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This paper discusses work being done at Lawrence Radiation Laboratory (LRL) in computing magnetic fields with the magnetostatic program called TRIM. TRIM has been used in the design of quadrupole and sextupole magnets. The irregular triangular mesh utilized by this program allows the computation of fields for both symmetric and asymmetric magnets of any shape. The program is so general that it permits any distribution of currents, several kinds of iron in the same magnet, and voids or currents within the iron. The attainable quality of the computed results is evidenced by comparing with (1) measurements at the CERN proton synchrotron magnet and (2) analytical solutions of simple geometries including an ideal quadrupole. Agreement with CERN measured gradients is within 1%, within the limits of the vacuum chamber. While the present coding permits evaluations of medium accuracy, the full potential of this program has not yet been realized.

Introduction

Within the past few years the use of magnetostatic computer programs in evaluating magnetic-field configurations has become an important technique in magnet design studies for several reasons: Two major reasons are:

1. The precision required in the design of magnetic fields has increased markedly with the increase in energy of present accelerators.

2. The high cost of new accelerators makes it worthwhile to study many models before construction of the magnets.

In this paper we discuss our experiences with the computer program TRIM, and the role that it is playing in designing the proposed 200-GeV proton synchrotron.

Method of Use

TRIM is a two-dimensional magnetostatic computer program for calculating magnetic fields. It can be used to calculate fields for both symmetric and asymmetric magnets with one, two, or no reflecting boundaries. It accomplishes this by finite-difference methods which approximate the partial differential equations involved, and solves the equations by a relaxation process described by the originator[1] of this program in a paper at this symposium.

This program consists of two major steps; generation of the irregular triangular mesh, and execution of the main program. A brief description of these two steps follows:

A. Mesh Generator

Once the geometry of the problem under consideration has been defined, the user proceeds to define areas of uniform material and current density called regions. A region may have any shape and it need not be logically convex, as long as it does not cross itself. A glance at Fig. 1 shows that this problem divides naturally into a minimum of four regions--two current-carrying regions, an iron region, and the air. Some boundary points of each region are specified by punched-card input, and the program interpolates for other boundary points by distributing them in the smoothest possible way.

The interior points are distributed by the program to produce triangles that tend toward equilateral or toward right triangles, as specified by input. After all region boundary points are determined, the mesh generator considers the types of triangles specified and proceeds to calculate miscellaneous quantities associated with each triangle--e.g., current, material, and sides of triangles--and to store this information on magnetic tape. Once a problem tape has been successfully generated, one usually makes oscillograph plots (Fig. 1) to examine the zoning and to determine whether the overall mesh has relatively few obtuse triangles, few triangles with elongated sides, smooth transitions between mesh points, etc. Successful generation means that the program has been able to define all mesh points without overlapping triangles, a condition which produces an error diagnostic.

In assigning regions in a problem one is not restricted to having the same number of regions as the types of materials present. That is, any part of the problem may be separated into as many regions as desired. The specification of types of triangles for the interior points of a region is arbitrary. However, experience with this program has shown that for most geometries, right triangles in air and equilateral in iron give the best results. Also for best accuracy, the median-plane region should be zoned uniformly.

The limited available mesh (40×40) necessitates careful distribution throughout the problem geometry. Areas where most accurate results are desired should be zoned with more mesh points, and conversely, fewer points should be used where high accuracy is not needed. This may be seen in Fig. 1, where the area occupied by the vacuum chamber on the median plane has been zoned with more lines (the distance between mesh lines is 0.4 cm).

This briefly describes the mesh generator which is written in machine language (FAP) and in FORTRAN II. The generator program may be operated on-line or under the FORTRAN II monitor system.

B. Main Program

Once the mesh generator has completed its function by transforming all information pertinent to the generated mesh on a magnetic tape, the user proceeds with the second phase of TRIM--execution of the main program. This program was written in machine language (FAP) and is operated only on-line.

The generated problem tape and the tape that contains the main program are placed on two magnetic tape units, and after certain control switches are manipulated, execution of the program begins. An on-line printout which occurs at regular intervals indicates the progress of the solution. The normal process of solution may be interrupted to change relaxation factors, convergence criteria, or currents, etc., depending on whether the solution proceeds smoothly. Upon convergence, the program prints the results as shown in Fig. 2. The columns in this figure represent, from left to right:

1 (labelled XB). The average X positions of successive pairs of mesh points, in centimeters.

2 (labelled B). The Y component of the magnetic flux density B, in gauss.

3 (labelled XBX). The X position of the mesh points, at which the vector potential (A) and its second difference are evaluated, in gauss-cm.

4 (labelled A). The value of the vector potential.

5 (labelled BX). The second derivative of the vector potential or gradient, in gauss/cm.

In addition to the tabulation of the midplane gradient, TRIM provides information on the energy stored in air and in iron. An additional program, BEDIT, may be used later to print out the average flux density in every triangle in air or iron.

Figure 3 shows oscillograph plots of flux lines for a quadrupole and a sextupole magnet.

Program Applications

Our work with TRIM has been almost entirely in connection with the design of magnet components for the proposed 200-GeV proton synchrotron. The precision required for such designs, is in general, higher than that required for many other possible applications. We have tested and used this program in several ways, including comparison of measured and computed fields, calculation of effects of misplaced conductors, calculation of magnets where analytical solutions can be obtained, evaluation of various quadrupoles and evaluation of a sextupole.

TRIM was available for use in the design of the gradient magnets for the proposed accelerator, but the geometry of those magnets was evaluated with another program, SIBYL, which has more mesh points and more "convenience" features in its operation. Before late summer of 1964, many runs were made with TRIM to optimize the operating parameters and check the accuracy of the computed output by comparison with measurements on the CERN proton synchrotron. (The measured data on those magnets were of sufficiently high quality for the comparison to be significant, although we did not have the best data at the time of these first comparisons.) Mr. Fred Andrews, formerly with LRL, Berkeley was responsible for the development of TRIM to its present state, and he was the only user of the code during this period. (He has also applied TRIM to problems other than magnetostatic.)

Last fall, we began to use TRIM on our own problems because we needed its generality to help design quadrupoles and sextupoles. The validation studies with the CERN magnet were repeated with better dimension and measurement data. The computed and measured gradients are shown in Fig. 4. Here the field index n, defined as $n = r_0/B_0\ (dB/dr)$, is shown as a function of radial distance from the equilibrium orbit. We assumed a stacking factor of 0.95 and a B(H) curve for pure iron with a saturation induction of 21.4 kG. As can be seen, the computed field index is within 1% of the measured.

The quadrupoles at each end of a straight section of the proposed 200-GeV accelerator are called Collins quadrupoles.[2] A section or outline of the proposed quadrupole is shown in Fig. 3 (top). The coils will be in series with the coils of the gradient magnets, and each conductor will carry about 5 kA at peak field. The number of turns per pole on a Collins quadrupole must be some small integer, and three turns per pole was selected. The half-aperture or bore radius and the length of the quadrupole are then variable within small limits to suit the overall design structure of the accelerator. TRIM has been used to evaluate several magnets of the general form of Fig. 3 (top), including the effects of iron saturation. The changes in shape with excitation are pleasantly small. The computed field shape, dB/dy, as a function of X and NI, as well as the magnetization curve, plotted as B'/NI vs B'(I), are shown in Fig. 5.

The matching of the quadrupole magnetization curve, B'(I), to the magnetization curve of the gradient magnets, B(I), is the problem of "tracking". Although the quadrupoles will have small auxiliary windings which can be excited separately to correct any deviations, the return path section of the quadrupole can be adjusted to reduce the correction currents. From runs with TRIM, we have obtained a computed tracking error of less than 0.1% Magnet measurements on models of the quadrupole and gradient magnets will give the real tracking error and TRIM will be used to design the final return path sections.

The sextupole magnet shown in Fig. 3(bottom) was also evaluated by using TRIM. One quadrant was defined in the mathematical model with two planes of symmetry. Note that the currents are unbalanced in this quadrant. That is, the sum of the currents does not need to be zero (unless all boundaries are Neumann) in TRIM. The computed gradient is shown in Fig. 6 for two runs on the identical geometry, but with differences in the location of mesh points within the problem. The differences in the curves are discussed in the next section, but the extent of the linear portion of the gradient curves is almost good enough with this first try. We know that small changes in the pole contour can achieve a useful sextupole field in the horizontal direction without changing the general location of the edge of the pole. The curves of Fig. 6 are for the "equipotential" solution, which assumes that the permeability of the iron is infinite. With finite permeability, this geometry has been excited up to a computed second derivative, or B", of 400 G/cm^2. The changes in the constancy of B" were small, only 1% at values of x greater than 5 cm.

Our attempts to calculate the fields along the radial line between a proximate and a remote pole have been inconclusive. We have computed the potentials and the radial and tangential components of B, but we do not know how reliable they are.

Quality of Computed Results

The most useful characteristic of TRIM is its adaptability to practically any two-dimensional magnet problem. It is easy to define a mathematical model to study entire magnets, including large borders of air. Subsurface voids, wanted or unwanted, may be modeled. Scalar equipotential surfaces can be defined by closing the magnetic circuit with infinitely permeable iron, permitting study of the flux flow through particular area of finite iron and air on a finer mesh. We have yet to find a problem that cannot be handled with TRIM. Any mathematical model introduces some error into the results from the necessary assumptions about the boundary conditions, but with TRIM these errors can be kept very small. This first version of TRIM achieves this flexibility easily by using exactly the same difference equation at every point in the mesh, so there is no such thing as a special point.

For any particular problem or geometry of air, current, and iron, we have observed that the computed distribution of flux depends upon the location of points of the mesh, even when the number of points in each region is not changed. This "sensitivity to zoning" is only partially understood. Certainly, part of the difference between the results with different zoning is due to the approximate nature of any numerical solution. The size of this zoning dependence appears to be larger than a simple discretization error and we are trying to learn more about the ultimate accuracy of the code. In areas with irregular triangles, the difference equations produce errors that are proportional to the second derivative of the potential. The gradient of flux density is just the second derivative of the vector potential, and high resolution of gradients is difficult to achieve. However, with repeated runs and careful zoning, high resolution may be obtained.

Comparison of computed and measured gradients magnets indicates a probable upper limit of about 1% on the accuracy of TRIM gradients with good zoning and the present number of available mesh points.

At the other end of the accuracy spectrum we have the sextupole runs identified as SEX1. Two runs with identical region boundaries, differing only in the distribution of mesh points within the air region, gave values for the maximum flux density (the first derivative of the potential) on the median plane that differed by 10%. The zoning was very bad, although the problem was successfully generated. Near the area of poor calculation we had many elongated triangles and abrupt transitions from one kind of triangle to another (see Fig. 7). This latter area could be improved, and our rezoning trials with other problems indicate that small improvements in zoning reduce the large errors quite rapidly. With improvement in the zoning, the midplane gradients of this sextupole can probably be evaluated with an accuracy of about 2%.

In most magnet problems, one is usually interested in the flux distribution in air, and the location of the surfaces and the currents dominate the resultant fields. The flux distribution within the iron usually has only a small effect on the distribution in air, the accuracy of calculations within the iron is very much less important than the accuracy of the calculations in air, and good solutions may be computed with very poor zoning within the iron. The location of points on and adjacent to the interfaces can significantly affect the quality of the fields in air and change the convergence rate. The system of equations for one problem where the zoning irregularities were swept to the interface and the mesh had some areas of very poor zoning took more than five times longer to solve than a normal problem.

With the additional experience we now have, we can avoid poor zoning and can change a well-zoned problem to be even better. We now zone as symmetrically as possible in the air regions, principally by defining rectangular subregions near the median plane. New users of TRIM might be dismayed with first runs if they want results of the highest accuracy, but rezoning can work apparent miracles. For many magnet problems, high accuracy and resolution of fine structure are not necessary, and what is disappointing to a perfectionist may be completely irrevelant to a practical engineer.

Future Plans

Our experiences with TRIM thus far have convinced us that TRIM is an excellent program. The generality of this code and its ability to compute fields of asymmetric magnets allows us to experiment with geometries impossible to model with other existing programs.

At present we have initiated work in two areas. First is to convert the present on-line version to a program operating under monitor, thus making TRIM much easier to use than it is now. Second, TRIM is being rewritten to increase the number of mesh points to more than 30,000, and the program is being adapted to the CDC 6600 computer system which is to be installed at LRL by March 1966.

The enlargement of the mesh size and the experience gained during the past few months will let us operate the program more effectively, and we hope to be able to obtain finer results.

Acknowledgments

We are much indebted to Dr. Alan Winslow for his advice in problems relating to the understanding of this program, and to Dr. Jonathan Young for his invaluable assistance in changing parts of the existing program.

Footnotes and References

*This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] Alan M. Winslow, Magnetic Field Calculations in An Irregular Triangular Mesh, Paper B-9, these proceedings; also Lawrence Radiation Laboratory Report UCRL-7784-T (Rev. 1), August 23, 1965.

[2] Robert A. Kilpatrick, Collins Quadrupole Magnets and Sextupole Magnet for a 200-GeV Proton Synchrotron, Paper C-8, these Proceedings; also Lawrence Radiation Laboratory Report UCRL-16375, August 30, 1965.

Figure Legends

Fig. 1. Collins quadrupole, generated mesh with equilateral triangles in air.

Fig. 2. Computer printout of results.

Fig. 3. Outline and flux distribution of (top) Collins quadrupole and (bottom) sextupole magnet.

Fig. 4. Computed and measured gradients for the CERN proton-synchrotron open-C magnet.

Fig. 5. Computed gradients (top) and computed magnetization curve (bottom) for a Collins quadrupole.

Fig. 6. Computed gradients, sextupole magnet.

Fig. 7. Portion of sextupole mesh showing bad zoning.

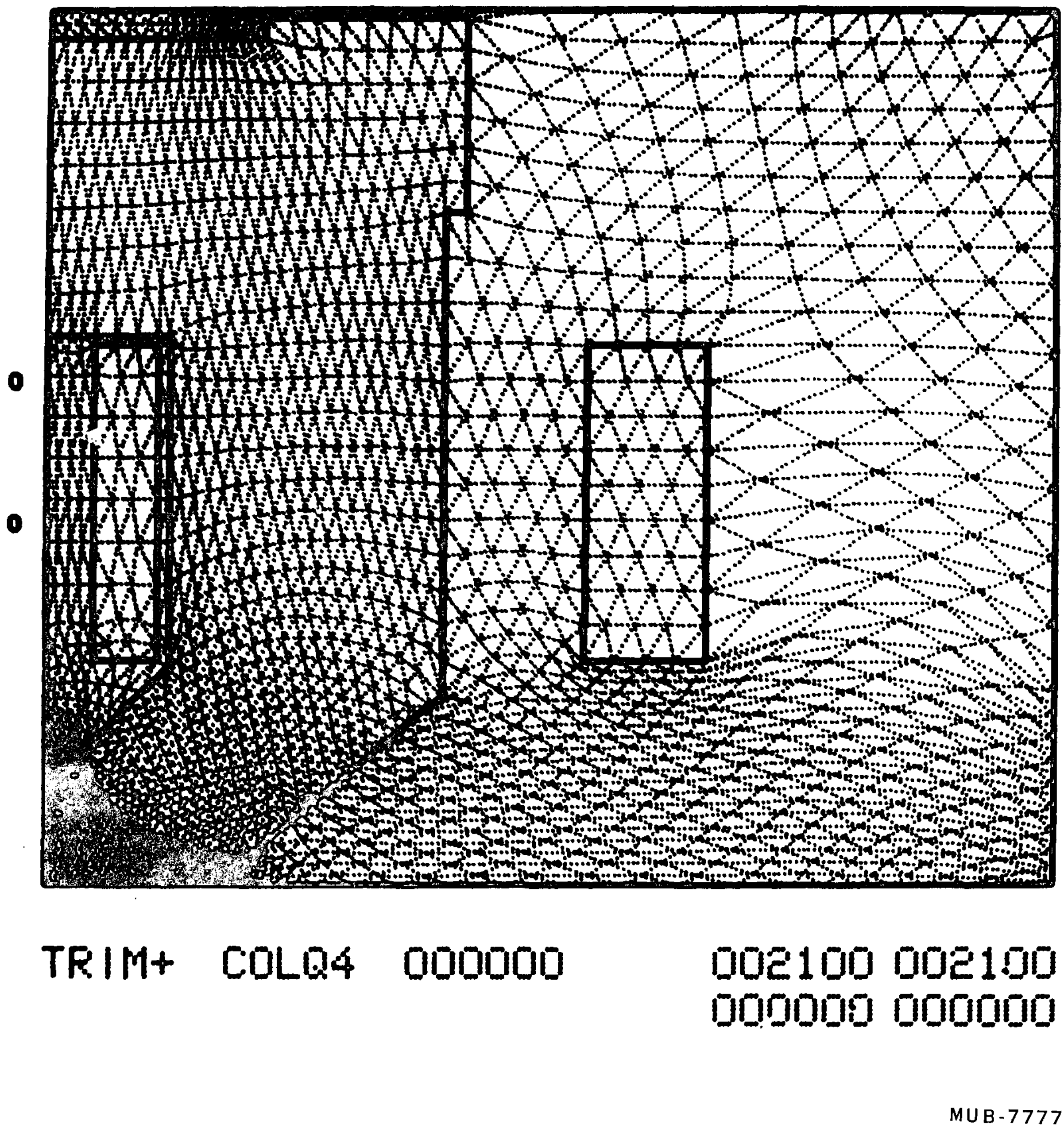

Fig. 1

XB	B	XBX	A	BX
+50.25000000	+53.28239063	+50.00000000	-56.10497335	+54.11295625
+50.75000000	+53.84560547	+50.50000000	-56.10483215	+54.11264297
+51.12500000	+54.14105273	+51.10000000	-56.10440935	+54.11298438
+51.17500000	+54.19763086	+51.15000000	-56.10370409	+54.11315625
+51.22500000	+54.25425566	+51.20000000	-56.10271593	+54.11324961
+51.27500000	+54.31090352	+51.25000000	-56.10144466	+54.11329570
+51.32500000	+54.36755547	+51.30000000	-55.99890138	+54.11330391
+51.37500000	+54.42422324	+51.35000000	-55.98052361	+54.11333555
+51.42500000	+54.48092559	+51.40000000	-55.95931244	+54.11340469
+51.47500000	+54.53767754	+51.45000000	-55.93526616	+54.11350391
+51.52500000	+54.59448106	+51.50000000	-55.90838229	+54.11360703
+51.57500000	+54.65129141	+51.55000000	-55.87865823	+54.11362070
+51.62500000	+54.70789258	+51.60000000	-55.84609366	+54.11320234
+51.67500000	+54.76399512	+51.65000000	-55.81069904	+54.11220508
+51.72500000	+54.81896973	+51.70000000	-55.77249928	+54.10994922
+51.77500000	+54.87117031	+51.75000000	-55.73155079	+54.10440117
+51.82500000	+54.91660820	+51.80000000	-55.68799228	+53.90875781
+51.87500000	+54.94685801	+51.85000000	-55.64216187	+53.60499609
+51.92500000	+54.94947705	+51.90000000	-55.59481897	+52.52380859
+51.96666667	+54.93127815	+51.95000000	-55.54734511	-53.43677368
+51.99999999	+54.86755258	+51.98333333	-55.51630251	-54.19117673
+52.10333333	+54.70982892	+52.10166667	-55.48738409	-54.47317091
+52.11500000	+54.55706045	+52.10500000	-55.46372313	-54.13094440
+52.13500000	+54.40407139	+52.12500000	-55.35231104	-53.76494531
+52.15500000	+54.29051810	+52.14500000	-55.27149676	-53.56776642
+52.17500000	+54.22118364	+52.16500000	-55.21339314	-53.34667230
+52.19433333	+54.17543073	+52.18500000	-55.16915641	-53.23665303
+52.21300000	+54.14233463	+52.20366666	-55.13640935	-53.17730051
+52.23166667	+54.11636099	+52.22233333	-55.10984021	-53.13914449
+52.25100000	+53.94997879	+52.24100000	-54.88119492	-53.11049886
+52.27100000	+53.77391962	+52.26100000	-54.69119917	-52.88029587
+52.29100000	+53.63475029	+52.28100000	-54.53641524	-52.69584664
+52.31100000	+53.52673734	+52.30100000	-54.40946518	-52.54006477
+52.33100000	+53.44578433	+52.32100000	-54.30411772	-52.40476501
+52.35100000	+53.38848447	+52.34100000	-54.21496085	-52.28649933
+52.37100000	+53.35200578	+52.36100000	-54.13726396	-52.18239342
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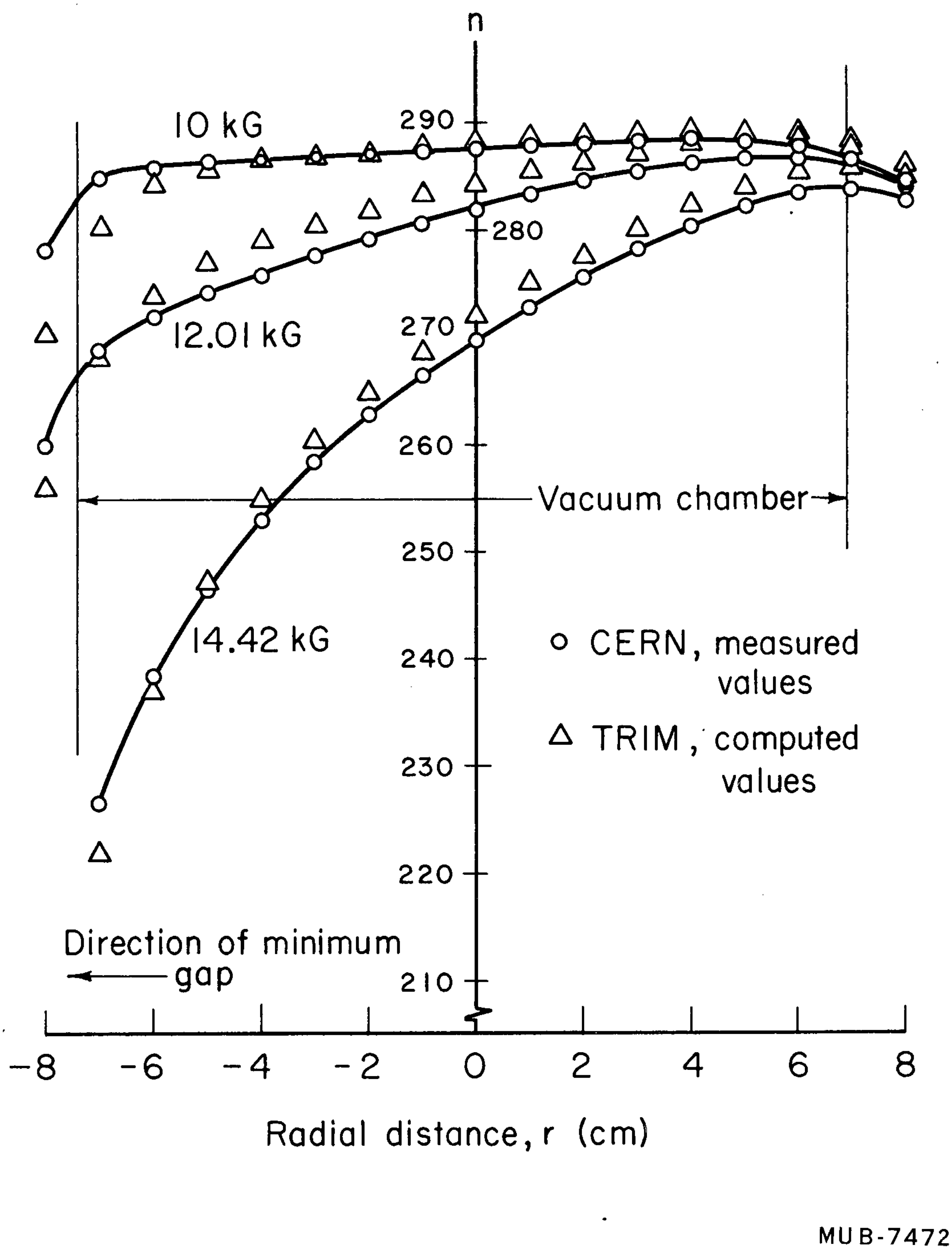
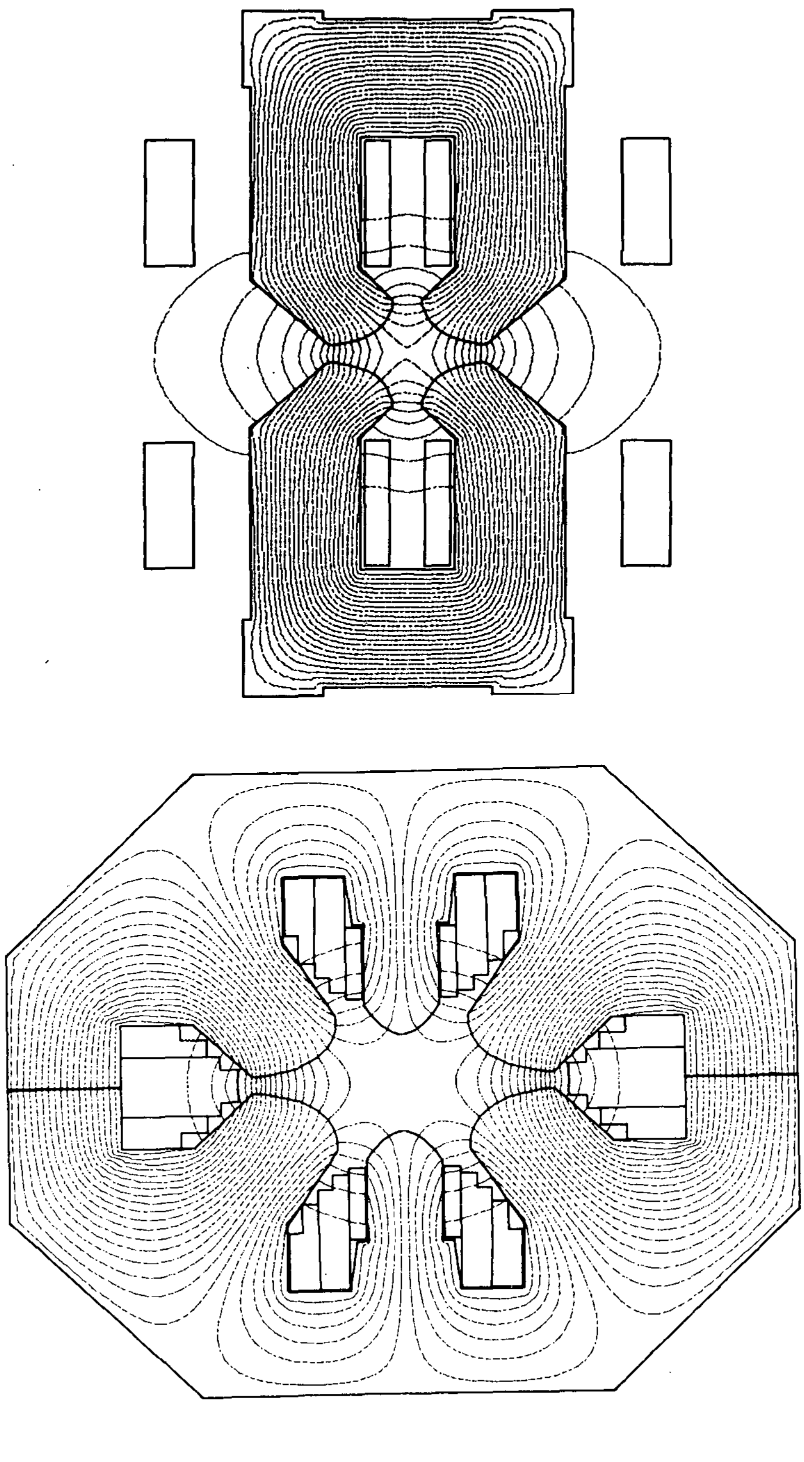
CVERGD

Fig. 2



n
290
280
270
260
250
240
230
220
210
10 kG
12.01 kG
14.42 kG
Vacuum chamber
○ CERN, measured values
△ TRIM, computed values
Direction of minimum gap
-8
-6
-4
-2
0
2
4
6
8
Radial distance, r (cm)
MUB-7472

Fig. 3



MUB-7647

Fig. 4

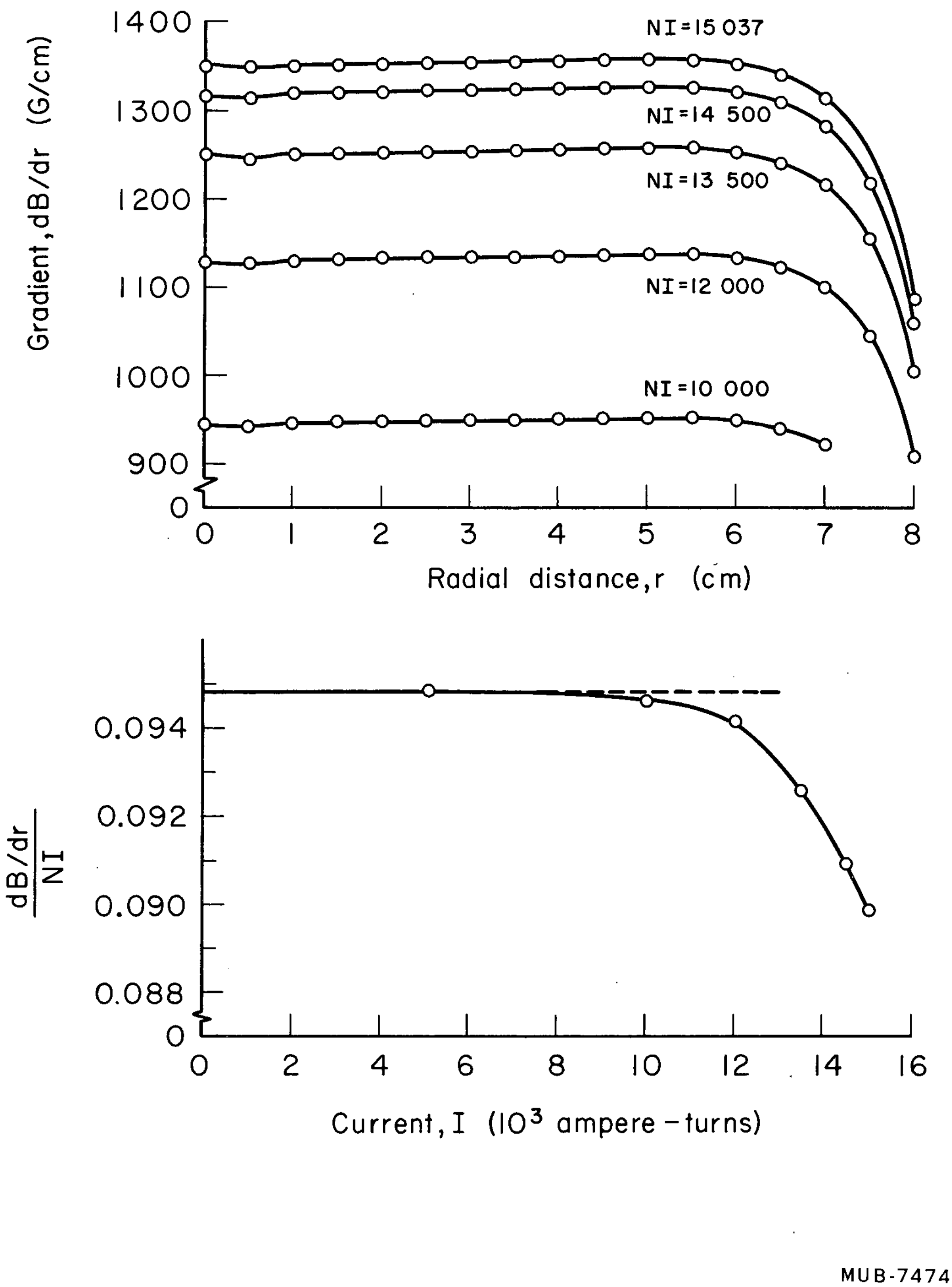

NI = 15 037
NI = 14 500
NI = 13 500
NI = 12 000
NI = 10 000
Gradient, dB/dr (G/cm)
1400
1300
1200
1100
1000
900
0
0
1
2
3
4
5
6
7
8
Radial distance, r (cm)
dB/dr / NI
0.094
0.092
0.090
0.088
0
0
2
4
6
8
10
12
14
16
Current, I (10^3 ampere - turns)
MUB-7474

Fig. 5

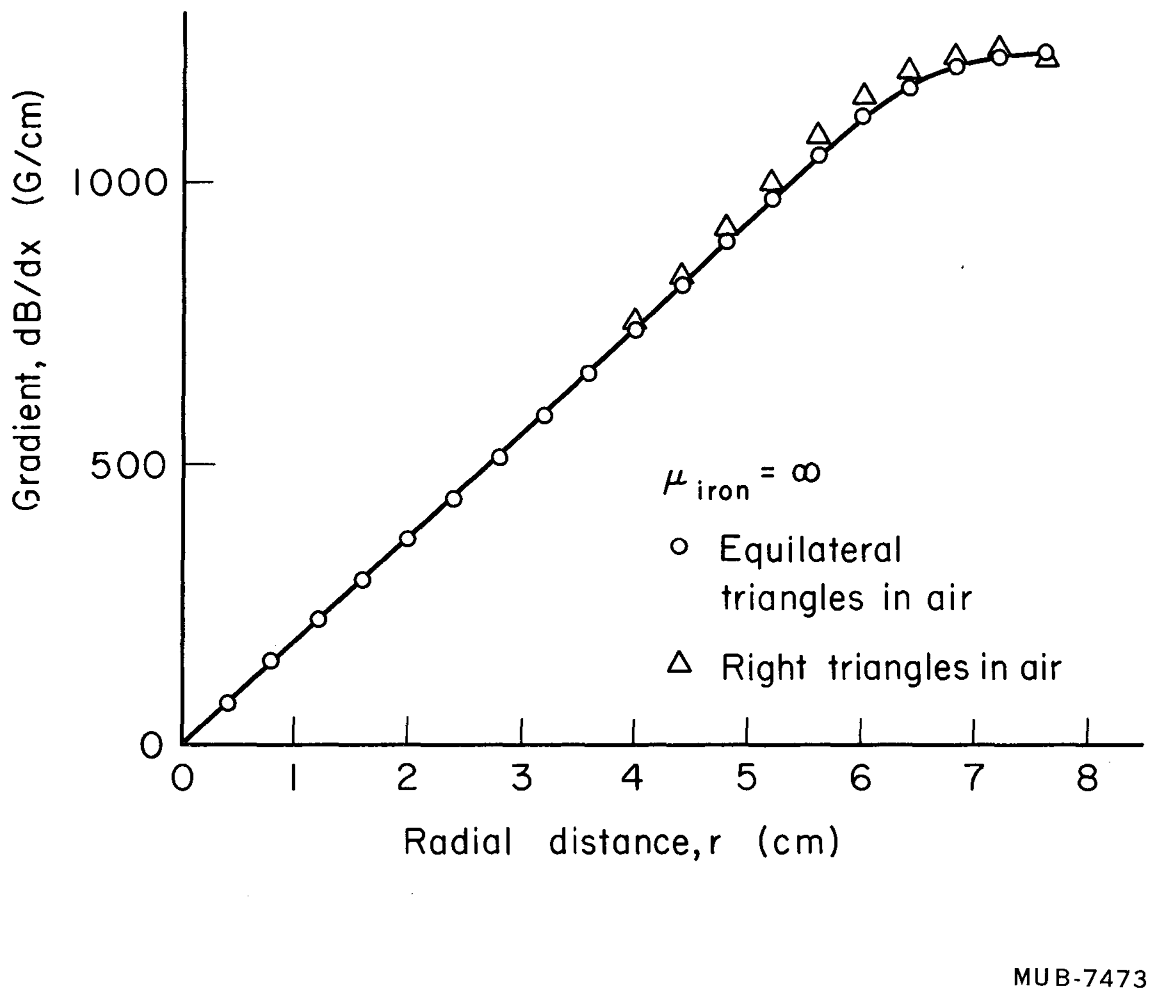
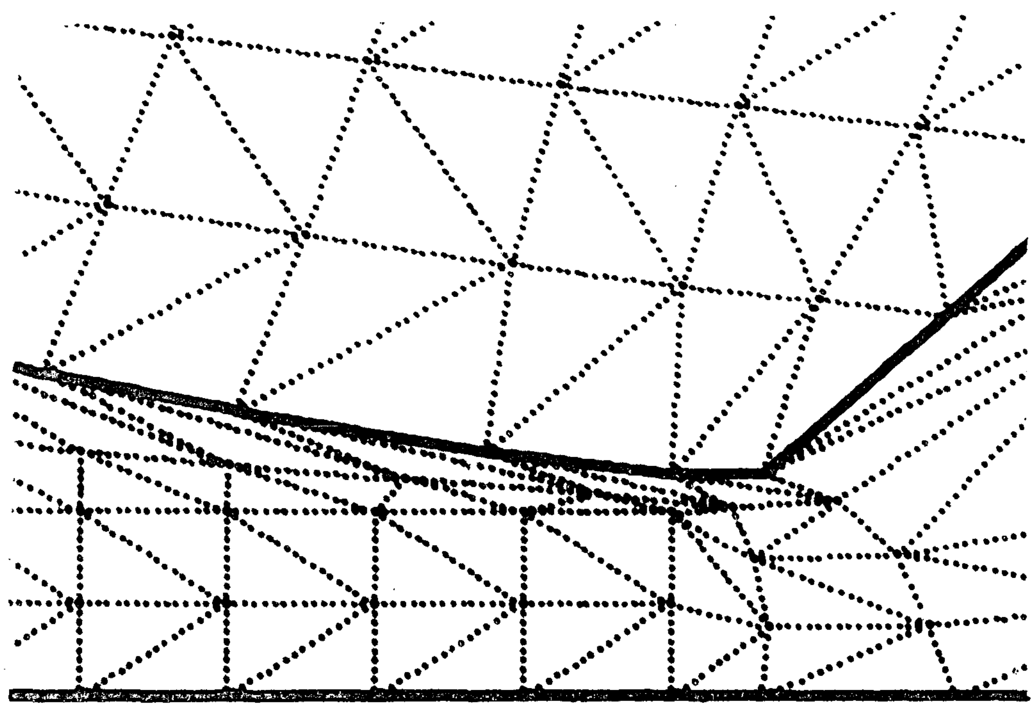

Gradient, dB/dx (G/cm)
1000
500
0
0
1
2
3
4
5
6
7
8
Radial distance, r (cm)
μ iron = ∞
○ Equilateral triangles in air
△ Right triangles in air
MUB-7473

Fig. 6



MUB-7776

Fig. 7