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MAGNETIC FIELD CALCULATIONS FOR THE 184-INCH SYNCHROCYCLOTRON

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February 1970

I. ABSTRACT

This paper describes our experiences with the use of a computer program to calculate the magnetic field change produced by a change in the coil excitation of the Berkeley 184-inch synchrocyclotron.

One of the interesting aspects of these calculations is the simulation of the magnet with a cylindrical pole face and a rectangular return yoke. The raw computed magnetic field compares to the azimuthally averaged measured field at the same excitation to within 1%.

A subtraction technique is used to cancel integration and systematic model errors and yields a calculated magnetic field that compares to within 0.1% with the measured fields at different excitations.

The calculations include the effects of the plate construction (stacking factor) of the magnet and assume median-plane symmetry, but do not include the small effects produced by the main-coil current symmetry shunts and nonuniform current distribution, although these could have been included.

II. INTRODUCTION

The field calculations reported herein were undertaken in order to determine if the change in the radial magnetic field profile of the 184-inch cyclotron produced by a corresponding change in the coil excitation could be calculated by computer modeling.

Two such models were constructed, one representing the 184-inch cyclotron magnet at the time of the 1957 field measurements and the other representing it at the time of the 1968 field measurements.

We find that the computed change in field produced by a change in coil excitation is in agreement with that measured for each model, to within 0.1%.

III. MAGNETIC FIELD MEASUREMENTS

The last complete magnetic field measurements were made during the conversion of the 184-inch cyclotron from 340 to 740 MeV in 1957. These measurements included a standard field with main-coil excitation of 1530 A, auxiliary coil excitation of 2660 A also at a main-coil setting of 1524 A for auxiliary coil currents of 2441, 2662, and 2743 A. We did not know at the time that the bottom pie of the lower main coil was intermittently shorting. In 1958 this pie was permanently disconnected and the excitations of the coils were adjusted for best operation. In 1962 the current-monitoring shunts were repaired without recalibration, so that when the calculations reported here were begun the magnetic field
was believed to be 200 to 300 G higher than the 1957 measurements indicated.

In February 1968 we measured the field along the azimuth of the main probe (105 deg) at a standard auxiliary coil current of 2678 A for three different main-coil currents of 1500, 1562, and 1620 A. These currents are based on a new (1968) shunt calibration. The field measurements undertaken at 105 deg provide the experimental data necessary to determine what effect a change in the main-coil excitation produces on the field, but are not indicative of the actual radial field. This is because at this azimuth the probe passes sufficiently close to the regenerator and regenerator compensation shims to see strong local field perturbations. The present measured field is approximately 100 G higher than the 1957 measurements.

IV. THE COMPUTER CALCULATIONS

The calculations were performed by simulating the cyclotron magnet shown in Fig. 1 by a computer program called TRIM. This program solves the two-dimensional magnetostatic problem by iterative overrelaxation of the finite-difference equation approximating the differential equation for the magnetic vector potential, \( A \),

\[
\nabla \cdot \left( \frac{1}{\mu_r} \nabla (r A) \right) = -4\pi J,
\]

where \( \mu_r \) is the permeability of the material and \( J \) is the current density. The computational model in TRIM consists of an irregular triangular mesh of approximately 4000 points. The magnet geometry is outlined in Fig. 2 and shows the computer-generated mesh of the 184-inch cyclotron magnet. Azimuthal and median-plane symmetry is required, so the magnet return yoke thickness was adjusted for constant area in cylindrical geometry, although the actual yoke is rectangular.

The exact magnet gap and the curved approximation used by TRIM are shown in Fig. 3. The gap has been corrected for radial distortions produced by magnetic loading, and is given in Table I. The average gap reduction produced by vacuum loading is 0.018 inch.

V. FIELD CALCULATIONS

Figure 4 shows the pie configuration of the coils. The bottom pie of the lower main coil (B1) was intermittently shorting at the time of the 1957 field measurements. This short was not discovered until a year after the measurements were completed. We have therefore calculated the magnetic field at each excitation used during the 1957 measurements with the B1 pie both in the circuit and out of the circuit.

Figure 5 shows a computer plot of the magnetic field flux lines generated by TRIM. These lines of flux should be interpreted as lines of constant \( r A \).

Figure 6 shows a computer plot of the median-plane magnetic field calculated by TRIM at the coil excitations at the standard 1957 measurements, along with the azimuthally averaged measured field at the same excitation.

Figures 7, 8, and 9 show the calculated fields (TRIM-10, TRIM-11, TRIM-12, TRIM-19, TRIM-20, and TRIM-25) and the measured fields at 162 deg azimuth. Comparing the calculated curves with those of Fig. 6, we see that apparently the B1 pie was not shorted at the auxiliary coil current of 2441 A, but was shorted at 2662 and 2743 A.

TRIM converged after 700 iterations and required 40 minutes of computer time on the CDC-6600. These calculations were carried out for the coil excitations given in Table II. The reciprocal of the iron permeability used in the calculations as a function of the square of the magnetic field is given in.
Table III.

The difference between the calculated field at various excitations and the calculated field at the standard excitation of the 1957 measurements (TRIM-8) should give the field change produced by the change in coil excitation, provided the integration errors are independent of excitation. Figure 10 shows the "smoothed" calculated median plane radial field profiles obtained by adding the difference between the calculated profile and TRIM-8 to the standard 1957 measured field. The calculated change in field produced by alteration of coil excitation and the measured change in field are in excellent agreement.

Figure 11 shows the 1968 measured magnetic fields obtained along the 105-deg probe line at three different main coil excitations and the calculated field profiles at the corresponding coil excitation. The bumps in the radial measured field reflect the close proximity of the magnetic regenerator centered at 116 deg. No attempt has been made to average the field azimuthally. However, the calculated change in field produced by alteration of coil excitation and the measured change in field are in excellent agreement. Figure 12 shows the "smoothed" field.

Figures 13 and 14 show the effect of the alteration of excitation on the radial field fall-off. Here, all smoothed calculated fields have been normalized to 23,075 G at 15 in. radius. The increase in field fall-off at higher excitations is obvious, and results from increased saturation near the pole edge.

VI. 1968 MEASURED FIELD

Figure 15 shows the 1957 and 1968 measured standard field and the computer-calculated field for present (1969) cyclotron excitations before correction for stacking factor or size of universe (see Section VII). The 1968 data (extending from 50 to 94 in. at 105 deg have been smoothed to eliminate the effect of the regenerator perturbations by subtraction of the 1957 data at the same azimuth and adding the difference to the 1957 standard field. The field between 2 and 50 in. is a smooth joint to the 1957 field scaled to match the 1968 data at 50 in.

The 1968 field measurements show that the magnetic field under present operating conditions is approximately 100 G higher than in 1957. The parameters defined by the new magnetic field and radius are summarized in Table IV. Here the proton energy $E$ (MeV) is found from the magnetic rigidity $B$ (gauss), $R$ (inches), and the rest energy $E_0 = 938.213$ MeV:

$$E = E_0 \sqrt{1 + \left( \frac{BR}{1.232103 \times 10^6} \right)^2}.$$  

Gamma is defined as $\gamma = E/E_0$. The rotational frequency $F$ (in hertz) of protons in this magnetic field $B$ (in gauss) is expressed by $F = 1526.73 B/\gamma$. The vertical and radial betatron oscillation frequencies in terms of the rotational frequencies are given by $\nu_z = n^{1/2}$, $\nu_r = (1-n)^{1/2}$, where $n$ is the usual field index determined by $-(dB/dR)(R/B)$.

Orbit calculations using the magnetic field, including the measured regenerator perturbations, show that the radial betatron phase space vanishes at 82.15 in., i.e., 747 MeV. Since the time of the field measurements the regenerator was moved outward 0.25 in., which should increase the beam energy by approximately 3 MeV to 750 MeV. This is then the maximum energy obtainable in the external beam for present operating conditions. The external beam energy at the peak in the particle spectrum is less than the maximum energy, since the available radial betatron phase space becomes smaller as the energy increases (smaller radial betatron amplitude). We find that the peak in the energy spectrum
for the measured internal radial betatron phase-space distribution\(^4\) occurs about 4 MeV below the maximum energy. The energy at the peak in the particle spectrum for the external beam should then be 746 MeV.

The energy of the external physics cave proton beam has recently been measured\(^5\) by determining its range in copper. Analysis of the data was undertaken with the computer code BRAGG,\(^6\) based on the range energy calculations by Steward and Wallace.\(^7\) The energy for the mean range was found to be 746 MeV. No corrections were made for the 6 in. of air preceding and following the copper or the aluminum exit window. Earlier, Freisen and Barkas\(^8\) measured the beam energy and found it to be 747 MeV according to the range energy relations of Sterneheimer. The calculated energy compares favorably with the measured energy.

VII. FURTHER COMPUTER MODEL IMPROVEMENTS

The finite mesh size (4000 points) that TRIM is capable of handling necessitated the approximation of the 184-inch cyclotron magnet with insufficient air border, which forces the fringing field through the magnetic core, producing a smaller field in the pole. The reason for this is the basic assumption in program TRIM, which does not allow any flux to escape the boundary of the "universe" in which the magnet geometry is described. In other words, the vector potential \(\mathbf{A}\) is zero at a nonreflecting boundary and it is not relaxed. This by no means restricts the program, since the variable-mesh feature of TRIM allows an expansion of the mesh to any arbitrary physical dimensions, as can be seen in Fig. 16.

Also, the steel in the yoke of the magnet is not solid, but consists of welded plates each 1.5 in. thick. Therefore the lamination stacking factor produced by the air and oxide surfaces reduces the total iron by about 2%. These effects were included in the modified computer model, and the results are shown in Figs. 17, 18, and 19. Here, 1000 points were allocated to describe the magnet geometry with uniform gap, and the remaining 3000 points were used for an air border (Fig. 16). The dimensions of the "universe" were enlarged to 1000 \times 1000 in. from the magnet universe of 180 \times 312 in. The resulting flux distribution is shown in Fig. 17.

Figures 18a and b show the same geometry with the "universe" reduced to 365 \times 1000 in.

The results of using these models with stacking-factor variations are given in Table V. It will be noticed that the effect of reducing the stacking factor is to reduce the field, whereas the effect of increasing the size of the universe is to increase the field. Figure 19 shows the change in field, \(\Delta B\), vs radius, \(R\), for the cases listed in Table V referenced to the standard computer model (stacking factor 1., universe of 180 \times 312 in.), described in Section V. The effect of a universe change beyond 1000 \times 1000 in. is small, so we do not consider larger universes. The 184-inch magnet should have a stacking factor of approximately 0.96. These corrections increase the calculated field by approximately 170 G, raising the calculated field at 70 in. from 22,400 to 22,570 G. The measured field at 70 in. is 22,514 G.

CONCLUSIONS

This paper shows that the field of a large synchrocyclotron can be calculated from a computer model to within 1%, and changes in the field produced by excitation changes can be calculated to within 0.1%, provided correction is made for the stacking factor and air boundary around the magnetic iron. (We are indebted to C. Dols for pointing this out.) The importance of this air boundary was not
sufficiently appreciated by the authors when this work was undertaken, and is of considerable importance in a highly saturated magnet such as the 184-inch cyclotron.

ACKNOWLEDGMENTS

The authors express their appreciation for several enlightening discussions of the 1957 field measurements with Joseph H. Dorst and Chuck Dols. Peter Watson made the 1968 field measurements, and Howard Heath performed the 1968 shunt calibration. The assistance of James L. MacMullen and Leal L. Kanstein in performing the range measurement is also acknowledged.

REFERENCES

3. Lawrence Radiation Laboratory Engineering Note 4121-12-M30 and M31 (1956).
5. A. C. Paul, unpublished data.
Table I. 1/84-inch cyclotron gap vs. radius.

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Table II.  Coil excitations used in calculations.

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<th>Trim run</th>
<th>Measured field</th>
<th>Fig.</th>
<th>Turns per aux. coil</th>
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<th>Aux. coil current (A)</th>
<th>Av. turns per main coil</th>
<th>Main coil B1 pie</th>
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Table III. Permeability table used in calculating $\mu$ vs $B^2$.

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B^2 & 1/\mu \\
0. & 2.250000 \times 10^{-4} \\
1.440000 \times 10^8 & 3.980000 \times 10^{-4} \\
1.960000 \times 10^8 & 4.500000 \times 10^{-4} \\
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<td>0.3112</td>
<td>1.076</td>
<td>2.7</td>
<td>94.48</td>
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<td>1.076</td>
<td>2.7</td>
<td>94.48</td>
<td>94.48</td>
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<tr>
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<td>0.3106</td>
<td>1.076</td>
<td>2.7</td>
<td>94.48</td>
<td>94.48</td>
</tr>
</tbody>
</table>
Table V. Median plane magnetic field as function of radius for various stacking factors, pole surface contours, and universe sizes.

<table>
<thead>
<tr>
<th>Top Boundary (in.)</th>
<th>180</th>
<th>180</th>
<th>180</th>
<th>200</th>
<th>365</th>
<th>1000</th>
<th>1000</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Boundary (in.)</td>
<td>312</td>
<td>312</td>
<td>312</td>
<td>352</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>312</td>
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<tr>
<td>Stacking factor</td>
<td>1.0</td>
<td>1.0</td>
<td>0.98</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td>Gap (pole)</td>
<td>Tapored</td>
<td>Flat</td>
<td>Flat</td>
<td>Tapored</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
</tr>
<tr>
<td>Total ampere turns</td>
<td>1537082.6</td>
<td>1537082.6</td>
<td>1537082.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Radius (in.) | 4.1364 | 8.2727 | 12.409 | 16.545 | 20.681 | 24.818 | 28.954 | 33.09 | 37.22 | 41.36 | 45.50 | 49.63 | 53.77 | 57.909 | 62.04 | 66.18 | 70.318 | 74.454 | 78.59 | 82.727 | 86.863 | 91.000 | 98.50 | 106.000 |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Total ampere turns | 23497 | 23089 | 22921 | 23363 | 23586 | 23626 | 23458 | 22578 |
| 8.2727       | 23206 | 23465 | 23294 | 23371 | 23967 | 24007 | 23835 | 22945 |
| 12.409       | 23141 | 23559 | 23386 | 23304 | 24060 | 24099 | 23927 | 23036 |
| 16.545       | 23057 | 23573 | 23401 | 23221 | 24074 | 24114 | 23941 | 23050 |
| 20.681       | 22988 | 23572 | 23399 | 23152 | 24072 | 24111 | 23938 | 23048 |
| 24.818       | 22932 | 23551 | 23378 | 23095 | 24050 | 24089 | 23918 | 23028 |
| 28.954       | 22868 | 23519 | 23347 | 23034 | 24018 | 24057 | 23885 | 22997 |
| 33.09        | 22799 | 23477 | 23305 | 22963 | 23975 | 24014 | 23843 | 22957 |
| 37.22        | 22726 | 23425 | 23254 | 22890 | 23923 | 23962 | 23792 | 22907 |
| 41.36        | 22659 | 23363 | 23192 | 22824 | 23860 | 23899 | 23729 | 22847 |
| 45.50        | 22601 | 23288 | 23118 | 22764 | 23784 | 23823 | 23654 | 22775 |
| 49.63        | 22546 | 23199 | 23030 | 22709 | 23694 | 23733 | 23564 | 22689 |
| 53.77        | 22494 | 23093 | 22924 | 22655 | 23585 | 23624 | 23457 | 22586 |
| 57.909       | 22440 | 22965 | 22797 | 22599 | 23454 | 23492 | 23326 | 22460 |
| 62.04        | 22391 | 22808 | 22641 | 22548 | 23293 | 23331 | 23166 | 22308 |
| 66.18        | 22365 | 22613 | 22448 | 22520 | 23092 | 23130 | 22967 | 22117 |
| 70.318       | 22345 | 22364 | 22201 | 22498 | 22836 | 22873 | 22711 | 21874 |
| 74.454       | 22331 | 22029 | 21869 | 22482 | 22489 | 22526 | 22366 | 21545 |
| 78.59        | 22318 | 21539 | 21381 | 22467 | 21984 | 22019 | 21862 | 21063 |
| 82.727       | 22140 | 20719 | 20565 | 22284 | 21144 | 21177 | 21025 | 20257 |
| 86.863       | 20866 | 19047 | 18906 | 21006 | 19450 | 19482 | 19343 | 18621 |
| 91.000       | 17116 | 15629 | 15516 | 17256 | 16018 | 16049 | 15937 | 15287 |
| 98.50        | 8976  | 8559  | 8505  | 9149  | 8945  | 8977  | 8924  | 8395  |
| 106.000      | 4493  | 4594  | 4565  | 4716  | 4985  | 5017  | 4988  | 4506  |
Fig. 1. The 184-inch cyclotron magnet.
Fig. 2. Triangular mesh generated by TRIM, no air boundary.

Fig. 3. 184-Inch cyclotron magnet gap and the smooth curved approximation used by TRIM.
Fig. 4. Magnet coil and current distribution.

Fig. 5. Magnet outline and computed magnetic flux, no air boundary.
Fig. 6. The measured (standard) magnetic field and computed magnetic field (TRIM-8) at the same excitation as a function of radius.

Fig. 7. The measured magnetic field at 162 deg at an auxiliary coil current of 2441 A and the calculated field at the same excitation.
Fig. 8. The measured magnetic field at 162 deg at an auxiliary coil current of 2662 A and the calculated field at the same excitation.

Fig. 9. The measured magnetic field at 162 deg at an auxiliary coil current of 2743 A and the calculated field at the same excitation.
Fig. 10. Measured fields at different excitations and the corresponding calculated fields after corrections for azimuthal averaging and after smoothing by subtraction of the integration errors.

Fig. 11. The measured magnetic field at 105 deg at the present auxiliary coil current of 2678 A and the main coil currents of 1500, 1562, and 1620 A and the corresponding calculated fields at the same excitations.
Fig. 12. The measured magnetic fields at 105 deg azimuth at the present auxiliary coil current of 2678 A and main coil currents of 1500, 1562, and 1620 A and the calculated fields at the same excitations after smoothing.

Fig. 13. Smoothed fields at main coil current of 1524 A and auxiliary coil currents at 2441, 2662, and 2743 A normalized to the same value at 15 in. radius.
Fig. 14. Smoothed fields at main coil currents of 1500, 1562, and 1620 A and auxiliary coil current of 2675 A normalized to the same values at 15 in. radius.

Fig. 15. The standard 1957 measured field. Curve 1 shows the 1957 measured field scaled to the 1968 field at 30 in. radius. Curve 2 shows the smooth calculated field for the present operation currents without stacking factor and universe corrections. Curve 3 shows the 1968 measured field at 105 deg smoothed to remove the regenerator perturbations by subtraction of the 1957 field at 105 deg.
Fig. 16. Modified mesh for extended "universe" of 1000×1000 in.
Fig. 17. Flux distribution with extended "universe" of 1000X1000 in.
Fig. 18. (a) Mesh with extended "universe" of $365 \times 1000$ in.
(b) Flux distribution with extended universe of $365 \times 1000$ in.

Fig. 19. $\Delta B$ vs Radius for modified model, showing effect of air boundary and stacking factor.
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