MEASUREMENT SYSTEM FOR MAGNETIC FIELD MONITORING IN CHARGED PARTICLE ACCELERATORS

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Abstract

Providing high radiation resistance of a measuring device is the foreground task for magnetic field monitoring in the open space, reactors and charged particle accelerators. Main element of the developed radiation resistant system is the specialized functionally integrated measuring transducer, containing the actuating coil with the field covering microcrystalline Hall generator. Taking into account differential component of the signal which value is defined by the magnetic field induction of the coil, one may determine the transducing function drift of the measuring circuit. Algorithms of the signal correction, operation of the specialized measuring transducer and the transducer-based system are considered.

1 INTRODUCTION

Magnetic field monitoring in the open space, reactors and charged particle accelerators requires development of radiation resistant magnetometric devices (MMD). Hall generators (HG) are used most often as the primary transducers of such devices. In order to provide high radiation resistance of HG special technologies of their manufacturing are developed [1]. Thus, optimizing the dopant concentration in discrete microcrystalline HG, one may reach instability of Hall voltage in the range of 0.15÷0.5 % under the high-energy neutron irradiation with the fluence of $\Phi=10^{14}$ n·cm^{-2} [2]. Works on radiation modification of HG materials are being carried out, which allow to improve radiation stability of the materials by several orders. However, restrictions on physical mechanisms of semiconductor HG operation almost do not permit further improvement of radiation stability of MMD based on HG.

Alternative way for stability improvement of MMD is inducing the feedback into measuring circuit [3]. The method is based on forming stable test magnetic field of known strength around the primary transducer. Transducing function of the measuring circuit is determined by means of measuring the HG signal change during test magnetic field formation. This allows performing continuous or periodic correction of measurement results of studied field. HG is located in the field of an actuating coil (miniature solenoid), which forms the test magnetic field. High radiation stability of such MMD is caused by the fact that radiation does not affect the test field of the actuating coil. When operating under hard radiation conditions change of the coil resistance made, for example, from copper wire, is much lower in comparison with the semiconductor HG parameter drift. Besides, when supplying stable current to the actuating coil, its resistance change does not lead to the test field magnitude change. Maximal efficiency of the method takes place when the measuring field around HG is fully compensated by the test field.

But in order to monitor high magnetic fields the test methods for MMD parameter stabilization are inefficient. The reason is an inability of forming high values of test or compensating magnetic fields. The present work is devoted to the development of theory and practice of test methods for parameter stabilization of radiation resistant MMD in order to monitor high magnetic fields.

2 CORRECTION ALGORITHM

The new algorithm for MMD transducing parameter correction we have developed, allows to avoid the problems of forming high test magnetic fields and is efficient for measuring fields of any magnitudes. Base solutions of the problem are:

- simultaneous analysis of the transducing parameter by integral and differential components of the signal;
- frequency separation of integral and differential components of the signal;
- special calculation method of values of transducing function and measuring magnetic field.

Frequency separation of differential and integral components of the signal which is the base of the given algorithm, is caused by necessity of high measurement accuracy of the signal change (differential component) at high value of the signal formed by measuring field (integral component). Thus when change is measured of the test field of actuating coil with the induction of $\Delta B = 1$ mT at relative measurement error of $\delta B = 10^{-3}$, device resolution should be not worse than $\Delta B_{min} = 1$ μT. Reaching such resolution and appropriate stability at magnetic field measurements up to 10 T presupposes providing the dynamic range of the signal in measuring circuit not less than 140 dB. It is obvious that such parameters are practically unachievable. Solution of the problem means the independent processing of differential and integral components of the signal. The simplest method of such separation is the processing of integral component in the direct current circuit, and test one – in frequency-selective circuit, when alternate current frequency is set up in the actuating coil. In each of the tracks dynamic range of 70÷80 dB is provided, which permits to obtain ratio of maximum measuring field value B_{max} to the resolution by test field ΔB_{min} near 140÷160 dB.

Depending on HG parameters and required measurement accuracy we consider the transducing function as linear relationship, polynomial one or mathematical model which links Hall voltage with electrophysical and design parameters of HG.

Taking into account rather good linearity of the HG transducing function, the function derivative may be considered to be constant value in all measuring range with the error within 0.1÷5.0 %. Then the problem of determination of HG transducing function which could drift during long-term operation under hard radiation, is reduced to the measurement of curvature $S = \Delta U_H / \Delta B$, where ΔU_H is the Hall voltage change, caused by test field with induction ΔB. In the case of analogous processing of the signal efficient method is correction of HG operating current in such a way that ratio $\Delta U_H/\Delta B$ is constant during all measurements.

The use of polinomial representation of the transducing function allows one to considerably improve the measurement accuracy. It is expected that nominal transducing function

$$U_{Ho} = \sum_{j=0}^{n} a_j \cdot B^j \qquad (1)$$

(a_j - coefficients of the polinomial series) drifts almost linearly ($U_{He} = G \cdot U_{Ho}$, where G - factor of proportionality). Graphic expression of the transducing function and quantities to be measured is presented at Fig.1. If change value $\Delta U_0/\Delta B$ of the measured voltage in the point of $U_{He}(B_x)$ is equal to nominal function derivative in this point, then HG parameter is constant. But, as one may see at Fig.1, when the transducing function drifts its change value is not constant too $\Delta U_e / \Delta B \neq \Delta U_0 / \Delta B$.

Having determined the transducing function derivative

$$\frac{dU_{He}}{dB} = \frac{d(G \cdot U_{Ho})}{dB} = G \cdot \frac{dU_{Ho}}{dB} = \qquad (2)$$

$$= G \cdot \sum_{j=1}^{n} j \cdot a_j \cdot B^{j-1}$$

and taking into account condition $\lim_{\Delta B \to 0} \frac{\Delta U_H}{\Delta B} = \frac{dU_H}{dB}$, let us write the system of equations for linear scaling

$$\begin{cases} U_{He}(B_X) = G \cdot U_{Ho}(B_X) \\ \dfrac{dU_{He}(B_X)}{dB} = G \cdot \dfrac{dU_{Ho}(B_X)}{dB} \end{cases} \qquad (3)$$

After appropriate transformations we receive

$$U_{He}(B_x) \cdot \sum_{j=1}^{n} j \cdot a_j \cdot B^{j-1} = \frac{\Delta U_e(B_x)}{\Delta B} \cdot \sum_{j=0}^{n} a_j \cdot B^j \qquad (4)$$

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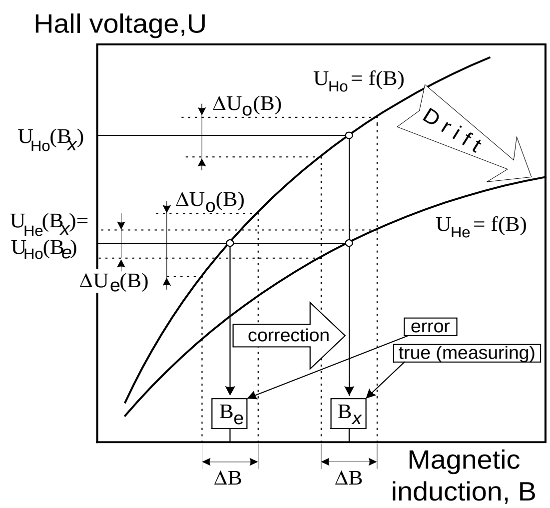

Fig.1. Graphic expression of the transducing function

In order to solve (4) by B_x with known values of integral $U_{He}(B_x)$ and differential $\Delta U_e(B_x)$ signal components and given actuating field value $\Delta B = const$, let us apply Newton iteration method. Let us transform (4) to the equation $f(B)=0$:

$$f(B) = \bar{U}_H \cdot \sum_{j=0}^{n} a_j \cdot B^j - \sum_{j=1}^{n} j \cdot a_j \cdot B^{j-1} = 0, \qquad (5)$$

where $\bar{U}_H = \frac{\Delta U_e(B_x)}{U_{He}(B_x)} \cdot \frac{1}{\Delta B}$ – normalized value of the signal. Taking into account that at the $[B_e, B_x]$ interval $\frac{d^2 f(B)}{dB^2} \neq 0$ and $f(B_e) \cdot \frac{d^2 f(B_e)}{dB^2} > 0$, the root is determined by $B_m = B_{m-1} - \frac{f(B_{m-1})}{df(B_{m-1})/dB}$ iteration. Initial iteration root we take as $B_1 = B_e$, which is determined by MMD without correction. Therefore second iteration root is

$$B_2 = B_e - \frac{\bar{U}_H \cdot \sum_{j=0}^{n} a_j \cdot B^j - \sum_{j=1}^{n} j \cdot a_j \cdot B^{j-1}}{\bar{U}_H \cdot \sum_{j=1}^{n} j \cdot a_j \cdot B^{j-1} - \sum_{j=2}^{n} j \cdot (j-1) \cdot a_j \cdot B^{j-2}} \qquad (6)$$

The iteration process is continued until the condition $|B_x - B_{m-1}| / B_m < \delta B$ is satisfied, where δB – relative error of the measurement. Calculation result will be true value of the field induction measured $B_x = B_m$. As it is resulted from the investigations carried out, error of the presented algorithm is in the range of 0.05% ÷ 0.1% and depends on the drift value of the HG parameters when operating under radiation conditions.

3 SYSTEM CHARACTERIZATION

During complex analysis of the problem of developing radiation resistant MMD we have found possible to unify the problem solutions for such devices on the base of specialized module – functionally-integrated magnetometric transducer (FIMMT). By means of combining the two elements of the transduction – semiconductor HG and copper actuating coil, which covers the HG and some construction elements, FIMMT allows to comprise many functions. Its main tasks are:

- direct measurement of magnetic field induction by means of HG;
- temperature measurement by the coil resistance (as a copper thermoresistor);
- HG thermostatting by means of controllable heating of the coil;
- measurement of weak magnetic field induction by means of compensation method;
- formation and measurement of stationary test magnetic fields;
- formation and measurement of pulsed magnetic fields with high induction values;
- formation and measurement of differential test magnetic field;
- thermostatting with simultaneous formation and measurement of compensating, test and differential magnetic fields;
- constant or pulsed periodical annealing of HG radiation defects.

Depending on the operation conditions and measured magnetic field range the actuating coil could be of different shape, for example cylinder, toroid etc. Thus, at Fig.2 one may see FIMMT with cylindrical coil from the lateral of which the bore is made to induce microsubstrate with HG crystal.

HG location in the coil corresponds to the criterion of maximum actuating field and its stability on the measurement plane. Depending on the temperature mode heat radiator or insulation is required for FIMMT.

The monitoring system consists of the basic unit, set of probes on the base of the FIMMT, voltmeter and personal computer with the IEEE-488 interface bus. The basic unit provides preliminary signal amplification, noise suppression, signal commutation, forming test signals etc.

The system includes three identical measurement channels. It allows to perform three-dimensional magnetic field monitoring. Moreover, one may considerably improve reliability of the measurement results under the long-term operation conditions in charged particle accelerators, by means of directing these three channels along one direction. It is one of the determinant functions of intelligent measuring devices.

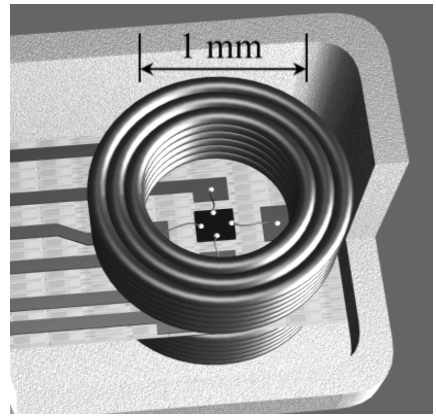

Fig.2. View of the FIMMT

Measurement system for magnetic field monitoring in charged particle accelerators is developed to be operated under radiation conditions (fast neutron fluence $\Phi=10^{14}\,n\cdot cm^{-2}$, neutron energy $E>100$ keV) with the measurement error less than 0.1% in the fields of $B=\pm5$ T.

4 CONCLUSIONS

Presented signal correction algorithms and operation principles of specialized measuring transducer for high-stable magnetometric instrumentation are the basis for development of the system for magnetic field measurements with instability no more than 0.1% under radiation conditions of charged particle accelerators which magnetic field $B = \pm5$T, fast neutron fluence $\Phi = 10^{14}\,n\cdot cm^{-2}$, neutron energy $E > 100$ keV.

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REFERENCES

[1] I.Bolshakova, Sensors and Actuators, A68(1998), pp.282-285.

[2] I.Bolshakova. Proceedings of the 6th European Particle Accelerator Conference, Stockholm, Sweden, June 22-26, 1998, pp.1923-1924. http://www.cern.ch/accelconf

[3] Measuring Current, Voltage and Power. Handbook of Sensors and Actuators Series, Volume 7, 1999. Edited by K.Iwansson.