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IMPLEMENTATION OF THE ORIC MAGNETIC FIELD MEASUREMENTS

T. P. Cleary†

Abstract

The experimental details and methods employed in an extensive remapping of the magnetic field of the Oak Ridge Isochronous Cyclotron (ORIC) were reported previously.[1] The medium- to high-field data (from 12 to 20 kgauss) have been Fourier analyzed and each of the coefficients parameterized in terms of the currents in the main coil, trim, harmonic and valley coils and the average field at each of the radii at which measurements were made. By inclusion of the average field in the formulation, the nonlinear effects of the iron are implicitly taken into account. This procedure has reduced the overall size of the data base by a factor of 100. Synthesis of the field from this parameterization reproduces the absolute field to within 10 gauss and the relative field to within 5 gauss. A field optimization program, which incorporates these results, is currently under development in an effort to enhance the heavy ion acceleration capabilities of the cyclotron and as an aid in the development of new beams.

Introduction

An extensive remapping of the magnetic field of the ORIC was completed in 1977. The previous field measurements did not cover the high field region at which ORIC is presently run. These measurements were made to provide the data necessary for performing injection, orbit and extraction studies for operating the cyclotron with a new 25 MV tandem electrostatic accelerator as an injector. These two accelerators comprise the Holifield Heavy Ion Research Facility.

The field was studied as a function of 23 variables--the currents in the main coil, 10 trim coils, 9 harmonic coils, and 3 valley coils. The data grid covered the entire median plane of the cyclotron from 0 to 38 inches (0 to 96.52 cm) in 1-inch (2.54 cm) steps and from 0 to 358 degrees in 2-degree steps. In figure 1 is plotted the measured dependence of the field at the center of the cyclotron on the current in the main coil I_M. The present analysis of the field data focussed on field excitations from 12 to 20 kG (indicated in the figure by the arrows). This field region covers the present normal operating range of the cyclotron and the anticipated range when the cyclotron is operated in a coupled mode with the tandem.

The total measured data base contains several million entrees. Such a quantity of data presents difficulties in terms of storage space, speed of access, and ease of use. The analysis of the data, therefore, proceeded with the following objectives in mind; the development of a formulation of the field that would

1) require a minimum number of parameters, hence producing a compact data base to completely and accurately describe the field, and
2) be well-suited for the determination of currents by means of field optimization for setting up the cyclotron for acceleration.

The present paper reports on the formulation of the field that was developed and the accuracy of the results in reproducing the actual cyclotron field.

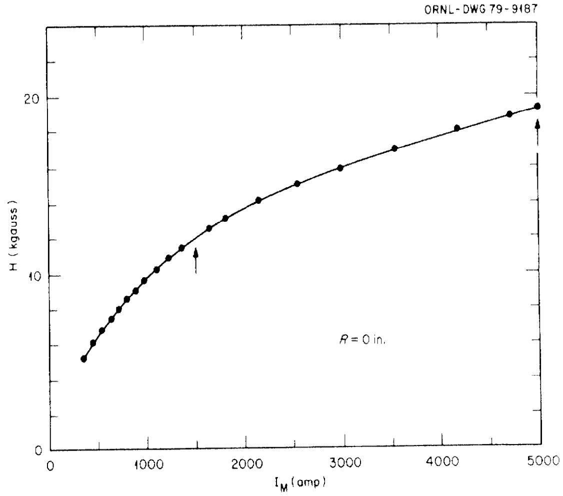

Fig. 1. Plot of the measured average field at the center of ORIC as a function of current in the main coil. The line through the data points is provided to guide the eye. The arrows, at 1500 and 5000 amps, designate the region of magnet excitation which the present analysis considered.

Representation of Field

For each run and for each radius the data were Fourier analyzed. The Fourier representation used was as follows:

$$H(R,\theta,\{I\}) = A_0(R,\{I\}) + \sum_{n=1} [A_n(R,\{I\})\cos n\theta + B_n(R,\{I\})\sin n\theta]$$

where R is the particular radius of the measurement and {I} represents the set of currents in the 23 coils. The first 10 Fourier coefficients and, since ORIC is a three-sector machine, every third up through the 48th harmonic were retained in the analysis. The effects of including only these coefficients in reconstructing the field are illustrated in fig. 2 for run 6598. The currents for this run yield the field that is normally used to accelerate $^{20}Ne^{6+}$ ions to 165.4 MeV. The average field is about 18 kG. The results shown in fig. 2 are for R = 30 in. (76.20 cm) where the field reaches a maximum and consequently provides the most sensitive test of the reproducibility of the field. The high frequency oscillations associated with truncating the Fourier series at the 48th harmonic should have little effect on the acceleration properties of the field. Each Fourier coefficient was parameterized in terms of the 23 coil currents and these parameters were then determined for each coefficient and radius by means of a nonlinear least squares analysis of the data.

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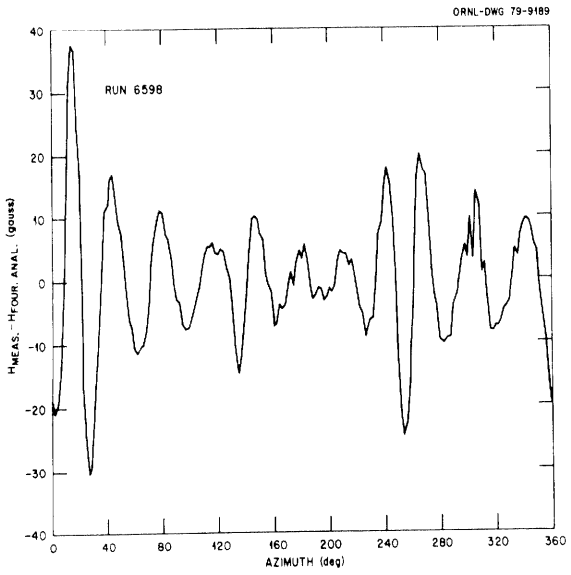

Fig. 2. Plot of the difference between the measured field and field synthesized from Fourier coefficients at R = 30 in. Shows the effect of truncating the Fourier series at the 48th harmonic. The field level is approximately 18 kG.

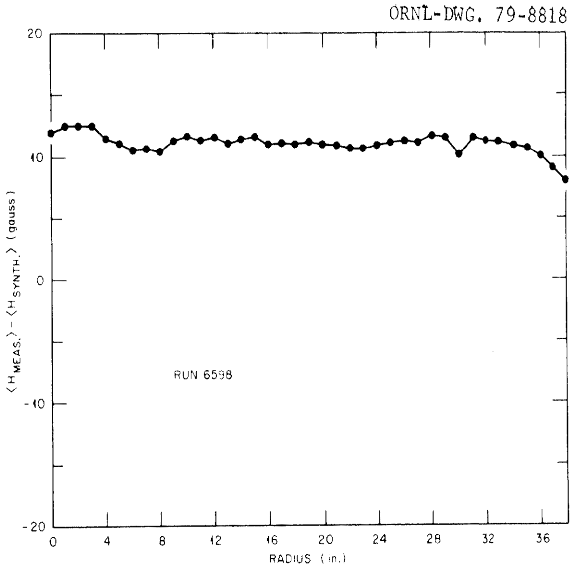

Fig. 3. Plot of the difference between the measured and synthesized average fields as a function of radius. Synthesized field is constructed from field parameterization discussed in text.

The Average Field - A_0

A convenient functional form for expressing the average field at each radius in terms of the 23 currents was found to be

$$A_0(R,\{I\}) = \sum_{i=1}^{7} a_i I_M^{2-i} + \left(\frac{a_8}{A_0} + \frac{a_9}{A_0^2} + \frac{a_{10}}{A_0^3} \right) I_M$$

$$+ \sum_{i=1}^{10} \left(a_{10+i} + \frac{a_{20+i}}{A_0} + \frac{a_{30+i}}{A_0^2} + \frac{a_{40+i}}{A_0^3} \right) I_{T_i}$$

$$+ \sum_{i=1}^{4} \left(a_{50+i} + \frac{a_{54+i}}{A_0} + \frac{a_{58+i}}{A_0^2} \right)$$

$$\times \left(I_{A_i} + I_{B_i} + I_{C_i} \right)$$

where I_M represents the current in the main coil, I_{T_i} the currents in the trim coils, and I_{A_i}, I_{B_i} and I_{C_i} the currents in the harmonic and valley coils in each of the 3 valleys. The parameters a_{20+i} were defined to be 0.0 and thus a total of 52 parameters were varied in an effort to determine the optimum representation of the effects of the 23 coils for field excitations from 12 to 20 kG. It is important to note that the average field, A_0, also appears on the right hand side of the above equation. This is simply a reflection of the fact that the variation of the field with respect to a change in any of the currents is also a function of the average field at that radius. By explicit reference to the average field in this way, the nonlinear effects of the iron are taken into account. For a given set of currents, the average field is readily generated from the above equation by means of iteration. Synthesis of the average field from this parameterization reproduces the absolute field to within about 10 gauss and the relative field to within 5 gauss. In figure 3 are compared the measured and synthesized average fields for run 6598.

The Harmonic Coefficients - A_n and B_n

The expression used in the parameterization of the harmonic Fourier coefficients was

$$A_n(R,\{I\}) = \sum_{i=1}^{5} a_i I_M^{2-i} + \sum_{i=1}^{10} \left(a_{5+i} + \frac{a_{15+i}}{A_0} \right) I_{T_i}$$

$$+ \sum_{i=1}^{4} \left[\left(a_{25+i} + \frac{a_{29+i}}{A_0} \right) \left(I_{A_i} + I_{B_i} \cos n\,120^\circ + I_{C_i} \cos n\,240^\circ \right) + \left(b_{25+i} + \frac{b_{29+i}}{A_0} \right) \left(I_{B_i} \sin n\,120^\circ + I_{C_i} \sin n\,240^\circ \right) \right] .$$

An analogous equation is obtained for B_n where the roles of the parameters a_i and b_i are interchanged. For the harmonic and valley coils, the effects of current variations in only the A valley were measured. Since the coils in valleys B and C are identical to those in A, the parameters obtained from the analysis of the valley A measurements can be rotated to obtain the corresponding parameters for B and C. It is this rotation which is embodied in the sine and cosine terms in the expression contained in the square brackets above. This expression simplifies considerably to

$$\sum_{i=1}^{4}\left(a_{25+i}+\frac{a_{29+i}}{A_0}\right)\left(I_{A_i}+I_{B_i}+I_{C_i}\right)$$

for n = 3, 6, 9 .... At most, 33 parameters were varied to fit each of the Fourier coefficients. For the higher harmonic coefficients, the number of parameters required to achieve a good fit to the data was much smaller. For example, contributions from the trim coils could be neglected above n = 21. As is the case in the equation for A_0, the variations of A_n and B_n with respect to the various currents are expressed as functions of A_0.

In Fig. 4 the azimuthal difference between the measured and synthesized fields are compared for R = 30 inches. The high frequency oscillations associated with the truncation of the Fourier series at n = 48 (see Fig. 2) have been removed from this plot so that the remaining oscillations reflect the cumulative reproducibility of the Fourier coefficients that were included in the analysis. The relative field is reproduced to within about 5 gauss. Shown in Fig. 5 are plots of the magnitude and phase of the measured and synthesized 1st harmonic coefficients as a function of radius. Very good agreement is again obtained.

Conclusion

The analysis of the ORIC magnetic field data for field excitations from 12 to 20 kG has been completed and a parameterization of the field in terms of the 23 currents and the average field at each radius developed. By including the average field in this formulation, the saturation properties of the iron are taken into account. The data base that is generated from this analysis consists of the parameters needed to construct each Fourier coefficient at each radius. This procedure leads to a reduction in the overall data base size by a factor of 100 from the original quantity of data. The absolute field is reproducible to within about 10 gauss and the relative field to within 5 gauss. This description of the ORIC field has now been incorporated in a field optimization program and is currently being evaluated in terms of cyclotron performance. Preliminary results have been extremely encouraging.

Reference

1. S. W. Mosko, et al., "Magnetic Field Measuring System for Remapping the ORIC Magnetic Field," IEEE Trans. Nucl. Sci. NS-24, No. 3 (1977) 1269.

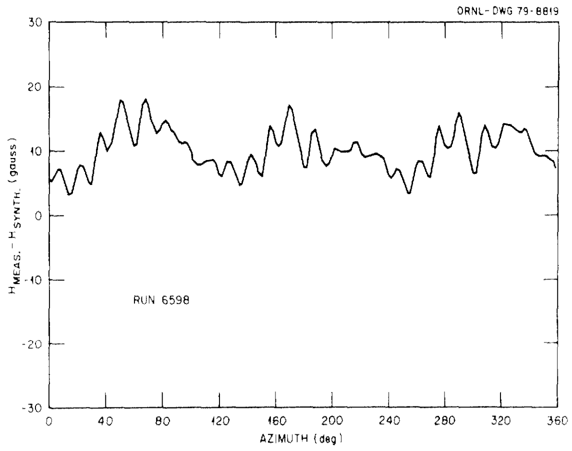

Fig. 4. Azimuthal plot of the difference between measured and synthesized fields at R=30 in. High frequency oscillations (see Fig. 2) associated with truncating Fourier series at 48th harmonic have been removed to emphasize cumulative reproducibility of Fourier coefficients analyzed.

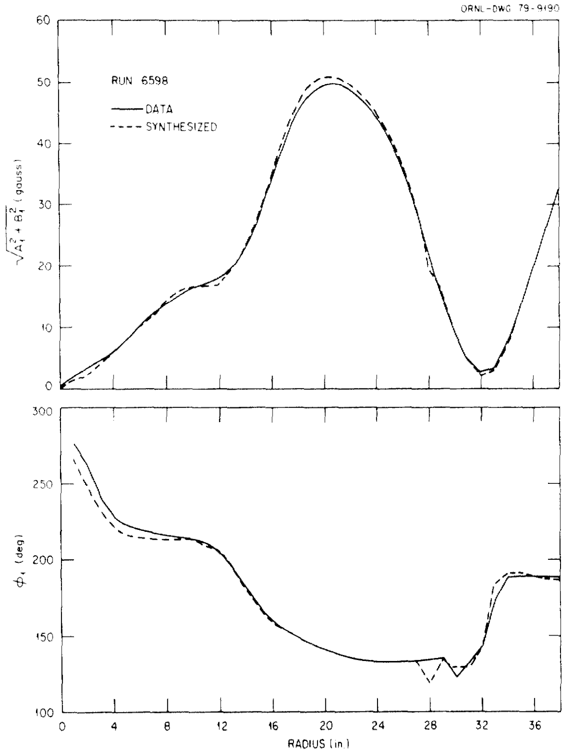

Fig. 5. Comparison of magnitude and phase of measured and synthesized 1st harmonic coefficients. Solid lines represent coefficients extracted directly from data while dashed lines represent the coefficients constructed from parameterization given in text.