MAGNETIC FIELD MEASUREMENTS OF THE DESY II MAGNETS

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Summary

A new method has been developed for the precise magnetic field measurements in ac magnets. The technique has been applied to the DESY II dipoles and quadrupoles. Movable coils of various lengths are used, and voltage induced by the ac excitatition is compensated by reference coil. A fast ADC triggered at different levels of magnet current converts the output of a low drift analogue integrator. Measurement and data handling are microprocessor controlled. The data are sent to the computer centre for analysis and storage. From there the results and a graphic display are sent back to a local interactive terminal for qualitative online checking.

Introduction

In fast cycling machines as DESY II one wants to know how the eddy current affects the fields in the magnets. To get a realistic answer to the question of how the field properties of the magnets change during acceleration, the same ac excitation as in future operation is used for the field measurements.

In order to use moving coils for the field measurements one must have a fast integrator capable of handling the high voltages from the coil.

Normally voltage-to-frequency converters combined with counter techniques are used for dc magnet measurements. But there is even in high frequency versions, a problem with signal dynamics: a 5 MHz VFC needs 13 ms for 16 bit resolution . The alternative method described below uses an analogue integrator and a high resolution ADC. In this way 16 bit resolution can be obtained in about 40 µs. The resolution required for the measuring system (about 10^{-4}) has been determined by particle beam tracking analysis. Since in DESY II the energy varies from .2 to 9 GeV between injection and ejection, the required resolution at injection is $2\cdot 10^{-6}$ of the maximum field and thus permits relative measurement only.

General Description

From Faraday's law of induction the voltage induced in a moving coil is:

$$V = N \frac{d \int_s \vec{B}\,\vec{n}\,da}{dt} = N \left\{ \int_s \frac{\partial \vec{B}}{\partial t}\,\vec{n}\,da + \oint_c (\vec{B}\times\vec{v})\,d\vec{l} \right\} \qquad (1)$$

The integral over the surface (s) of the coil with N windings only describes the time dependence of the normal component B (x,t), while the second integral over the coil contour (c) derives from the change in position when the coil moves with velocity $\vec{v}$.

Thus with an ideal integrator with infinite voltage range one gets

$$\int^t V dt = NA\,\bar{B}(\bar{x},t) + k \qquad (2)$$

where $\bar{B}(\bar{x},t) = \frac{1}{A}\int_s \vec{B}\,\vec{n}\,da$

A = coil area,
k = integration constant
and $\bar{x}$ describes the coil position.

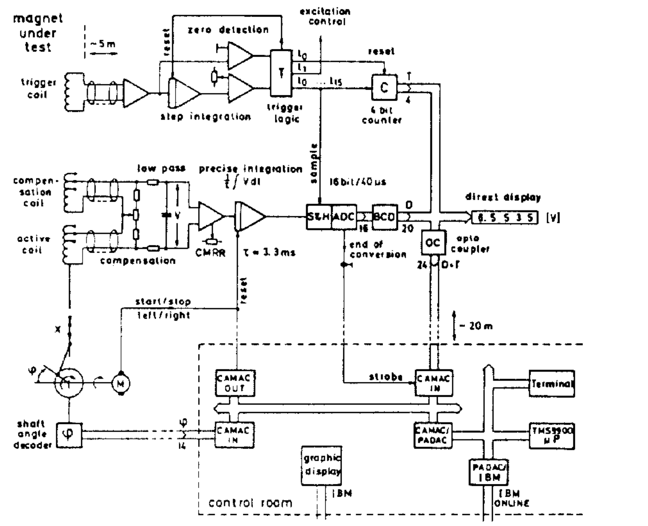

Fig. 1 Circuit diagram of magnet measuring device

For an ac field survey, measurements must be made at distinct time values (t) to distinguish between time and spatial effects.

These time markers are derived from measurements of the yoke field $B_y(t)$ which is related to the field at the centre of the gap. The trigger for the minimum field (at time t_o) is derived by detecting the zero slope (Fig. 2):

$$\dot{B}_y(t_o) = 0 \quad \text{where } t_o = m \cdot 2\pi/\omega \quad m = 0,1,2 \ldots$$

A sampling trigger (t_1) for the current control is locked to t_o with a time delay Δt which is adjusted so that, with constant $I(t_1)$ = injection level, we have $I(t_o) = 0$.

This is important for absolute measuring capability: if the "power off" procedure is always carried out in the same manner (e.g. first ac, then dc off), the remanent minimum field, can be measured afterwards.

The remaining triggers $(t_2 \ldots t_{15})$ correspond to equal increments of B_y and are derived from step integration.

$$\Delta B = \int_{t_o, t_2 \ldots}^{t_2, t_3 \ldots} \dot{B}_y(t)\,dt = \text{const.}$$

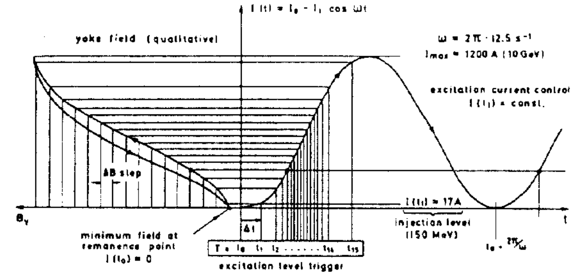

Fig. 2 ac excitation diagram

With these triggers, which repeat at period $2\pi/\omega$ and always occur at the same yoke field, the integrator output can be used to measure the spatial variation of the field.

Special Hardware

Integrator:
Design using chopper stabilized amplifiers (ICL7650, Intersil)
preamplifier (gain = 50) with high common mode rejection
integrator can be automatically adjusted to a drift of less than .1 mV/s just before field measurement starts
time constant .1 s
phase shift -2(-18) degrees at 12.5(100) Hz
output amplifier (gain = .6) for adaptation to the ADC.

ADC:
BCD output, resolution .1 mV (also short time stability)
sample & hold amplifier (MP260, Analogic)
acquisition time = 5 µs
analog-digital converter (MP8016, Analogic)
conversion time = 40 µs
resolution 16 bit

Shaft angle decoder:
ROC 500/13 (J. Heidenhain, W.-Germany)
resolution 13 bit/360 degrees
accuracy ± 1 bit

Dipole Measurement

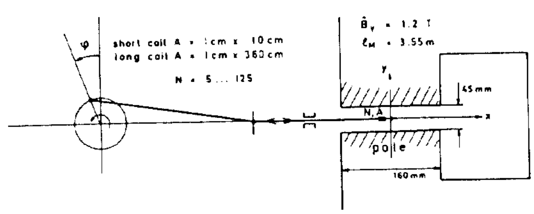

Fig. 3 Dipole measuring device

For dipoles the variation of the local field and the integral field in the median plane is measured using a short or a long coil, respectively, that is laterally moved by a crank shaft.

Since the maximum input level of the preamplifier is limited to 70 mV while for a coil with $N \cdot A = .2\ m^2$, the coil voltage can be as large as 8 V, it is necessary to compensate the ac component of the coil signal by subtracting a second ac signal of similar shape and magnitude. This compensating signal is derived from a fixed coil at an appropriate position inside a reference magnet supplied with the same current.

The integrator drift, which was assumed to be constant during 10 s of measurement cycle, was numerically compensated by the computer. In accordance with Eq. (2) the output from the ADC can be written as (Fig. 1):

$$D(\bar{x},T) = \frac{NA}{\tau} \cdot \bar{B}(\bar{x},T) + D_{o,T} \qquad x = x(\varphi)$$

All coils have a similar resolution ($\Delta B \simeq \pm 1.5 \cdot 10^{-6}$ tesla) since the maximum compensatable N•A is determined by the compensation coil.

Fig. 4 shows a typical normalized computer output which, for 4 different magnet excitations gives the transverse variation of the integral field in the median plane.

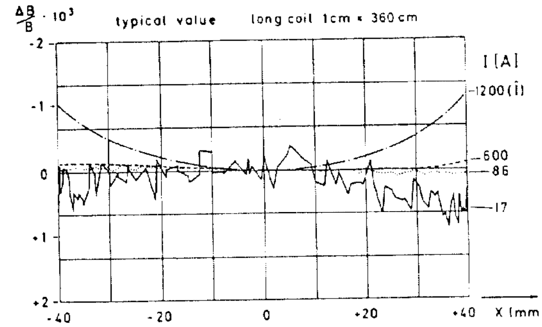

Fig. 4 Computer output from measurement of integral dipole field

A typical fit from a measurement with a short coil is displayed in Fig. 5, showing the transverse field variation ΔB_y in the median plane for 3 different excitation currents with central fields of about 5,160 and 800 Gauss respectively.

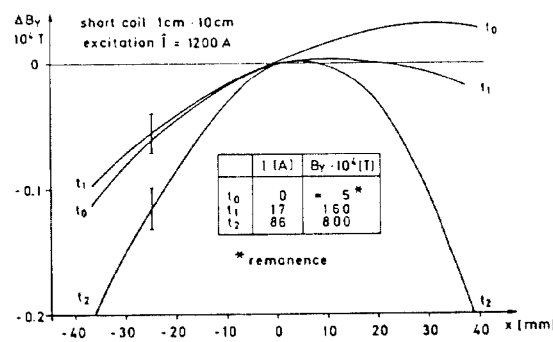

Fig. 5 Measurement of local field variation at injection level (t_1) and in the vicinity (t_o,t_2)

The measurements have shown that the newly designed and built DESY II dipoles satisfy the field quality requirements at injection as well as over the whole energy range.

Quadrupole Measurement

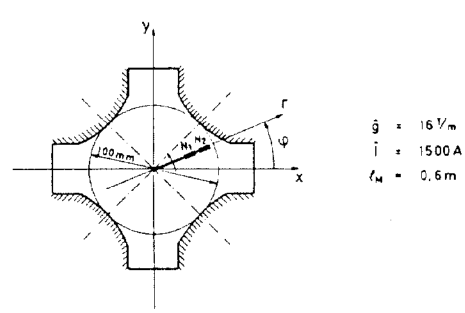

Fig. 6 Quadrupole measuring device (principle)

A solution of the 2-dimensional Laplace equation for the scalar potential in cylindrical coordinates is given by

$$U(r,\varphi) = - \sum_{n=1}^{\infty} \frac{r^n}{n} (b_n \sin n\varphi + a_n \cos n\varphi) \qquad (3)$$

The normal component of the induction at the measuring coils is

$$B(r) = -\frac{\partial U(r,\varphi)}{r\,\partial\varphi} = \sum_{n=1}^{\infty} r^{n-1}\, c_n \cos(n\varphi + \delta_n) \qquad (4)$$

and is equivalent to a Taylor expansion of the radial dependence

$$B(r) = \sum_{n=1}^{\infty} \frac{g^{(n-1)}}{(n-1)!}\, r^{n-1} \qquad g^{(n-1)} = \frac{\partial^{(n-1)} B(r)}{\partial r^{n-1}}$$

so that $g^{(n-1)} = (n-1)!\; c_n \cos(n\varphi + \delta_n)$ (5)

For magnets with quadrupole-like symmetry, i.e. $U(\varphi + \pi/2) = - U(\varphi)$, only the harmonic numbers $n = 2, 6, 10, 14, 18 \ldots$ are expected. For our quadrupoles two simultaneously rotating coils (with numbers of turns N1, N2) mounted in the same plane have been used to obtain proper compensation (Fig. 6). Thus the data output is proportional to the difference in coil fluxes $\Delta\Psi$. For two coils sufficiently longer than the effective magnet length l_M, we have

$$\Delta\Psi = l_M \left\{ N_2 \int_{r_{21}}^{r_{22}} B(r)dr - N_1 \int_{r_{11}}^{r_{12}} B(r)dr \right\}$$

$$= l_M \sum_{n=1}^{\infty} c_n \cos(n\varphi + \delta_n)\, \frac{1}{n} \left\{ N_2 (r_{22}^n - r_{21}^n) - N_1 (r_{12}^n - r_{11}^n) \right\}$$

so that the ADC output D can be written as:

$$D(\varphi,T) = \sum_{n=0}^{\infty} \bar{c}_n\, \bar{r}^{\,n-1}\, c_{n,T} \cos(n\varphi + \delta_n) \qquad (6)$$

with a correction factor $\bar{c}_n$ specific to each harmonic due to the coil arrangement.

A Fourier analysis applied to $D(\varphi,T)$ yields components C_n up to n=15. From the C_n the derivatives of the gradient (using Eqs. (6), (5)) or the deviation Δg at a certain radius $\bar{r}$ can be calculated.

$$(\Delta g \cdot \bar{r})_T = \sum_{n=3}^{\infty} \frac{C_{n,T}}{\bar{c}n} \cos(n\varphi + \delta_n) \qquad (7)$$

The dipole component is strongly affected by mechanical tolerances and external fields. Therefore its contribution to Δg is neglected in Eq. (7).

Also the sextupole component is influenced by mechanical adjustments of the coil rotation. A value less than $1 \cdot 10^{-4}$ indicating excellent adjustment is possible only with a sufficient number of coil supports.

A normallized data set from a typical quadrupole is displayed in Fig. 7. It indicates the kind of relative accuracy obtained and shows that the remaining quadrupole contribution is of the order of 1 %.

The result of the harmonic analysis is composed in Tab. 1, which gives the relative strength of the significant field harmonics at r = 40 mm together with the accuracy of the measurement at excitation currents of 120 A, 600 A and 1200 A, respectively.

Most of the harmonics are less than $1 \cdot 10^{-4}$ of the quadrupole component. Only the terms n=4 and n=6 are larger, but still in tolerance. The term n=4 indicates a slight deviation from the ideal quadrupole symmetry.

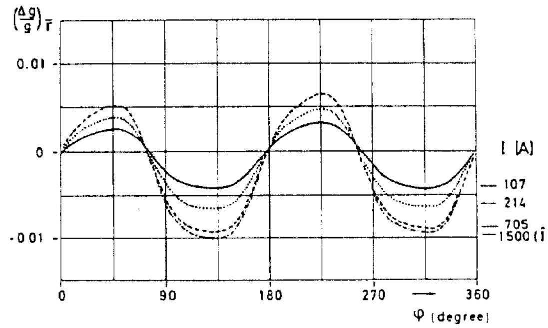

Fig. 7 Computer output from quadrupole measurement

Tab. 1

Relative strength of the field harmonics at r=40 mm from a typical quadrupole ($\cdot 10^{-4}$)

n	120 A		600 A		1200 A	
3	0.3	±0.10	0.5	±0.020	0.7	±0.010
4	1.6	06	2.3	12	2.0	06
5	0.1	5	0.3	10	0.3	5
6	3.3	4	6.9	08	7.5	4
10	0.1	3	0.3	6	0.2	3

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