density signs in iron is indicated by negative signs.

### B. TRED

This program was written with the intention of improving the quality of the existing edit routine.[7] It edits the last dump on a TRIM dump tape (B7); it obtains partial derivatives of vector potentials by a least-squares method, using harmonic polynomials through first, second, or third degree. It edits at vertices or at triangle centers.

The output consists of a tabular listing of all pertinent quantities (vector potential, field, and gradient) for either the median plane only, or throughout the mesh.

## ACKNOWLEDGMENTS

I am grateful to Fred Andrews and Dr. Alan Winslow, who wrote the computer program, for their help and suggestions.

PROGRAMMER J. S. COLONIAS

PROBLEM CERN 1 EXT.

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# FORTRAN

APPENDIX I.a

Input data for CERN1 magnet

FORTRAN STATEMENT

```
YY    TRIM      CERN1
L0-1A6A23A64 L4-1. L7+1.0E-7 L18+1.0416 Y
  LOA1D1+0+0A2
  LOD0A0+0+0
    D0A5+0+36 D0A16+0+58 D0A53+0+95 D0A57+0+115 D0A64+0+150
    D23A64+58+150 D23A57+58+115 D23A52+58+94 D23A16+58+58
    D23A0+58+0 D15A0+22+0
-OM
  LOA2D2+0+0A1
  LOD0A0+0+0
    D0A5+0+36 D7A5+7.4+36 D14A5+21.3+36 D15A5+22+36 D15A6+22+38
    D15A16+22+58 D7A16+8.526+58 D7A17+6.976+59 D6A17+6.2+59.5
    D6A18+4.94+60.5 D5A19+4.06+61.5 D5A20+3.769+62 D4A20+3.536+62.5
    D4A21+3.369+63 D4A22+3.322+64 D4A23+3.414+65 D4A24+3.522+66
    D4A25+3.639+67 D4A26+3.762+68 D4A27+3.882+69 D4A28+4.010+70
    D5A29+4.147+71 D5A30+4.293+72 D5A31+4.451+73 D5A32+4.620+74
    D6A32+4.709+74.5 D6A33+4.802+75 D6A34+5+76 D7A35+5.215+77
    D7A36+5.448+78 D7A37+5.704+79 D8A37+5.813+79.4 D8A38+5.985+80
    D8A39+6.295+81 D9A40+6.639+82 D9A41+7.023+83.0 D9A42+7.454+84
    D10A42+7.642+84.4 D10A43+7.941+85 D10A44+8.497+86 D11A45+10.028+87
    D11A46+11.596+88 D11A47+13.163+89 D12A47+13.9465+89.5
    D12A48+14.730+90 D13A49+16.298+91 D13A50+17.865+92 D
    D14A50+18.649+92.5 D14A51+19.433+93 D14A52+21.0+94 D23A52+58+94
    D23A16+58+58 D23A0+58+0 D15A0+22+0
-OM
  LOA3D1-40250+0A2
  LOD7A6+8+37
```

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PROGRAMMER ______ DATE ______

PROBLEM ______ EXT. ______ PAGE 2 of 2

# FORTRAN

C ← FOR COMMENT | STATEMENT NUMBER | CONT | FORTRAN STATEMENT

```
    D14A6+21+37
    D14A15+21+57
    D7A15+8+57
-OM
  LOA4D1+40250+0A2
  LOD8A53+8+95
    D14A53+21+95
    D14A57+21+115
    D8A57+8+115
-OM
  LOA5D1+0+0A2
  LODoA16+0+58
    D2A16+2+58
    D2A53+2+95
    D0A53+0+95
-OM
  LOA6D1+0+0A2
  LOD14A5+21.3+36
    D15A5+22+36
    D15A6+22+38
-OM
Z
Z
Z
```

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PROGRAMMER J. S. COLONIAS

PROBLEM COLQB EXT.

DATE DEC. 10/65

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# FORTRAN

APPENDIX I.b

Input data for Collins Quadrupole

FORTRAN STATEMENT

```
YY    TRIM        COLQB
L0-1ASA39A39 L4-1.L18+1.0526 L20+1 L7+1.0E-7  Y
L0A101+0+0A2
     L0D0A0+0+0
       D 0A18+ 0  + 9.0
       D 0A19+ 0  + 9.25
       D 0A20+ 0  +10.0
       D 0A21+ 0  +10.7
       D 0A22+ 0  +11.5
       D 0A23+ 0  +12.5
       D 0A24+ 0  +14.5
       D 0A25+ 0  +16.5
       D 0A26+ 0  +19.0
       D 0A32+ 0  +35.0
       D 0A36+ 0  +41.0
       D 0A39+ 0  +47.0
       D 2A39+ 1.0+47.0
       D 4A39+ 1.5+47.0
       D19A39+ 9.0+47.0
       D20A39+10.5+47.0
       D29A39+25.0+47.0
       D38A39+40.0+47.0
       D39A39+41.0+47.0
       D39A36+41.0+41.0
       D39A32+41.0+35.0
       D39A27+41.0+20.0
       D39A19+41.0+10.0
```

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PROGRAMMER ______ PROBLEM ______ EXT. ______

# FORTRAN

DATE ______

PAGE 2 OF 3

C ← FOR COMMENT | STATEMENT NUMBER | CONT | FORTRAN STATEMENT

```
      D39A 8+41.0+ 5.7
      D39A 2+41.0+ 0.5
      D39A 0+41.0+ 0
      D37A 0+39.69+ 0
      D30A 0+ 25.8+ 0
      D29A 0+25.3+ 0
      D28A 0+24.0+ 0
      D22A 0+12.0+ 0
      D20A 0+10.0+ 0
      D17A 0+ 8.5+ 0
      D  2A 0+ 1.0+ 0
-OM
LOA2D1+0+0A2
      D0A0+0+0 D0A18+0+9 D2A18+1+9 D2A0+1+0
-OM
LOA3D2+0+0A1
    LOD30A0+25.8+0 D30A11+25.8+5.5 D30A12+25.8+5.72 D29A12+25.3+5.72
     D20A12+10.2+5.72 D19A12+10.1+5.6 D19A11+10.0+5.5 D18A10+9.5+5
     D18A9+9.25+4.75 D17A9+9.0+4.5 D17A8+8.5+4.0 D16A7+8.0+3.5
     D16A6+7.75+3.25 D15A6+7.5+3.0 D15A5+7.0+2.5 D14A4+6.48+1.905
     D13A5+6.097742+1.905 D12A4+5.8081+2.0 D11A5+5.162755+2.25
     D10A5+4.646480+2.5 D9A6+4.224072+2.75 D8A6+3.872066+3.0
     D8A7+3.318914+3.5 D7A8+2.904050+4.0 D7A9+2.581377+4.5
     D7A10+2.323240+5.0 D7A11+2.212609+5.25 D6A11+2.112036+5.5
     D6A12+1.936033+6.0 D6A13+1.787107+6.50 D5A14+1.659457+7.0
     D5A15+1.548826+7.5 D5A16+1.498864+7.75 D4A16+1.452025+8.0
     D4A17+1.366611+8.5 D4A18+1.290688+9.00 D4A19+1.290688+9.44882
```

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PROGRAMMER ______ DATE ______

PROBLEM ______ EXT. ______

# FORTRAN



C ← FOR COMMENT | STATEMENT NUMBER | CONT | FORTRAN STATEMENT

```
    D5A20+1.75+10.0 D5A21+2.18+10.5 D5A22+3.0+11.5 D6A22+3.41667+12.0
    D7A23+3.83334+12.5 D8A23+4.25+13.0 D9A23+4.66668+13.5
    D10A23+5.08335+14. D11A24+5.5+14.5 D12A24+5.91669+15.0
    D13A25+6.33336+15.5 D14A24+6.75+16.0 D15A25+7.1667+16.5
    D16A25+7.58337+17.0 D17A26+8.0+17.5 D18A25+8.4167+18.0
    D19A26+8.8334+18.55 D20A26+10.5+18.55 D29A26+25.3+18.55
    D32A26+31.6+18.55 D32A27+31.6+19.5 D38A27+40.64+19.5
    D38A19+40.64+10.1 D37A19+39.69+10.1 D37A8+39.69+5.7 D37A0+39.69+0
-OM
LOA4D1-15037+0A2
  LOD20A5+10.5+2.23
    D20A10+10.5+5.22
    D29A10+25.3+5.22
    D29A 5+25.3+2.23
-OM
LOA5D1+15037+0A2
  LOD20A31+10.5+25.15
    D20A35+10.5+30.85
    D29A35+25.3+30.85
    D29A31+25.3+25.25
-OM
Z
Z
Z
```

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## II. TRIMON

(Supplementary writeup to TRIM Magnetostatic Program)

Identification: TRIMON (A modified version of the on-line code called "TRIM").

Author: Bobby Powell November 8, 1965

Machine language: Fortran II and FAP

Basic machine required: IBM 7090 or 7094

Purpose: To enable TRIM to run as an off-line operation (i.e., to run TRIM under the FORTRAN monitor system) and to include the asymmetric case.

Usage: (a) Start the problem

1. Obtain a source or object deck for the code TRIMON and a 'dump tape'. **

**Note: There are two versions of this code (1) KMAX = 39 and LMAX = 39, and (2) KMAX = 64 and LMAX = 24. To create versions other than those mentioned change KMAX to the derived value, under the condition that (KMAX)(LMAX) $\leq$ 1600 points.

(a) The object deck to be submitted should consist of the following:

(1) An '* ID' card

(2) '* XEQ' card

(3) The Fortran calling program

(4) A copy of the Fortran subroutine '$EXIT' (2 binary cards)

(5) A copy of the Fortran subroutine '$TES' (2 binary cards)

(6) The program called TRIMON

(7) '* DATA' card

(8) An end of file card

(b) The dump tape to be submitted is obtained from the code called GENMON (the monitor version of the mesh generator) and is used as input to TRIMON. *

* Note: The input (dump tape) tape is B7.

Termination:

(1) Automatic termination:
Automatic termination occurs if and only if the convergence criterion has been satisfied in both Air and Iron (see Note 2).

(2) Forced termination:
Forced termination is the procedure used to terminate a problem after a specified time limit (where time limit refers to the maximum run time on the computer).

(a) Sense switch #1 is used for forced termination.
(b) When sense switch #1 is down, the following sequence of events occurs:

1. The information necessary to restart the problem from the last iteration is written on the dump tape (B7).
2. An edit similar to the final one is obtained.
3. Transfer of control over the machine to the FORTRAN monitor system is executed (see Note 2).

Note 2: Tape B7 (the dump tape) should be saved.

Restart procedures:

(1) The restart procedure is the same as that used in starting the problem.
(2) The problem will restart from the last iteration or dump.

Space: The memory requirements for the two versions of TRIMON are:

(1) For the 39 by 39 generated mesh, the code TRIMON, the information from the input tape (dump tape), and the FORTRAN monitor programs use $31{,}680_{10}$ locations.
(2) For the 23 by 64 generated mesh, the code TRIMON and the FORTRAN monitor program use $30{,}597_{10}$ locations.

Format: The format of the printed output from TRIMON differs from the output described in the writeup (to which this paper is supplementary) in only two respects: (1) the decimal point between the excess fifty exponent and the fraction is omitted, and (2) zeros are represented by a dash (-).

Alterations:

Two procedures are suggested for changing the permeability tables. Both procedures require reassembling the program TRIMON.

(1) A direct replacement of the present table with new $B^2$ and gamma values.
(2) Obtain a listing of the program TRIMON and do the following:
(a) Find the subroutine PERM in the listing.
(b) Scan the listing of the subroutine PERM until you find

```
        TRA     PRE1
                PUT REGION NAMES HERE.  PZE  ,,NAME
        PZE     ,,2          MATERIAL NO. 2.  CARBON STEEL.  CFE
PRE1    LAS     *,4
        TRA     *+2
        TRA     EUREKA
        TIX     *-3,4,1
        HTR     *            NONEXISTENT NAME
```

PUT CORRESPONDING TABLE SIZES HERE. PZE FWABSQ,,NMAX

PZE CFE,,CFEG-CFE MATERIAL NO. @. CARBON STEEL. CFE
EUREKA CLA *,4

(c) Make the above indicated changes and
(d) Assemble the program.

Timing: The time required for a complete solution in Air and Iron ranges from 15 to 25 minutes.

Program stops:

(a) A program stop will occur for the following reasons:
  (1) Negative B squared
  (2) Negative coupling sum.
  (3) Zero material
  (4) Nonexistent name

PROGRAMMER J. S. COLONIAS

PROBLEM BED IT EXT.

# FORTRAN

DATE DEC. 10/65

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APPENDIX III

Input data for BEDIT program

FORTRAN STATEMENT

| STATEMENT NUMBER | CONT | FORTRAN STATEMENT |
|---|---|---|
| 0000 | | |
| 0010 | | |
| 0020 | | |
| 0030 | | |
| 0040 | | |
| 0050 | | |
| 0060 | | |
| -999 | | |
| | | END OF FILE CARD |

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IV.a. Successful generation of GENMON

```
REGIONS        K MAX         L MAX
-00460         000047        000047
                      PARITY
               -51.10000000
 REGION NO.   000001         MATERIAL       NAME 001000        000001
                      CURRNT         DENSTY
                50.0          50.0
 REGION NO.   000002         MATERIAL       NAME 002000        000001
                      CURRNT         DENSTY
                50.0          50.0
 REGION NO.   000003         MATERIAL       NAME 001000        000002
                      CURRNT         DENSTY
                54.32000000 50.0
 REGION NO.   000004         MATERIAL       NAME 001000        000002
                      CURRNT         DENSTY
               -54.32000000 50.0
                      TL             RHO
                47.99999999 51.16000000
                      QF             PF
                53.10000000 51.10000000
                      QF             PF
                53.10100000 51.20000000
                      QF             PF
                53.10200000 51.30000000
                      QF             PF
                53.10300000 51.40000000
                      QF             PF
                52.47000000 51.10000000
                      QF             PF
                52.48000000 51.20000000
                      QF             PF
                52.49000000 51.30000000
                      QF             PF
                52.50000000 51.40000000
                      QF             PF
                52.51000000 51.50000000
GENERATION COMPLETED
```

IV.b. Unsuccessful generation of GENMON

```
                              TRIM   AIR  QUAD4
 -00460       000047          000047
                   PARITY
              -51.10000000
  REGION NO. 000001          MATERIAL        NAME 001000          000001
                   CURRNT          DENSTY
               50.0          50.0
  REGION NO. 000002          MATERIAL        NAME 002000          000001
                   CURRNT          DENSTY
               50.0          50.0
  REGION NO. 000003          MATERIAL        NAME 001000          000002
                   CURRNT          DENSTY
               54.32000000 50.0
  REGION NO. 000004          MATERIAL        NAME 001000          000002
                   CURRNT          DENSTY
              -54.32000000 50.0
                   TL              RHO
               47.99999999 51.16000000
                   QF              PF
               53.10000000 51.10000000
                   QF              PF
               53.10100000 51.20000000
                   QF              PF
               53.10200000 51.30000000
                   QF              PF
               53.10300000 51.40000000
                   QF              PF
               52.47000000 51.10000000
                   QF              PF
               52.48000000 51.20000000
                   QF              PF
               52.49000000 51.30000000
                   QF              PF
               52.50000000 51.40000000
                   QF              PF
               52.51000000 51.50000000

              NEG OR ZERO LW AREA.  K IS     000036L IS  000007
              NEG OR ZERO UP AREA.  K IS     000036 L IS 000007
GENERATION COMPLETED
```

V. Iterative printout of TRIMON

```
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119399999     -              -               -              -        -       -
  RATIO       RESIDUAL      RES/LEN        RHOCP
    -            -             -          4962500000
  I PLUS       I MINUS      I SUM           NRG FE      NRG AIR
5540250011 -5540250011 -4748828125           -            -
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119399999  5220000000 -5565474912  5525864406  5420126250  -    5669557853
  RATIO       RESIDUAL      RES/LEN        RHOCP
5110223972  5537206688  4953490276  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119384729  5240000000 -5612457307  5526747009  5415895585  -    5715776629
  RATIO       RESIDUAL      RES/LEN        RHOCP
5110033442  5530891871  4919580780  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119460097  5260000000 -5617559189  5523733610  5413428046  -    5723297813
  RATIO       RESIDUAL      RES/LEN        RHOCP
5098810022  5526953381  4911569060  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119517474  5280000000 -5621735736  5519442696  5411014296  -    5729999208
  RATIO       RESIDUAL      RES/LEN        RHOCP
5099817655  5523736140  4879122557  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119517474  5310000000 -5625475889  5515327145  5399384960  -    5736012299
  RATIO       RESIDUAL      RES/LEN        RHOCP
5099101351  5520669813  4857396537  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119612130  5312000000 -5629154616  5511963970  5394950781  -    5741825999
  RATIO       RESIDUAL      RES/LEN        RHOCP
5099898398  5520430896  4848847359  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119645584  5314000000 -5632502700  5492204144  5385470703  -    5747216906
  RATIO       RESIDUAL      RES/LEN        RHOCP
5099147305  5517929261  4837972122  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119657685  5316000000 -5635331554  5472457852  5370697265  -    5751823378
  RATIO       RESIDUAL      RES/LEN        RHOCP
5098763851  5514693837  4828353685  4962500000
TRIM AIR  CERN1              AMIN            AMAX          DMAX     BMAX   LENGTH
5119661616  5318000000 -5637589313  5457775734  5357056250  -    5755506698
  RATIO       RESIDUAL      RES/LEN        RHOCP
```

## VI. Final printout of TRIMON

| XB | B | XBX | A | BX BX |
|---|---|---|---|---|
| 5135999999 | -5511671922 | - | - | -5432422006 |
| 5210799999 | -5511690867 | 5171999998 | -5584037837 | -5126313442 |
| 5217999999 | -5511689028 | 5214399999 | -5616821208 | 5025543212 |
| 5225199999 | -5511617880 | 5221599999 | -5625237309 | 5198817442 |
| 5232399999 | -5511539818 | 5228799999 | -5633602183 | 5210841945 |
| 5237000000 | 5314172265 | 5236000000 | -5641910852 | 5425394653 |
| 5239000000 | 5344182226 | 5238000000 | -5641882507 | 5315004980 |
| 5241000000 | 5375975195 | 5240000000 | -5641794143 | 5315896484 |
| 5243000000 | 5411068750 | 5242000000 | -5641642192 | 5317356152 |
| 5245000000 | 5414959765 | 5244000000 | -5641420817 | 5319455078 |
| 5247000000 | 5419446582 | 5246000000 | -5641121622 | 5322434082 |
| 5249000000 | 5424788417 | 5248000000 | -5640732691 | 5326709179 |
| 5251000000 | 5431378457 | 5250000000 | -5640236922 | 5332950195 |
| 5253000000 | 5439817949 | 5252000000 | -5639609353 | 5342197460 |
| 5255000000 | 5451008085 | 5254000000 | -5638812994 | 5355950683 |
| 5257000000 | 5466128535 | 5256000000 | -5637792832 | 5375602246 |
| 5258500000 | 5481338007 | 5258000000 | -5636470262 | 5410139648 |
| 5259500000 | 5492964687 | 5259000000 | -5635656882 | 5411626679 |
| 5260500000 | 5510576515 | 5260000000 | -5634727235 | 5412800468 |
| 5261500000 | 5511867554 | 5261000000 | -5633669583 | 5412910390 |
| 5262500000 | 5512978429 | 5262000000 | -5632482828 | 5411108750 |
| 5263500000 | 5513730832 | 5263000000 | -5631184985 | 5375240234 |
| 5264500000 | 5514036140 | 5264000000 | -5629811901 | 5330530859 |
| 5265500000 | 5513993878 | 5265000000 | -5628408287 | -5242261718 |
| 5266500000 | 5513748664 | 5266000000 | -5627008900 | -5324521484 |
| 5267500000 | 5513404589 | 5267000000 | -5625634033 | -5334407421 |
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# FOOTNOTES AND REFERENCES

1. Alan Winslow, An Irregular Triangle Mesh Generator UCRL-7880 (1964).
2. Alan Winslow, "Equipotential" Zoning of Two-Dimensional Meshes, UCRL-7312 (1963).
3. Alan Winslow, Numerical Calculation of Static Magnetic Fields in an Irregular Triangle Mesh, UCRL-7784 (1964).
4. Supplementary write-up for TRIM by Bobby Powell (attached).
5. Fred Andrews's paper on TRIM, unpublished.
6. J. S. Colonias and J. H. Dorst, Magnet Design Application of the Magnetostatic Program called TRIM, UCRL-16382 (1965).
7. This program was written by Alan Winslow of LRL, Livermore.