STRONG FOCUSING MAGNET MEASUREMENTS

by

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INTRODUCTION

Prior to their installation in the ISR tunnel, the 264 main magnet units were subjected to systematic magnetic measurements in order to detect any possible faults in fabrication and to furnish a complete set of experimental values representative of the spatial field repartition with respect to the alignment elements and which will be used for the calculation of the real machine beam orbit. The special features of these measurements are their high precision and speed of execution. This article describes the general measuring method while the associated electronic equipment and data processing are treated in the paper of K.N. Henrichsen(2).

The magnet units, focusing (F) or defocusing (D), are made from open C iron cores and may be long or short. All cores are of the same length, one core alone being used to make a short unit, two cores together at a small angle on a girder, a long unit. The units are equipped with main excitation windings, correction windings and poleface windings.

The theoretical magnetic field has a sextupole component(1), and the field index and its derivative are given by the following:

\[
\frac{n}{\rho} = -3.133 \, \text{m}^{-1} \quad \text{for F} \\
\frac{n}{\rho} = -1.940 \, \text{m}^{-2} \quad \text{for D}
\]

\[
\frac{n'}{\rho} = 3.018 \, \text{m}^{-1} \\
\frac{n'}{\rho} = 1.496 \, \text{m}^{-2}
\]

MAGNETIC MEASUREMENTS AND CHOICE OF METHOD

The reference axes used in the measurements are defined by the alignment elements of the units. As the same elements are used for the alignment in the tunnel, the measured values represent (except for the errors involved in this alignment) the real field as seen by the particles. These alignment elements, consisting of two targets \( M_1 \) and \( M_2 \) and a spirit level supporting jig \( G \) (Fig. 1), are positioned in function of the mechanical measurements of the individual cores and define the three axes \( O_x, O_y, O_z \) in the following way: the ideal median plane \( x, y \) is parallel to and at a given distance from the plane defined by \( M_1 M_2 \) and the level \( G \), and the \( y \) axis (central orbit) is the orthogonal projection of the line \( M_1 M_2 \) in this plane.

Measurements are made in the plane \( x, y \) and give values for:

- magnetic induction \( B_z \) (o, y) along the y axis
- gradient \( G(x, y) = \frac{\partial}{\partial x} B_z(x, y) \) for \( x = -6, 0, 6 \) cm
horizontal component of field \( B_x \).

As the length of a magnet unit is small compared with the betatron wavelength, to a first approximation we are only interested in the integrated values:

- **bending power**: \( P_b = \int_{-\infty}^{+\infty} B_z (o, y) \, dy \)
- **focusing power**: \( P_g (x) = \int_{-\infty}^{+\infty} G (x, y) \, dy \)

\( P_b \) and \( P_g (x) \) are measured for 7 values of excitation current \( I \) corresponding to field levels of from 0.1 to 1.3 Tesla with and without PFW excited, and with a precision of 1 part in 100000. Measurement of the current \( I \) is replaced by that of the field \( B_r \) in a reference unit excited in series. \((\sigma = B_x / B_z)\) is measured with a precision of \( \pm 0.0001 \) rad at two field levels 0.4 and 1.2 Tesla.

All measurements are performed using glass cored coils and electronic integrators, the integrated voltage measured with a digital voltmeter being proportional to the change of flux through the coil:

\[ V = \frac{1}{\tau} \Delta \varphi = \frac{1}{\tau} S \cdot \Delta B , \]

where \( \tau \) is the time constant of the integrator (determined experimentally). The effective surface area \( S \) of the measuring coil is found by comparison with a standard coil in an a.c. energised homogeneous field.

The error due to integrator drift is compensated for by making two measurements with voltage of opposite sign.

Long coils are used because these enable a more direct evaluation of the required mean values. The use of Hall plates is precluded especially for gradient measurements because of the insufficient resolution and uncertainty of their magnetic centre in strongly inhomogeneous fields.

Coils are displaced end to end over the length of the unit (Fig. 1 and 2), and the integrated values \( P_b \) and \( P_g (x) \) are given by the sums:

- **bending power**: \( P_b = l_B \sum \overline{B} (o) \)
- **focusing power**: \( P_g (x) = l_g \sum \overline{G} (x) \)

where \( l_B \) and \( l_g \) are the lengths of the field and gradient measuring coils (more precisely the effective displacement of these coils) and \( \overline{B} (o) \) and \( \overline{G} (x) \) the measured values.

In general, these formulas are only true for precisely rectangular coils but in the special case of longitudinal symmetry of field, gradient and measuring positions, they also hold for trapezoidal coils. Higher order irregularities can be ignored because of the small contribution of the end effects.
FIELD MEASUREMENT

$B (o, y)$ is measured using a flip coil. The influence of the sextupole component is eliminated by a proper dimensioning of the coil (3), and the average value of $B (o, y)$ is given by the change of flux when the coil turns through $180^\circ$:

$\Delta \varphi = 2 \bar{B} (o) \cdot S_F ,$

$S_F$ being the effective surface area of the coil.

In the measurement of $\frac{\bar{B} (o)}{B_r}$, the effect of a possible strain of excitation current is eliminated by a special sequence (Fig. 3) which enables the exactly simultaneous measurement of $\bar{B} (o)$ and $B_r$.

Initially, the coils of surface area $S_F$ and $S_r$ are connected in opposition to the integrator, of time constant $T_F$. Referring to Fig. 3 it can be shown that the integrated voltages $V_{F}^{t1}$, $V_{F}^{t2}$ at time $t_1$ and $t_2$ can be expressed in the form:

$$V_{F}^{t1} = \frac{1}{T_F} \left\{ 2 S_r B_r^{t1} - \left[ S_r (B_r^{t1} - B_r^{t0}) - S_F (\bar{B}^{t1} - \bar{B}^{t0}) \right] \right\}$$

$$V_{F}^{t1} - V_{F}^{t2} = \frac{1}{T_F} \left\{ 2 S_F \bar{B}^{t1} - \left[ S_r (B_r^{t2} - B_r^{t1}) - S_F (\bar{B}^{t2} - \bar{B}^{t1}) \right] \right\}$$

The terms in square brackets tend to zero for $S_F = S_r$ and $\bar{B} = B_r$, so that $V_{F}^{t1}$ and $V_{F}^{t1} - V_{F}^{t2}$ measure $B_r^{t1}$ and $\bar{B}^{t1}$ at the same time $t_1$.

For our series of measurements the relevant constants are as follows:

| Measuring coils | Long unit | 10 x 10 x 608 mm |
| Short unit | 10 x 10 x 700 mm |
| Surface area | $S_r = S_F = 0.5 \, \text{mm}^2$ |
| Integrator time constant | $T_F = 0.141 \, \text{s}$ |

The coil is mounted between two glass bars (Fig. 4) and rotated by means of a pneumatic piston.

GRADIENT MEASUREMENT

It is not possible to deduce $G (x)$ from two field values $B (x - \Delta)$ and $B (x + \Delta)$ with a precision of 1 part in $10^4$ because with $\Delta \simeq \text{cm}$ this would require the measurement of $B$ to be accurate to $1 \, \text{ppm}$.

Gradient is therefore measured directly using a coil of surface area $S_G$ displaced from position $x - \Delta$ to $x + \Delta$. Coils cross section and displacement $2 \Delta$ are chosen to eliminate the influence of an octupole component(3), and the average value of $G (x)$ along the length of the coil is deduced directly from the change of flux:

$$\bar{G} (x) = \frac{\Delta \bar{G}}{S_G \cdot 2 \Delta}$$

By connecting in opposition a fixed compensating coil, the required stability of the excitation current is reduced from $\sim 10^{-6}$ to $\sim 10^{-4}$. The actual measuring sequence, given in Fig. 3, includes a measurement
of $B_r$. With the notation of Fig. 3, it can be shown that $V_G^{tl}$ can be expressed either as

$$V_G^{tl} = \frac{1}{\tau_G} \left\{ \left( B^{to}(x-\Delta) - B^{to}(x+\Delta) \right) S_G - \left\{ \left( B^{tl}(x-\Delta) - B^{to}(x+\Delta) \right) S_G - \left( B_C^{tl} - B_C^{to} \right) S_C \right\} \right\},$$

or $V_G^{tl} = \frac{1}{\tau_G} \left\{ \left( B^{tl}(x-\Delta) - B^{tl}(x+\Delta) \right) S_G - \left\{ \left( B^{tl}(x-\Delta) - B^{to}(x-\Delta) \right) S_G - \left( B_C^{tl} - B_C^{to} \right) S_C \right\} \right\},$

$S_C R_C$ being the flux in the compensating coil.

The terms in square brackets tend to zero, and depending on the exact value of the flux in the compensating coil, gradient is measured at time $t_0$ (if $S_C R_C = S_C R_B (x-\Delta)$) or time $t_1$ (if $S_C R_C = S_C R_B (x+\Delta)$). It will be described later how compensation also occurs for global displacement of these two coils.

In our case the characteristics of the gradient measuring system are as follows:

<table>
<thead>
<tr>
<th>Gradient Coil</th>
<th>Long Unit</th>
<th>18 x 26 x 608 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Unit</td>
<td>18 x 26 x 700 mm</td>
<td></td>
</tr>
<tr>
<td>Effective Surface Area</td>
<td>$S_G = 3.8 \text{ m}^2$</td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>$2\Delta = 18 \text{ mm}$</td>
<td></td>
</tr>
</tbody>
</table>

Integrator time constant $\tau_G = 0.030 \text{ s}$

In order to obtain the required precision, it is necessary to measure the stroke $2\Delta$ to the nearest micron. Our system is illustrated in Fig. 5. The measuring coil is fixed to a carriage supported on ball bearing runners and the stroke, obtained pneumatically, is defined by two mechanical stops. This carriage is fixed to an assembly which can be moved by means of two pneumatic pistons to permit gradient measurements in three radial positions and on which is mounted the compensating coil. In this way the unavoidable displacement of the assembly (a few microns) when the carriage strikes the stop gives rise to a change in flux in both measuring and compensating coils and is cancelled out in the result.

MEASUREMENT OF THE HORIZONTAL COMPONENT OF FIELD $B_x$

$B_x$ is deduced from the measured values of $B_z$ and the angle $\alpha_0 = B_x / B_z$. The magnetic measurements are made referring to the mechanically defined horizontal plane $x, y$ and $\alpha_0$ is found by measuring the change in flux in a coil of surface area $S_M$, with magnetic axis in the $x$ direction, when the field is changed by an amount $\Delta B_z$. The coil can pivot about an axis in the $y$ direction and is attached to an arm which can be levelled horizontally by means of a spirit level $N$ (see Fig. 6). Most of the mechanical errors are eliminated by turning the coil $180^\circ$ about the $x$ axis (Fig. 4), remeasuring, and taking the average. Referring to Fig. 6, the changes in flux are, for small angles:
\[ \Delta \varphi_1 = S_M \Delta B_z (\alpha_o - c) \]
and \[ \Delta \varphi_2 = S_M \Delta B_z (\alpha_o + c) \]
so that \[ \alpha_o = \frac{1}{2} \frac{\Delta \varphi_1 + \Delta \varphi_2}{S_M \Delta B} \]
The remaining errors are negligible (to within \(10^{-5}\) radians).

The characteristics of the system are as follows:

- **coil dimensions**
  - long unit: 10 x 55 x 674 mm
  - short unit: 10 x 55 x 766 mm
- **effective surface area** \(S_M = 5.7 \text{ m}^2\)
- **integrator time constant** \(\tau_M = 0.030 \text{ s}\)
- **field variation** \(\Delta B_z = 0.2 \text{ Tesla}\)

**MEASURING BAYS**

Long and short magnet units are measured in two separate measuring bays using common electronic apparatus and power supplies. In each case measuring coils are mounted on carriages which move along very precise and rigid granite benches. The carriages can be moved from one measuring position to the next using an electric motor and at each position, determined by stops, they are blocked rigidly to the bench by means of small pneumatic jacks. One carriage is fitted with field measuring coils and another with the gradient coil assembly. For measuring the long unit (Fig. 7) two identical granite benches, placed end to end and having the same small angle as the cores, are used. Measurements can be made on either side of the benches according to whether the unit is F or D type (Fig. 2).

**ALIGNMENT OF THE MAGNET WITH RESPECT TO THE MEASURING BENCHES**

The same alignment elements are used for the setting up of a magnet unit for its magnetic measurements as is used to position the unit in the ISR. These elements, consisting of two targets \(M_1\) and \(M_2\) and a spirit level supporting jig G (Fig. 1) are positioned in function of the mechanical measurements of the individual cores.

The required alignment precision is \(\sim 1/100 \text{ mm}\) in the \(x\)- and \(z\)-directions, and \(\sim 1 \text{ mm}\) in the \(y\)-direction.

Referring to Fig. 1, the procedure for a short unit is the following:

i) determination of the axis of rotation of the field coil by use of telescopes \(T_1\) and \(T_2\)

ii) definition of this axis by 2 spherical targets \((E_1, E_2)\)

iii) vertical translation to \(E'_1, E'_2\) by means of a pyrex rod equipped with a spirit level

iv) alignment of \(E'_1, M_1, M_2, E'_2\) using telescopes \(T'_1\) and \(T'_2\) and levelling of the spirit level G.

For the alignment along the \(y\) axis the position of the core is measured directly with respect to the bench.
The same procedure is used to align long units but it is necessary to displace \( E_1 \) and \( E_2 \) horizontally before the vertical translation using the pyrex rods (Fig. 2).

CONCLUSION

The methods outlined above have been used successfully to measure all units for the ISR main magnet. These measurements took 18 months and their reproducibility was within 1 part in 10 000. Measurements for the ISR field display will be based on the same principles.

ACKNOWLEDGMENTS

B. Autin, K.N. Henrichsen, and C. Mazeline have also been associated directly with this work.

REFERENCES

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(2) K.N. Henrichsen - The automatic measuring system for the CERN ISR main magnet - Paper presented at this Conference

(3) B. de Raad - Measurements of strongly inhomogeneous magnetic fields - Thesis, Delft, 1953
Fig. 1 - Measurements of short units.
Fig. 3 - Timing of measurements.
FIG. 4 - Field measurement assembly
Fig. 6  Measurement of the horizontal component of the field ($B_x$)
FIG. 7 - Measuring bays for long and short units