MAGNETIC MEASURING DEVICES TO BE USED UNDER EXTREME OPERATING CONDITIONS

Inessa Bolshakova(1), Roman Holyaka(1), Masayuki Kumada(2), Claude Leroy(3)

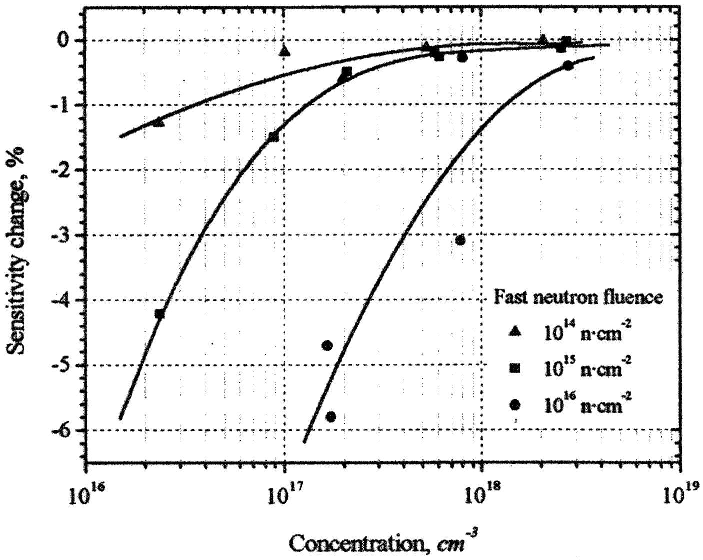
1) *Magnetic Sensor Lab., Lviv Polytechnic National Univ., Ukraine*
2) *National Institute of Radiological Science, Chiba, Japan*
3) *Montreal University, Canada*

Materials for sensors: microcrystals and epitaxial films → **Sensors** → **Sensor-based instruments: indicators, measuring devices and systems**

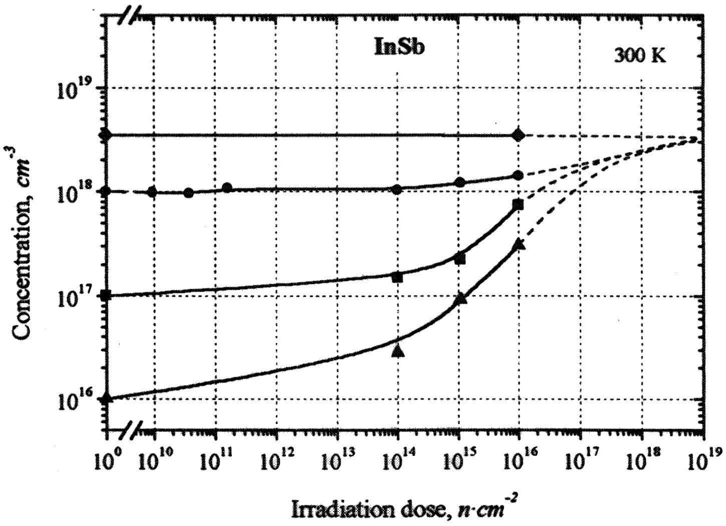
Sensor parameters

Material	**InSb, InAs, GaAs**
Sensitive element dimensions	**$0.05\times0.02\times0.01$ mm^3**
Weight	**10^{-6} g**
Power consumption	**10^{-3} W**
Measuring field range	**10^{-4} T $\div$ 12 T**
Magnetic sensitivity	**20 mV/T $\div$ 150 mV/T**
Sensitivity change after irradiation by neutrons	**0.03%**

STUDY OF RADIATION RESISTANCE OF InSb-BASED MAGNETIC MICROSENSORS UNDER THE FAST NEUTRON IRRADIATION

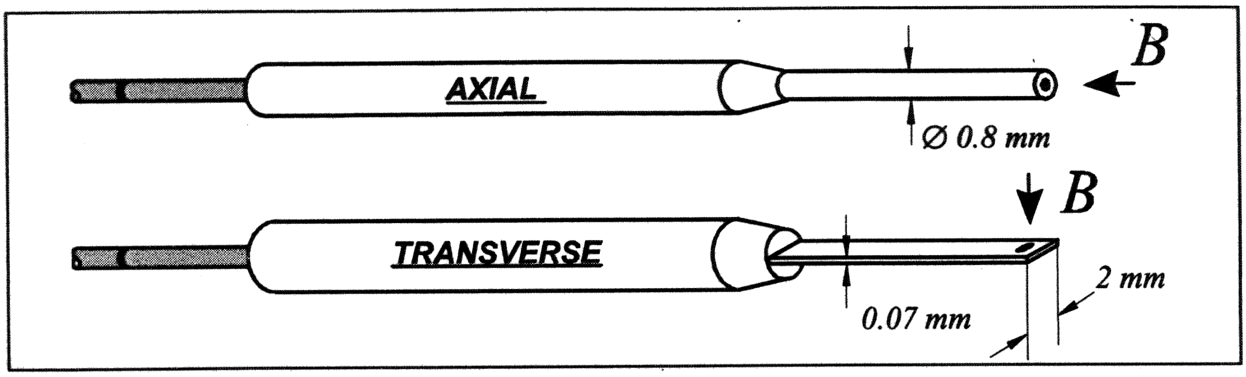


Change of microsensor sensitivity after irradiation with fast neutrons up to the fluences of $10^{14} \div 10^{16}$ $n \cdot cm^{-2}$

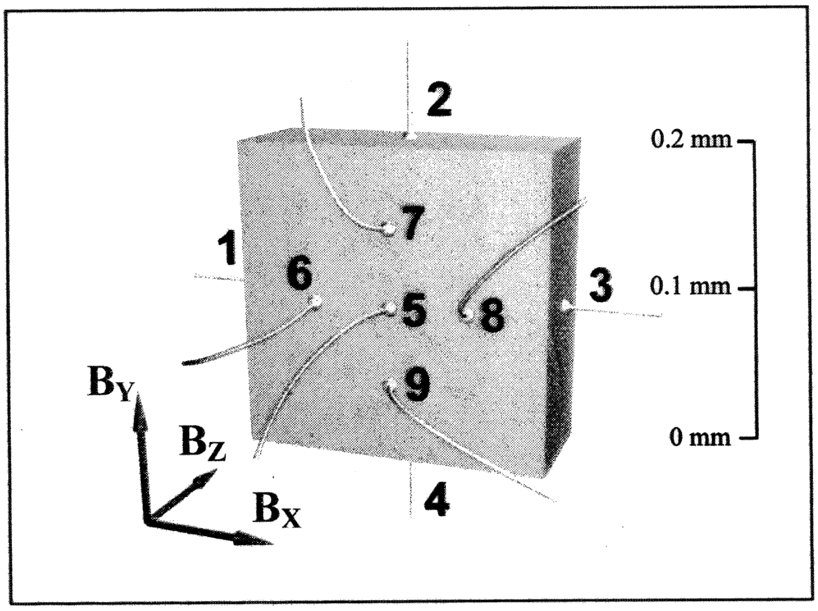


Dose dependence of the charge carrier concentration in microcrystals of sensors after the fast neutron irradiation with the average energy of 13 MeV

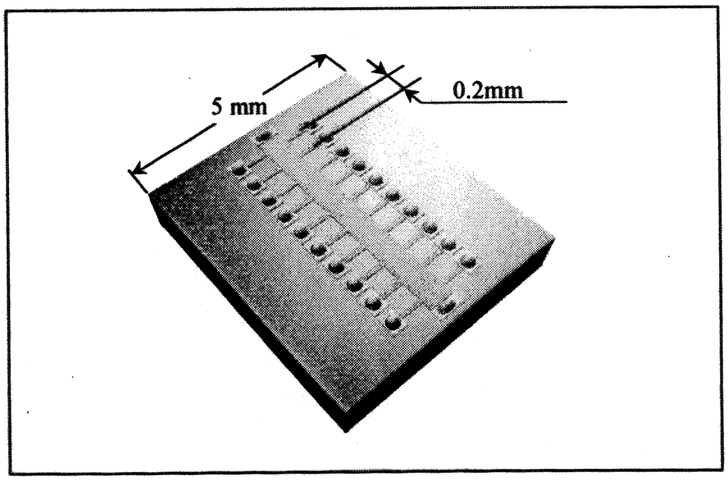
PROBES WITH MICROSENSORS



Axial and transverse probes
for measurements in small holes and narrow gaps



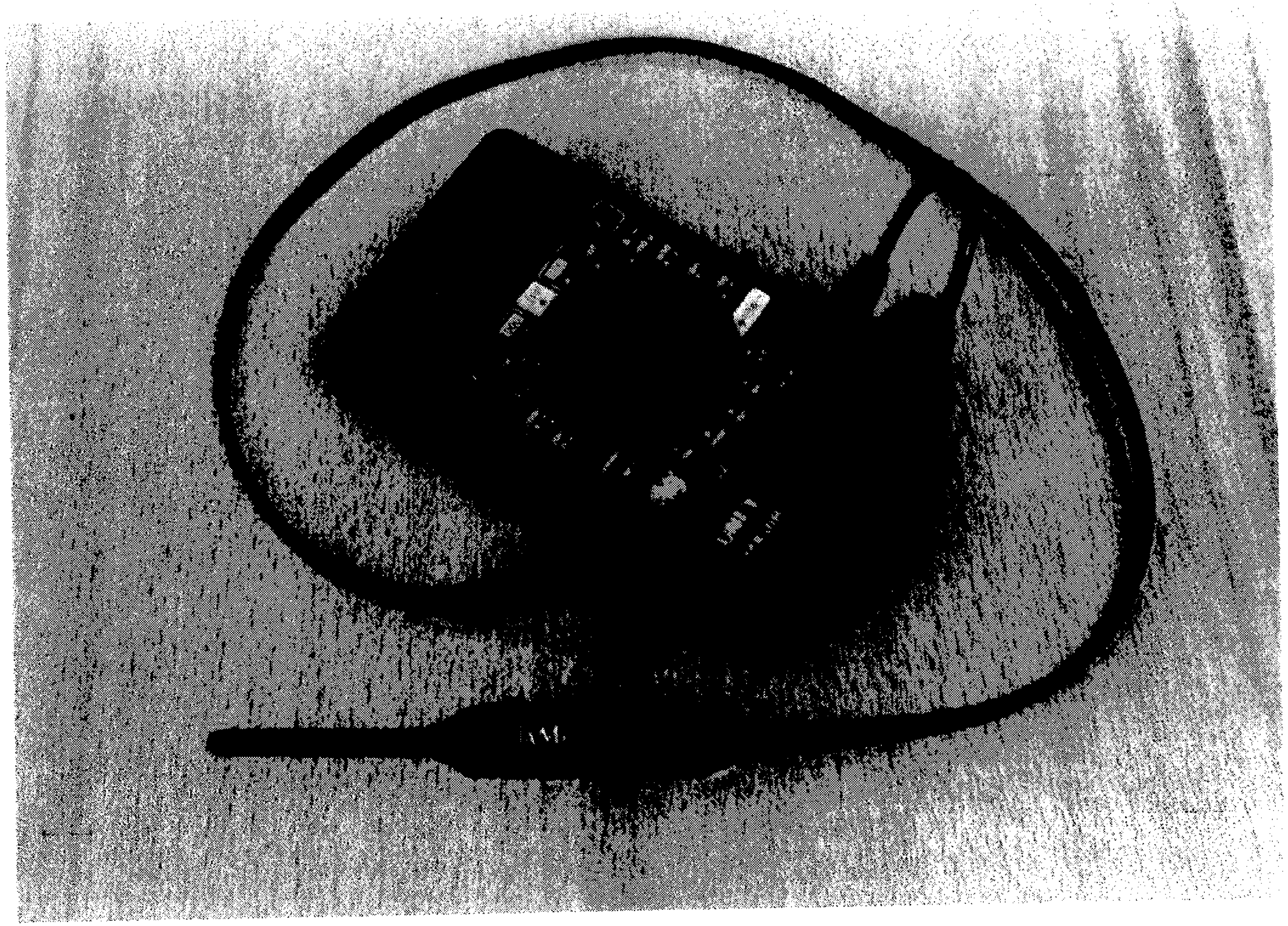
Sensor for 3D-measurement of magnetic field distribution



Multisensor (10 magnetic field sensors)

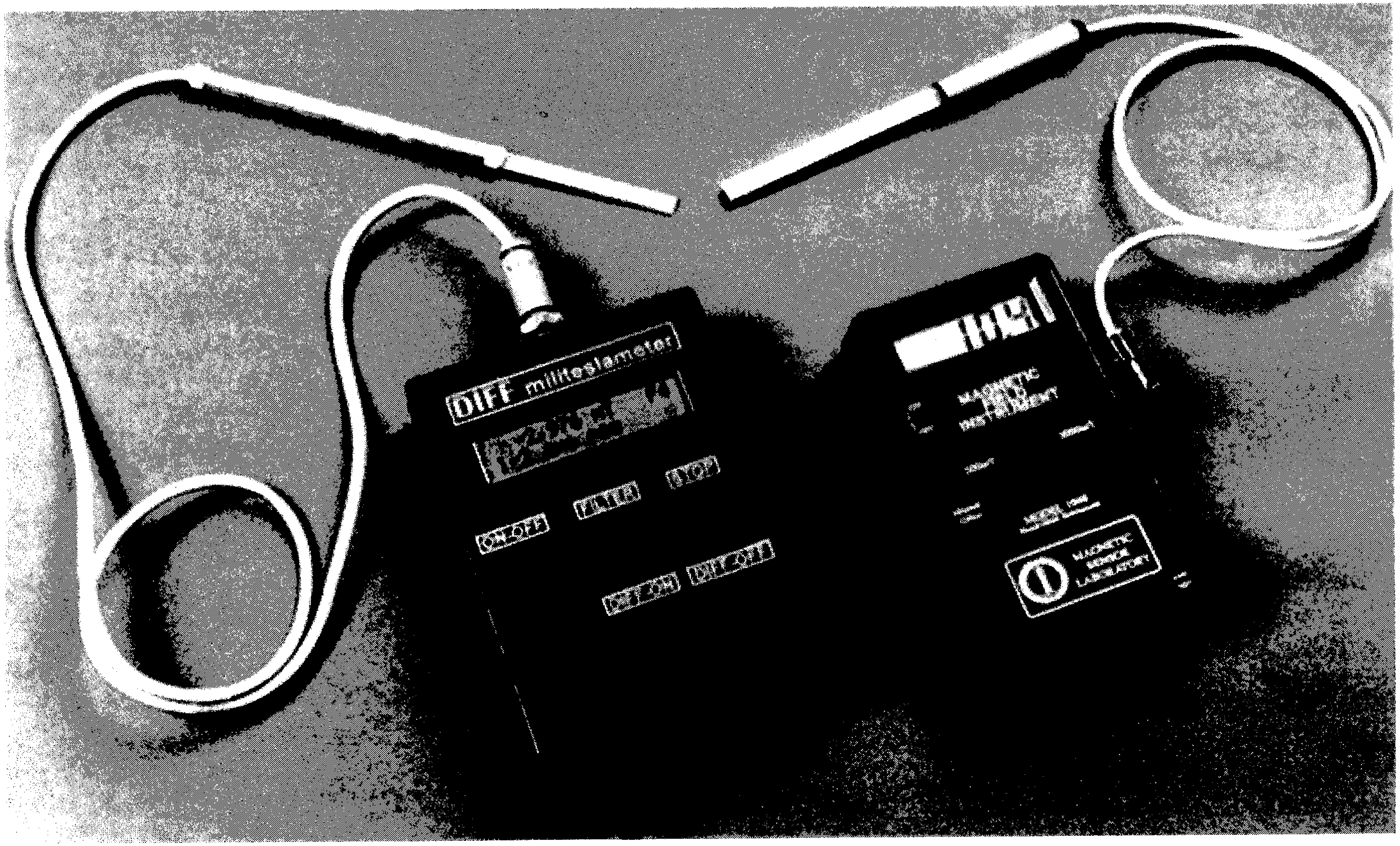
PORTABLE MAGNETIC MEASURING DEVICES

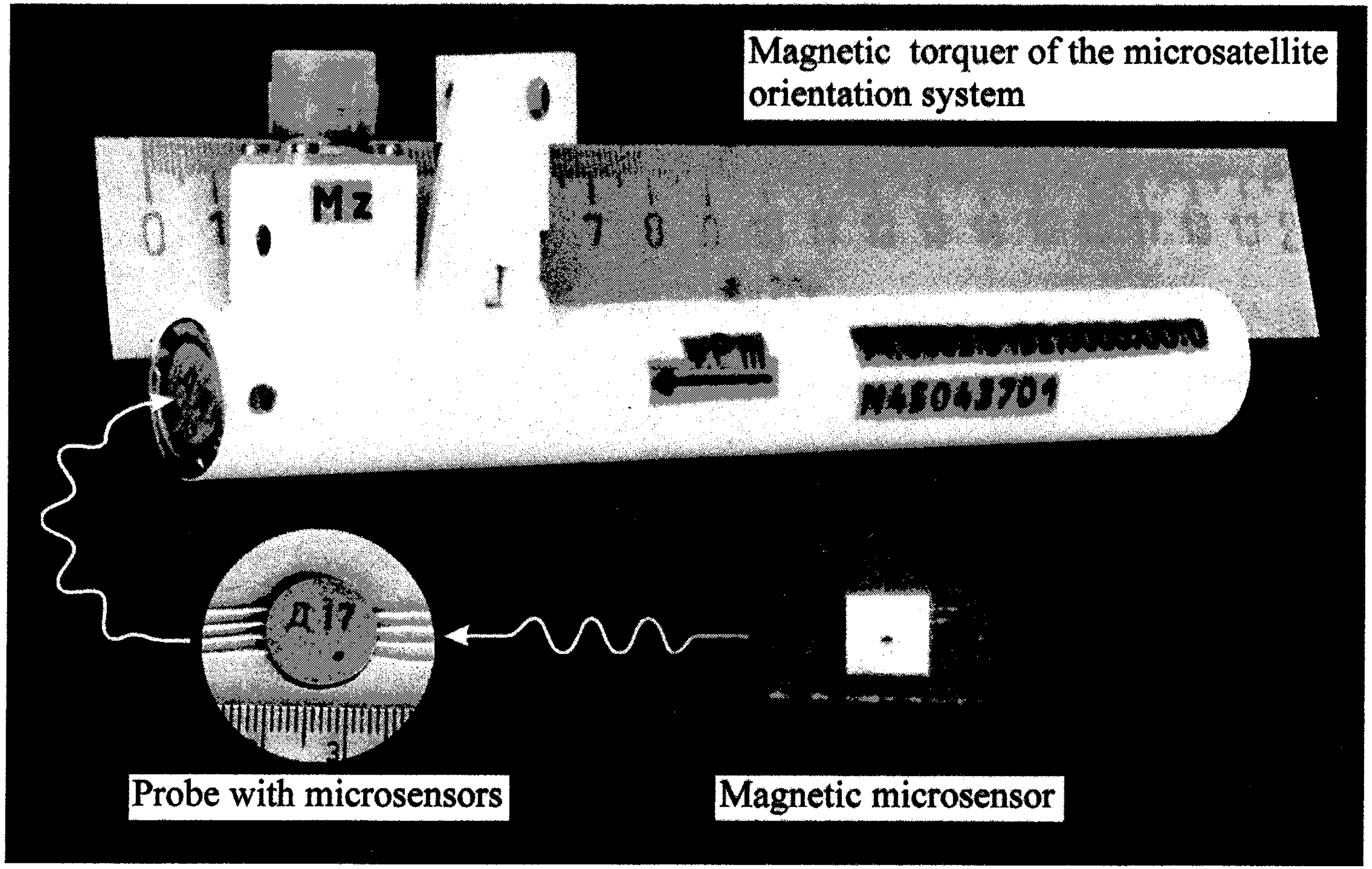
Probe - teslameter
with hand-held multimeter

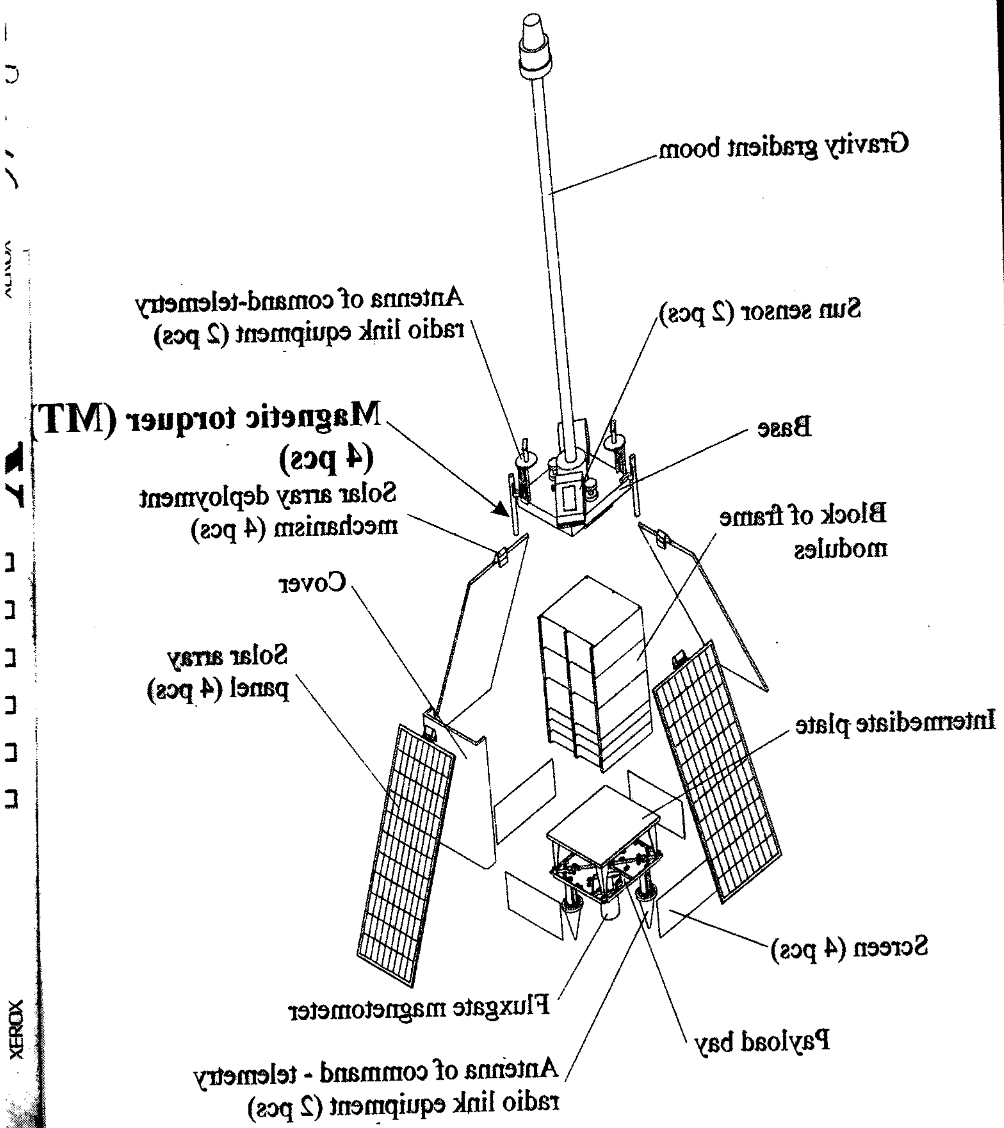


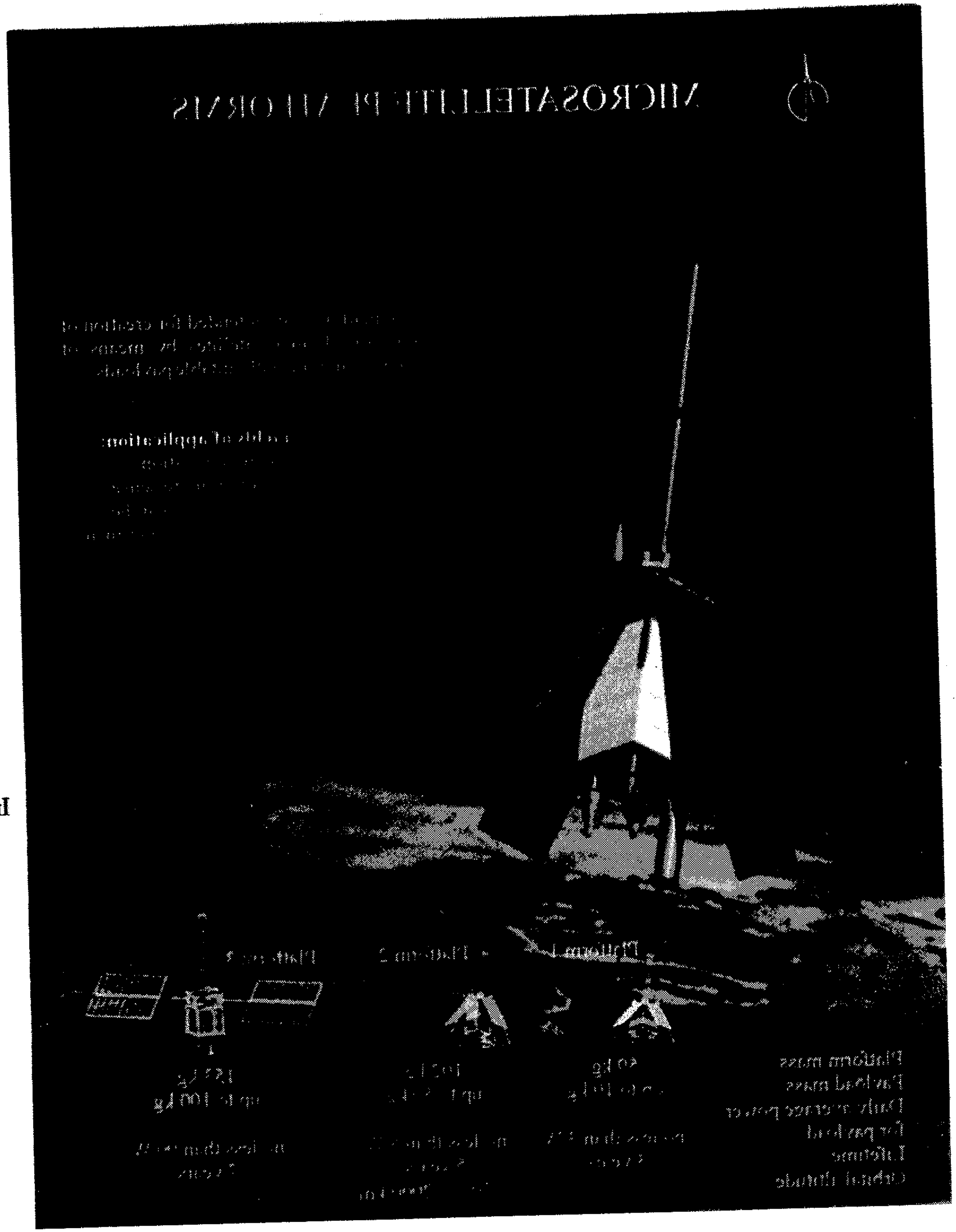
0 5 10 cm

Hand-held teslameters
for gradient measurements

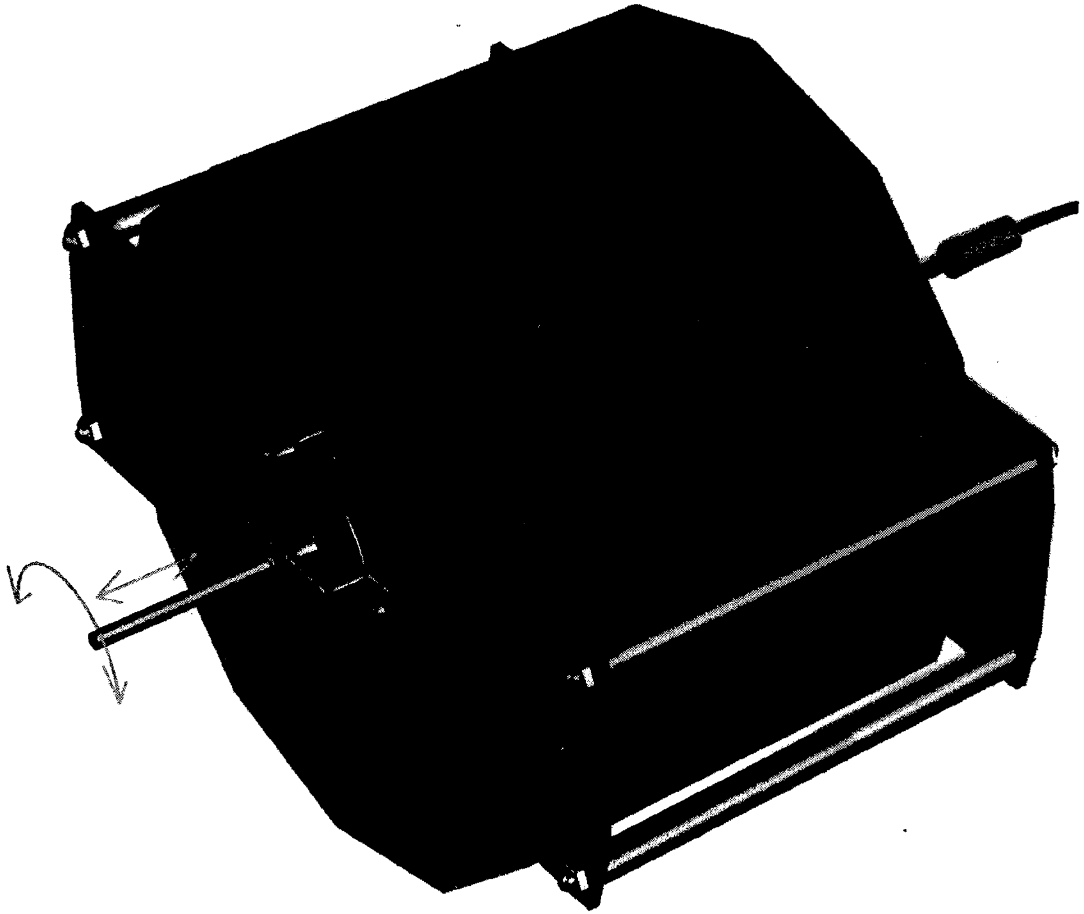


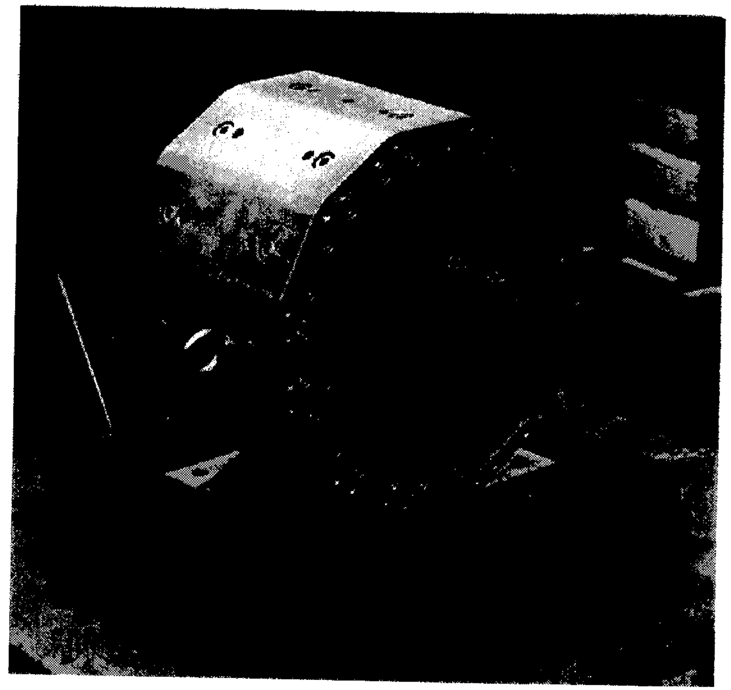

Magnetic torquer of the microsatellite orientation system
Mz
Probe with microsensors
Magnetic microsensor


Gravity gradient boom
Antenna of comand-telemetry radio link equipment (2 pcs)
Sun sensor (2 pcs)
Magnetic torquer (MT) (4 pcs)
Base
Solar array deployment mechanism (4 pcs)
Block of frame modules
Cover
Solar array panel (4 pcs)
Intermediate plate
Screen (4 pcs)
Fluxgate magnetometer
Payload bay
Antenna of command - telemetry radio link equipment (2 pcs)


MICROSATELLITE PLATFORMS
Platform 1
Platform 2
Platform 3
Platform mass
Payload mass
Daily average power
for payload
Lifetime
Orbital altitude

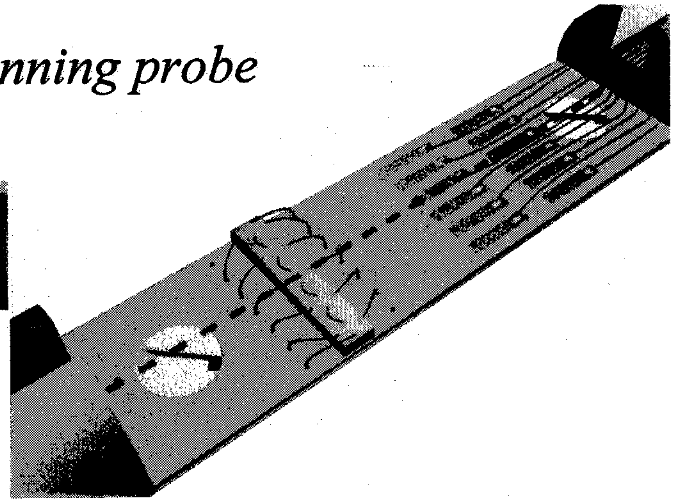
HARDWARE-SOFTWARE COMPLEX FOR 4 T PERMANENT MAGNET OF NIRS (Japan)



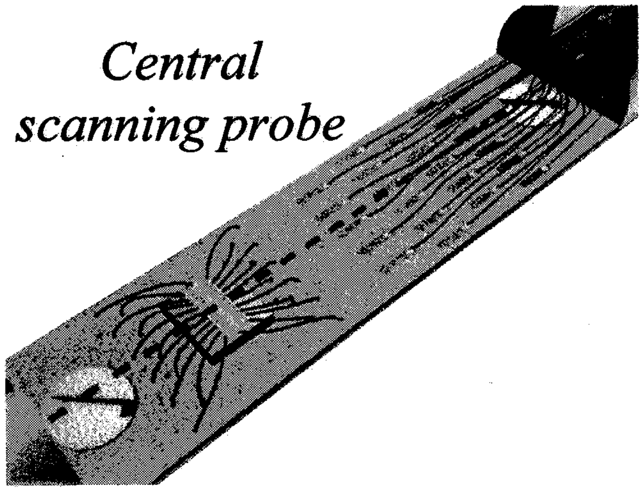


PROBE SET FOR FIELD MAPPING IN THE 4 TESLA PERMANENT MAGNET OF DR.MASAYUKI KUMADA

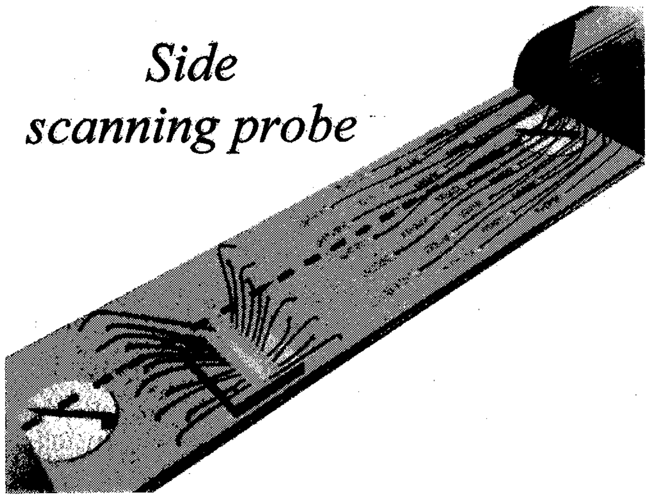
General scanning probe



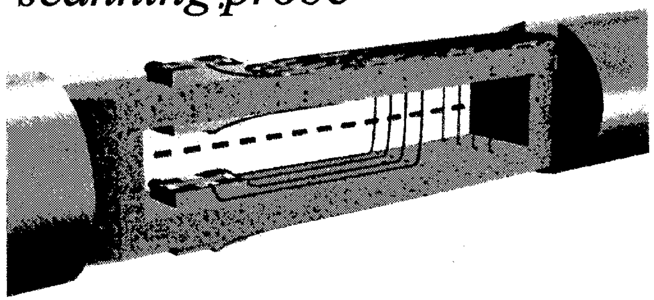
Central scanning probe



Side scanning probe

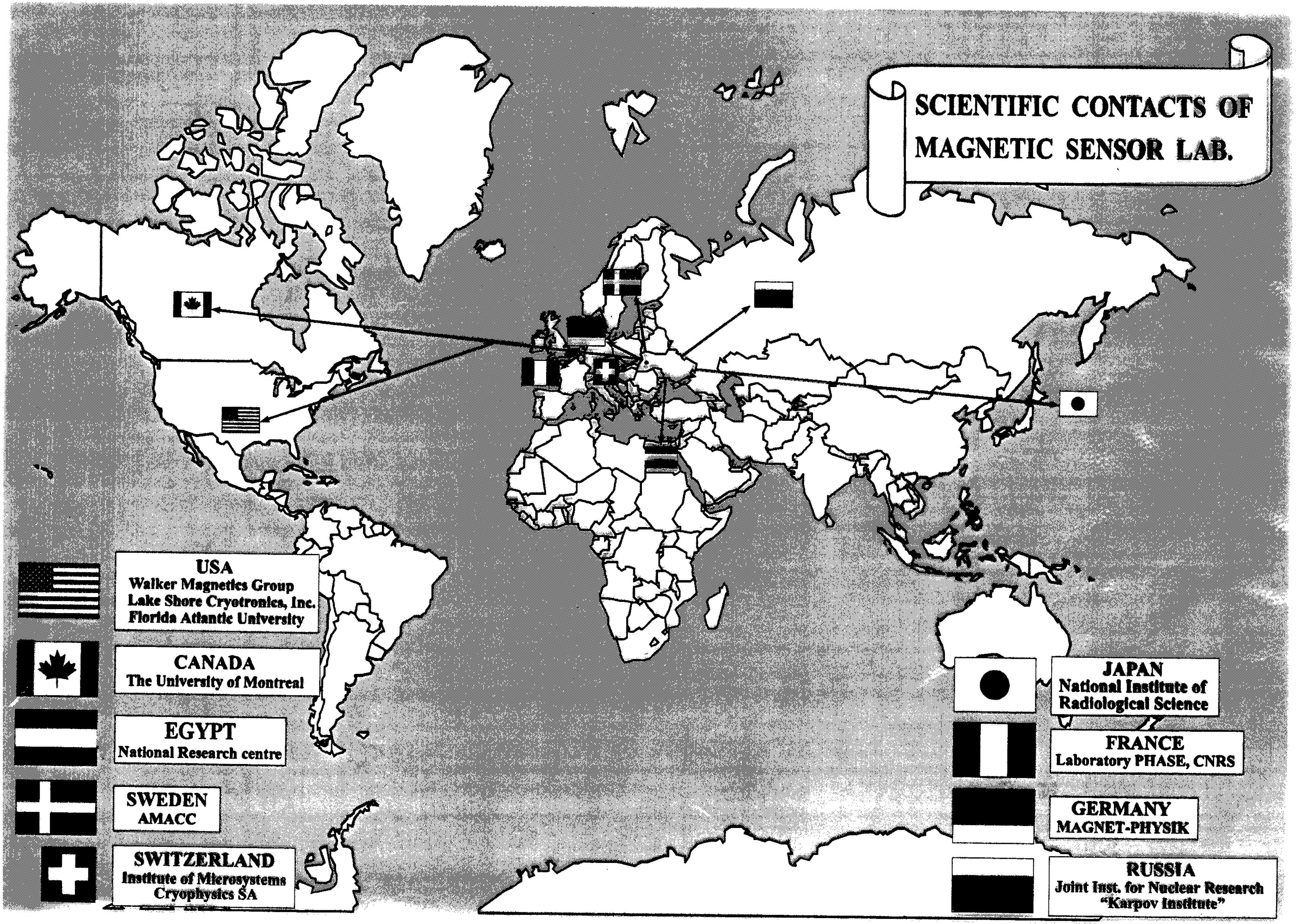


Radial scanning probe



0 10 mm


MEASUREMENT SYSTEM FOR MAGNETIC FIELD MONITORING IN CHARGED PARTICLE ACCELERATORS
BASE SOLUTION
FUNCTIONALLY INTEGRATED MAGNETOMETRIC TRANSDUCER
CALCULATION ALGORITHM


SCIENTIFIC CONTACTS OF
MAGNETIC SENSOR LAB.
USA
Walker Magnetics Group
Lake Shore Cryotronics, Inc.
Florida Atlantic University
CANADA
The University of Montreal
EGYPT
National Research centre
SWEDEN
AMACC
SWITZERLAND
Institute of Microsystems
Cryophysics SA
JAPAN
National Institute of
Radiological Science
FRANCE
Laboratory PHASE, CNRS
GERMANY
MAGNET-PHYSIK
RUSSIA
Joint Inst. for Nuclear Research
"Karpov Institute"

Novel approaches towards the development of Hall sensor-based magnetometric devices for charged particle accelerators

Inessa Bolshakova[1], Roman Holyaka[1], Claude Leroy[2]

[1] Magnetic Sensor Laboratory, Lviv Polytechnic National University,
1 Kotliarevsky St., Lviv 79013, UKRAINE
tel/fax: +380 322 970 393, e-mail: inessa@mail.lviv.ua

[2] Laboratoire R-J.A.-Levesque, Universite de Montreal
C.P.6128, Succursale "Centre-Ville",
Montreal (Quebec), H3C 3J7 Canada,
e-mail: leroy@lps.umontreal.ca

***[1]Abstract*--The problem of improvement of operation stability of Hall sensor-based magnetometric devices is solved in the paper. The problem is solved through the development of intelligent measurement system for magnetic field monitoring based on test algorithms for stabilization of transducing parameters. The basic element of the developed measurement system is functionally integrated magnetometric transducer, which combines a radiation resistant Hall microsensor and a microsolenoid to form test signal. Test algorithms for stabilization of transducing parameters are considered in the paper as well as the structure and parameters of magnetic field monitoring system development for charged particle accelerators. Magnetic field microsensors are also successfully applied in magnetometric devices for non-contact investigations of parameters of high-temperature superconductors (HTS): critical field and temperature, critical current density and amount of superconducting phase.**

***Index Terms*-- high magnetic field monitoring, magnetometric system, radiation resistance.**

I. INTRODUCTION

Magnetic field monitoring in charged particle accelerators requires a number of specific features to be met by the magnetometric devices (MMD). Long-term high radiation resistance of the sensors, noise-immunity, accuracy and stability under the conditions faced in an accelerator experiment are the most important features to be dealt with.

Novel approaches are presented towards the development of Hall generator (HG) sensor-based magnetometric devices for charged particle accelerators. Unlike nuclear magnetic resonance (NMR) transducer-based magnetometric devices, which are conventional for magnetic field measurements in charged particle accelerators, Hall devices are featured with many advantages. Firstly, Hall sensors can be operated in non-uniform magnetic fields. This advantage is of particular importance for charged particle detectors where the magnetic field is non-uniform. Secondly, the small dimensions of Hall sensors allow the building of multi-channel measuring devices without the spatial limitation problem, which is found in NMR transducers. Thirdly, Hall sensors allow the measurement of the direction of the magnetic field induction, not only its absolute value.

II. STATEMENT OF PROBLEM

However, the instability of commercially available Hall sensors prevents the building of high-stable devices for magnetic field monitoring, especially regarding the long-term operation under the radiation conditions, which prevail in experiments performed at charged particle accelerators.

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 non-stability of Hall voltage in the range of 0.15÷0.5 % under the irradiation by high-energy neutrons with fluence of $\Phi=10^{14}\ n\cdot cm^{-2}$ [2]. Works on radiation modification of HG materials are being carried out, which allow one to improve their radiation stability 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 test stable magnetic field of known strength around the primary transducer. Transducing function of the measuring circuit is determined by means of measuring HG signal change at forming test magnetic field. This permits one to carry out continuous or periodic correction of measurement results of studied field. HG is located in the field of a microsolenoid, 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 microsolenoid. When operating under hard radiation conditions change of the microsolenoid 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 microsolenoid, its resistance change does not lead to test field magnitude change. Maximal efficiency of the method takes place at the full compensation of the measuring field around HG 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 development of the theory and practice of test methods for parameter stabilization of radiation resistant MMD in order to monitor high magnetic fields.

III. 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 measuring change of test field in microsolenoid 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 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, set up at alternative current frequency in actuating microsolenoid. 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.

Using polynomial representation of the transducing function allows one to considerably improve the measurement accuracy. It is expected that nominal transducing function

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

(a_j - coefficients of the polynomial 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 $\Delta U_e / \Delta B \neq \Delta U_0 / \Delta B$.

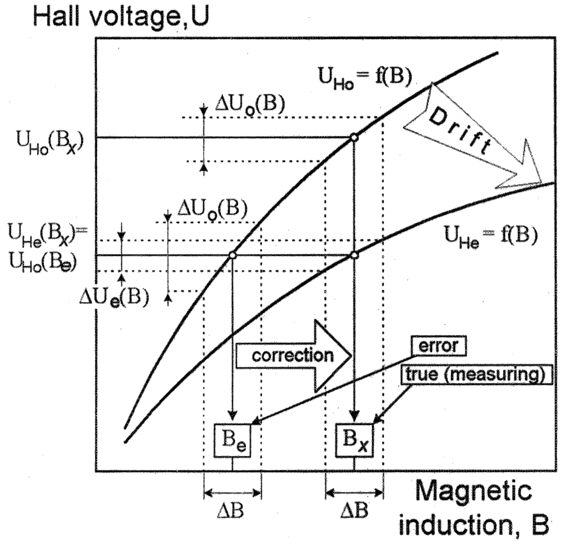


Fig.1. Graphic expression of the transducing function

Having determined the transducing function derivative

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

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

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

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

After appropriate transformations we receive

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

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 $f(B)=0$:

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

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

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

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% ÷ 0.5% and depends on the drift value of the HG parameters when operating under radiation conditions.

Further improvement of the correction accuracy requires analysis of HG mathematical model parameters. The analysis is carried out with respect to the main parameter change, in this case to Hall mobility of the charge carriers. The correction procedure is close to the above given.

IV. Functionally Integrated Magnetometric Transducer

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 the combining two elements of the transduction – semiconductor HG and copper microsolenoid, 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 microsolenoid resistance (as a copper thermoresistor);
- HG thermostatting by means of controllable heating of the microsolenoid;
- 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 microsolenoid could have different form, for example cylinder, toroid etc. Thus, at Fig.2 one may see FIMMT with cylindrical microsolenoid from the lateral of which the bore is made to induce microsubstrate with HG crystal.

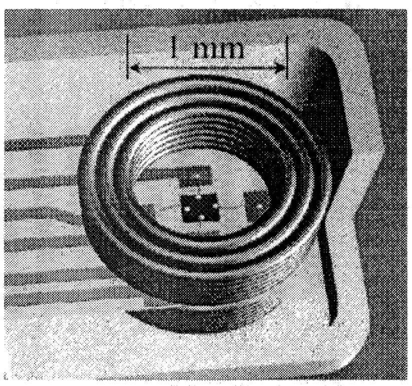


Fig.2. FIMMT structure

By means of investigations carried out, optimal correlations are determined for the bore width ΔL for HG, internal microsolenoid diameter D, wire diameter d, number of windings n in each of m layers and operating current I_{CM}.

HG location in the microsolenoid 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.

V. Functional Parameters of the System

Presented in the paper signal correction algorithms and operation of specialized measuring transducer are the basis for development of the Monitoring system for magnetic field measurements (fig.4). 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.

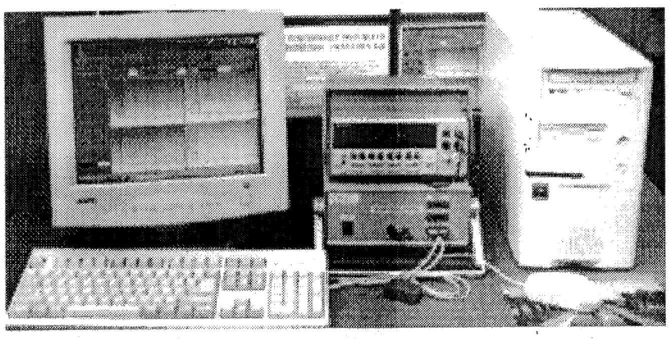


Fig.4

Main functions of Monitoring system are described below.

Direct measurement of magnetic field induction is performed in the conventional way for high-precision magnetometers, which expects alternative current to be supplied to the HG, and further synchronous signal detection. This provides high noise immunity, which is important, when HG in the magnetic measuring zone with hard radiation is distanced from the signal processing instrumentation.

Dynamic measurement mode of the magnetic field induction is based on direct supply current to the HG without synchronous signal detection. Unlike the previous function, this mode provides high measurement performance and observation of transition process shapes. Measurement accuracy of this mode is limited by its low noise immunity. The dynamic mode shows the particular efficiency at the periodical change of magnetic field, which is specific for kicker electromagnets accelerators.

Measurement of weak magnetic field induction is carried out by means of compensation method. During the measurement process the field is formed in the microsolenoid which compensates the measuring field. Measurement parameter is the current running through the microsolenoid, which provides zero value of the Hall voltage. Such measurement mode does not have the disadvantages connected with the time and radiation instability of the HG..

Thermocompensation of transducing parameters is performed by means of FIMMT temperature measurement and is realized by means of microsolenoid serving as the thermoresistor. Taking into account a large distance between FIMMT and signal processing circuit, measurements are carried out by means of synchronous detection.

Measurements of electromagnetic fields forming contaminating signals are performed by means of microsolenoid as an antenna.

Magnetic flux change through the microsolenoid is measured by means of integrating the emf induced on microsolenoid by the certain time interval.

Transducing parameter correction is performed be means of supplying alternative current to the microsolenoid, and direct current to the HG. During test field formation, operating current through the microsolenoid is equal to 30 mA. Measurements are carried out in several stages. FIMMT temperature is measured (by means of measurement of the copper microsolenoid resistance change) on the first stage after finishing transition heat mode. Second stage expects differential component of Hall voltage to be measured, which is caused by the test magnetic field of the microsolenoid. Integral component of the Hall voltage is measured during the third stage, which follows to determination of first approximation of the field induction to be measured. Such measurements allow calculating the HG transduction curvature, and, when compared to the calibration value, appropriate correcting the measurement results.

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 one 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 by one direction. It is one of the determinant functions of the intelligent measuring devices.

VI. CONCLUSION

Results are presented concerning the novel approaches towards the development of Hall sensor-based magnetometric devices for charged particle accelerators development of the magnetic monitoring system 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=5 T. The developed system meets the intelligent measuring device criteria by its functional parameters. Among them – self-diagnostics, ability of choosing measurement algorithm and its adjustment to an experiment conditions.

VII. 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