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RESEARCH ARTICLE

Performance of Hall Sensor-Based Devices for Magnetic Field Diagnosis at Fusion Reactors

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In the paper, we report the results on the development of Hall sensor-based devices possessing the functions of selfdiagnostics and automatic correction, which are aimed at the improvement of the magnetic field measuring accuracy in radiation environment of thermonuclear reactors. Developed devices are based on radiation-hard semiconductor sensors. The method for device stabilization is offered, which is based on a test method of measurements, where sensor and actuator are combined in a single primary transducer. New algorithm of correction of the transduction function on the basis of frequency separation of differential and integral signal components is proposed. The results of the testing of developed Hall sensor-based devices, applied for the magnetic field measurement at the largest European thermonuclear reactors TORE SUPRA (France) and JET (Great Britain), are presented.

Keywords: Galvanomagnetic Sensor, Fusion Reactor, Magnetic Diagnostics, Radiation Hardness.

1. INTRODUCTION

There is a number of magnetic systems, in which the application of conventional Hall sensors and magnetometers for the measuring of magnetic field induction is impossible. Those systems include thermonuclear reactors (tokamaks), in which magnetic field plays a key role for the plasma confinement. Extremely harsh conditions existing there (great doses of high-energy neutrons, high temperature, wide frequency range from DC to hundreds kilohertz) make it impossible to apply the conventional semiconductor sensors for magnetic field monitoring.

However, inductive sensors being currently in use at tokamaks, have a number of deficiencies and can not provide the required level of the magnetic field measuring accuracy.[1] Such deficiencies include, first of all, the impossibility to measure accurately enough the DC magnetic fields. Secondly, inductive transducers acquire certain undesirable radiation induced effects under the tokamaks' irradiation conditions, namely: the radiation induced electromotive force (RIEMF), radiation induced conductivity (RIC), radiation induced electric degradation (RIED). As the study showed,[2] magnetic field measuring error if using the inductive transducers under such conditions equals to 3.5%, which is one order of magnitude higher than is allowed for the measuring error.

As a result, the tasks were set to increase the radiation hardness of semiconductor Hall sensors (HT), which in contrast to the pick-up coils would be capable of measuring the magnetic field in a wide frequency range from DC up to hundreds kHz, as well as to create Hall sensor-based magnetic measuring devices, aiming at the improvement of the magnetic field measuring accuracy in the tokamak environment. In this paper, we present the results of the research work on the creation of radiation hard Hall sensor-based devices, as well as the results of the experiments on the application of these devices in the largest European tokamaks TORE SUPRA (France) and JET (UK), which are presently considered to be the test beds for ITER (International Thermonuclear Experimental Reactor).

2. DEVELOPING THE GALVANOMAGNETIC DEVICES BASED ON THE RADIATION HARD HALL SENSORS

For the development of magnetic diagnostics instrumentation based on Hall sensors to be applied at the existing tokamaks and ITER, the following tasks should be

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accomplished: improvement of radiation stability of magnetic field semiconductor sensors, development of the method for stabilization and adjustment (correction) of magnetometric devices operable in the irradiation environment, thermal compensation of transduction function, electromagnetic noise suppression, magnetic field induction measuring in a wide frequency range.

Improvement of radiation stability of magnetic field semiconductor sensors. It is known, that instability of semiconductor materials under neutron irradiation restricts the semiconductor sensors' use for thermonuclear reactors' magnetic field measuring. The instability of semiconductors' electrophysical properties is caused by the shifting of Fermi level position due to the accumulation of radiation defects, as the Fermi level position is defined by the balance between the donor- and acceptor-type radiation defects.

The practical solution to the problem of creating the radiation-hard semiconductor materials for sensors is based on the theoretical model of Fermi level pinning to its boundary position in the irradiated crystals.[3]

Radiation-hard microcrystals and thin films of InSb semiconductor compound, on which the Hall sensors are based, were grown by the CVD method, and were doped during the growing process by the doping complex inclusive of Sn, Al, Cr doping elements at specific ratio.[4] Stannum was a basic element in this complex and provided for the required initial charge carrier concentration. It was taken into account that stannum is the end product of the nuclear reactions resulting from the indium transmutations induced by thermal neutrons which are always partially present in the fast neutron flux. Considering that indium is one of the basic crystalline lattice elements, the cross-section of the thermal neutron trapping by the indium atoms is much larger as compared to the other possible nuclear reactions (97.5% of all possible transmutations).

$$^{113}\mathrm{In}\,(n,\gamma),\ ^{114}\mathrm{In} \xrightarrow[\text{49 days}]{\beta} {}^{114}\mathrm{Sn} \tag{1}$$

$$^{115}\mathrm{In}\,(n,\gamma),\ ^{116}\mathrm{In} \xrightarrow[\text{54 min}]{\beta} {}^{116}\mathrm{Sn} \tag{2}$$

Other doping components of the impurity complex Al and Cr should interact with the residual impurities in the crystals and move them to the inactive state. They should also create the drains for the radiation defects by means of the crystalline lattice deformation due to the difference in sizes of the impurity and basic lattice atoms radii, which also improves the stability of sensors under the irradiation.

Stability of sensors under irradiation conditions is estimated according to their sensitivity change $S = U_H/\mathrm{B}$, which is inversely proportional to the charge carrier concentration n in sensor's material. Speed of charge carrier concentration change in the sensor's material is a function of initial concentration and might be presented by the following quasi-linear dependence:

$$\Delta n/\Delta F = \alpha - \beta(n_{\mathrm{in}} + \alpha F - n_i) \tag{3}$$

where F is neutron fluence (cm^{-2}); α is coefficient which characterizes the introduction of stannum atoms (cm^{-1}) by means of nuclear doping; β is cross-section of the acceptor-type defects formation (cm^2); n_{in} is initial electron concentration in InSb at $T = 300$ K. At certain values of charge carrier concentration, the dependence $\Delta n/\Delta F$ verges towards zero. At that, optimal initial charge carrier concentration n_{opt}, when $\Delta n/\Delta F = 0$, also depends on reactor neutron spectrum in irradiation region.

Experimental investigations performed at IBR-2 reactor in Dubna (Russia) allowed to determine the optimal initial charge carrier concentrations in InSb-based sensors' material, which appeared to be equal to $n_{\mathrm{opt}} = 6.7 \cdot 10^{17}$ cm^{-3} during irradiation with neutron flux in which the ratio of fast, thermal, intermediate, and resonance neutrons was equal to 51%, 20%, 25%, and 4% correspondingly. Sensitivity change in the sensors with n_{opt} did not exceed 0.05% during the irradiation up to the fluence of $F = 1 \cdot 10^{15}$ n $\cdot$ cm^{-2} (such neutron fluence can be, for example, accumulated in the CMS detector at CERN during the 10-year operations of Large Hadron Collider). During the irradiation up to higher fluences $F = 3 \cdot 10^{16}\,\mathrm{n} \cdot \mathrm{cm}^{-2}$ in IBR-2 reactor sensitivity in sensors with n_{opt} changed by 0.8% at the temperature of 17 °C.[5]

The investigation of the sensors at even higher ITER-relevant neutron fluences of $F = 10^{17} \div 10^{18}$ cm^{-2} was performed at LVR-15 reactor in Řež (Czech Republic) at the increased temperature of 90 °C. The sensitivity change in the sensors with optimal charge carrier concentration was equal to 7% at such increased doses. For sensors with other initial charge carrier concentrations these changes were equal to $20 \div 30\%$ (Table I). Convenient industrial sensors of well-known companies Lake Shore Cryotronics and F. W. Bell were also investigated in this environment and shown the sensitivity change from 56% to 95%, with one of them being destroyed.[6]

The method for stabilization of magnetometric devices operable in the irradiation environment. One can see from the results given above regarding the investigation of Hall sensors' radiation stability that existing conventional sensors can not be used under the harsh irradiation conditions of fusion reactors at the neutron fluence of the order of

Table I. Results of sensors' investigation in LVR-15 reactor.

No.	Type of sensor	Manufacturer	Neutron fluence ($E > 1$ MeV) (n $\cdot$ cm^{-2})	Sensitivity change (%)
1	MSL-1	MSL, Ukraine	$2.5 \cdot 10^{17}$	23
2	MSL-2	MSL, Ukraine	$3.0 \cdot 10^{17}$	7
3	MSL-3	MSL, Ukraine	$1.1 \cdot 10^{18}$	38
4	MSL-4	MSL, Ukraine	$1.3 \cdot 10^{18}$	30
5	HGT-3010	Lake Shore, USA	$4.8 \cdot 10^{17}$	56
6	HGT-3030	Lake Shore, USA	$8.4 \cdot 10^{17}$	94
7	HS-100	F. W. Bell, USA	$3.6 \cdot 10^{17}$	75
8	GH-800	F. W. Bell, USA	$9.8 \cdot 10^{17}$	destroyed

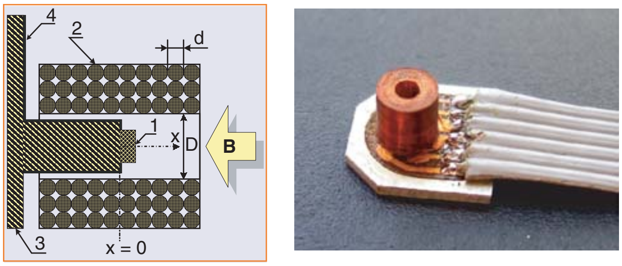

Fig. 1. Integrated magnetic transducer (IMT): (a) structural lay-out 1—Hall sensor, 2—microsolenoid's coil, 3—base, 4—outputs, $D = 1$ mm—microsolenoid's inner diameter, $d = 0.05$ mm—copper wire diameter, B—magnetic field induction), (b) photo of IMT without the case.

$F = 10^{18}$ cm^{-2}. At such the extremely high irradiation doses the sensitivity of even our best radiation-hard sensors is changed by 7%, thus their function of transductions should be corrected so that to achieve the necessary accuracy (<1%) of tokamak's magnetic field measuring. This caused the necessity to develop new methods and devices for stabilization of the sensors' transduction function under irradiation.

The developed stabilization method is based on the test measurement method, i.e., the generation of the 5 mT test magnetic field around the Hall transducer (HT) by means of small solenoid with copper coil's diameter of $1 \div 2$ mm, which acts as an actuator (Fig. 1). Microsolenoid and sensor altogether compose the integrated magnetic transducer (IMT), with the case dimensions of $(10 \times 10 \times 6)$ mm.[3]

The preference of this device is that it is available for periodical calibration, and in this way it is possible to correct the sensitivity change of the HT under the long-term effect of the penetrating irradiation. For such periodical calibration we use the test field, which is periodically generated in the microsolenoid in the following way: current of the known value is driven through the microsolenoid, and thus resulting test field can be calculated. The value of Hall sensor's sensitivity in this known field shows the necessity of performing the device calibration. Of fundamental importance is that the test magnetic field value does not depend on accumulated radiation dose. It is known that the magnetic field induction depends on geometric parameters of solenoid's coil, loops quantity, and supply current. None of these parameters is dependant on irradiation effect, so even when wire's parameters, which coil is made of, are changed under irradiation, the test magnetic field value remains constant if keeping the current thorough the solenoid's coil stable.

Correction Method. Newly developed algorithm of the transduction function correction allows to avoid the complications with forming the strong test magnetic fields, but is efficient for measuring the fields of any magnitudes. The algorithm is based on three basic solutions: simultaneous analysis of the transduction parameter by integral and differential components of the signal; frequency separation of integral and differential components of the signal; advanced method of transduction function and magnetic field calculations.

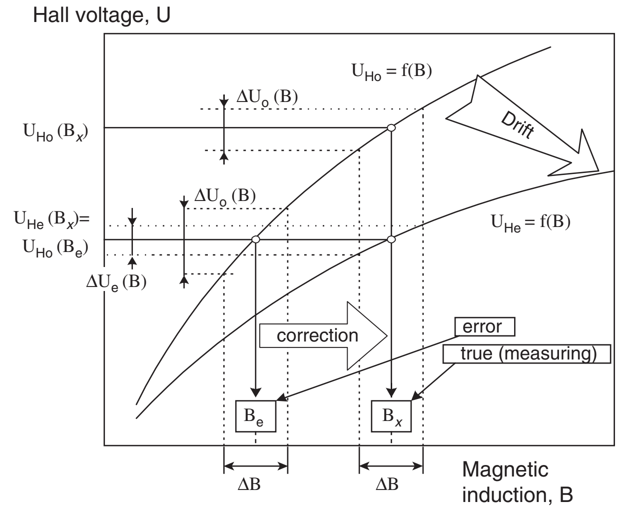

Fig. 2. Correction algorithm.

Graphic representation of the transduction function and measured values is given in Figure 2.

Transduction function of the measuring circuit may be presented in a polynomial way

$$U_{\mathrm{Ho}} = \sum_{j=0}^{n} a_j \cdot B^j$$

and the algorithm of its correction is based on the system of equations as follows:

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

where U_{Ho}, U_{He} are nominal and measured values of the Hall voltage respectively, B_X is magnitude of magnetic field induction to be measured, a_j is coefficient of the polynomial series, G is coefficient of transduction function drift, which is determined during the test measurements. Hall voltage derivatives of the magnetic field induction dU_{H}/dB are determined by means of measuring the differential test field of the microsolenoid (Fig. 2).

The correction of the transduction function is conducted in the mode, in which the microsolenoid is supplied with alternating current, and Hall sensor with direct current. Operating current through the microsolenoid during the generating of the test field is 10 mA. The measurements are conducted in several stages. At the first stage, after the transition thermal mode, the measuring transducer's temperature is estimated by means of measuring the copper microsolenoid voltage change. At the second stage, we measure the differential component of Hall voltage, which is defined by the microsolenoid's test magnetic field. At the third stage, the integral component of Hall voltage is measured, which is used for the estimation of the induction of the field to be measured. Measurements conducted in such way make it possible to calculate microsensor's sensitivity, and, by means of further comparison with the calibrated value, it is possible to give more precise definition to the measurement results. The correction error is $\leq 0.1\%$.

Thermal compensation of the transduction function is performed by the measuring of the transducer's temperature, and is realized by the microsolenoid acting as thermoresistor. Temperature measuring error is 0.1 °C. Measured value of the temperature serves for the thermal compensation of the Hall transducer's parameters. The correction is performed by the software and is based on the temperature dependence of the IMT parameters, being measured during the calibration.

The device also performs *suppression of the electromagnetic field noise and the drift in time of the measuring circuit*. These functions are provided by the synchronous signal detection, up-to-date methods of analogue-to-digital transduction and non-drift amplifiers with periodic zero adjustment.

Magnetic field induction measuring in a wide frequency range. Magnetic field diagnosis at fusion reactors needs a wide-band measurement up to 100 kHz. However, the magnetic field measuring accuracy decreases significantly if using traditional HT, when the field frequency is above several tens of kHz. A reason for this might be the electromagnetic noise appearing on the HT outputs. To solve this problem we proposed a range of novel circuit design solutions for wide-band magnetometers. Wide-band magnetometer is based on the original galvanomagnetic transducer, which integrates the HT and the loop for electromagnetic compensation in a single chip. Signals of such sensor are amplified by a wide-band two-channel transducer. The first channel amplifies a signal from the Hall sensor's potential output. This signal has two components: a useful component, which is an informative value of the magnetic field and a parasitic component, which is caused by the electromagnetic noise. The second channel amplifies a signal from the loop of electromagnetic compensation. The compensation function means that certain part of the second channel signal is extracted from the first channel signal, which allows to define the useful component of the signal. The high frequency amplifier is realized on the wideband rail-to-rail operational amplifier of the AD8604 type (8 MHz, 5 V/μs). Signal digitization is performed by analog-to-digital transducer of AD 7663-type (16-Bit 250 kSPS). The results of transduction are recorded to the on-line storage, the volume of which is 128 Kbytes

The developed Hall device comprises three identical measuring channels, which allow to monitor the magnetic field in three-coordinate system. The structure of the sensor device is shown in Figure 3. The device comprises: electronics unit, probe set based on IMT, voltage supply, and personal computer. The electronics unit provides for the preliminary amplification of signals, noise suppression, signal commutation, forming of test signals. The electronics unit is based on the up-to-date elemental basis of

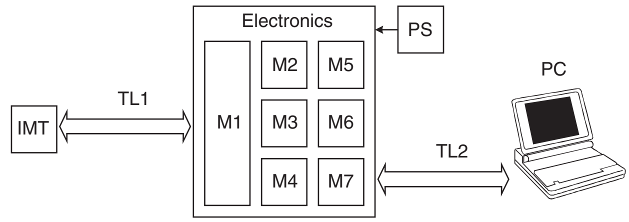

Fig. 3. Structural lay-out of the sensor-based device: IMT—integrated magnetic transducer; PC—IBM-compatible PC; TL1, TL2—signal transmission lines; PS—power supply unit (7...15 V, 1 A); Electronics—electronic unit (M1—commutation unit; M2—DC low frequency path; M3—AC low-frequency unit with synchronous detector; M4—high frequency unit; M5—IMT supply unit; M6—analog-to-digital transducer; M7—interface unit).

Analog Devices company (USA). The dimensions of its case are $(200 \times 200 \times 100)$ mm.[3] The measuring algorithm, mathematics, logic, and statistics processing of results are done by the corresponding software.

The created sensor device by its functional characteristics meets the requirements towards the intelligent measuring instrumentation, namely: self-diagnostics, possibility to choose the measuring algorithm, and its adaptation to the experiment conditions. The measuring accuracy under magnetic fields of the order of ± 5 T is better than 0.1% under the neutron irradiation.

3. FIRST EXPERIMENTS WITH HALL SENSOR-BASED DEVICES AT TORE SUPRA AND JET TOKAMAKS

Created Hall sensor-based devices were successfully applied for the measuring of magnetic field pulses in the largest European thermonuclear reactors: TORE SUPRA, which is situated in Cadarache (France), and Joint European Torus (JET), which is situated in Culham (Great Britain).

In both cases IMT was set close to the reactor's toroidal vacuum vessel on its outer side. Electronics unit was placed in the reactor hall as well, but at the several meters distance from the reactor vessel, while the PC providing the measurement process controlling was located in the controlling and monitoring hall allowed for the personnel at the distance of several tens meters from the reactor hall.

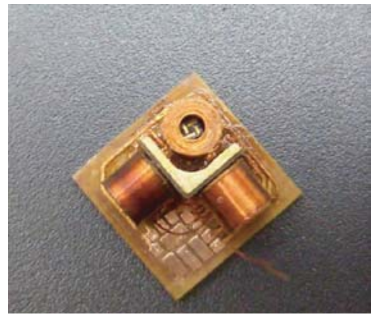

Fig. 4. Three-coordinate magnetometric transducer.

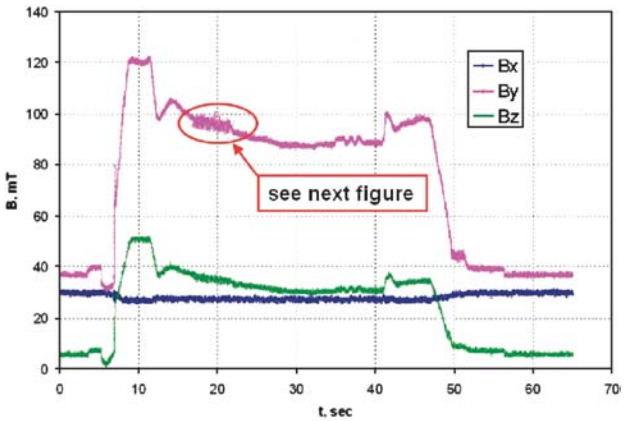

Fig. 5. An example of magnetic field measurement at TORE SUPRA tokamak, France. (Experiment #34085 on plasma confinement).

In such a way, an interface of the digital transmission line TL2 has to provide a high-quality data transmission at a distance up to 100 m. The interface type depends on the required length of the line and speed of data transmission between the electronics unit and PC. The device provides the capability of applying one of two possible interface types: RS232 or RS485.

For the measuring of three components B_X, B_Y, B_Z of the magnetic field induction vector, three-coordinated measuring transducer, so called 3D-probe, was created, in which three functionally integrated transducers were placed along three coordinates (Fig. 4).

At TORE SUPRA reactor the 3D-probe was located out of the reactor toroidal vessel, the electronic unit of the device was located in the reactor hall at 15 m distance from the measuring probe. The signals from the device were transmitted by a fiber cable to the controlling and monitoring hall allowed for the personnel, and then displayed on the computer monitor. Illustrative results of measuring the three orthogonal components of the magnetic field B_X, B_Y, and B_Z are shown in Figure 5, concerning the experiment #34085 at TORE SUPRA. The duration of quasi-stationary phase of magnetic field in the experiment #34085 was equal to 30 s. The value of the main component of magnetic field in this position of the 3D-probe location was equal to approximately 0.1 T. The second and the third components were equal to 0.04 T and 0.03 T, respectively. During the quasi-stationary phase of the discharge, oscillations between 0.09 T and 0.1 T were observed. The magnetic field magnitude was controlled by the plasma confinement control system in such a way that the spatial position of plasma was maintained in the desired range. The discharge fragment in the enlarged scale is shown in Figure 6.

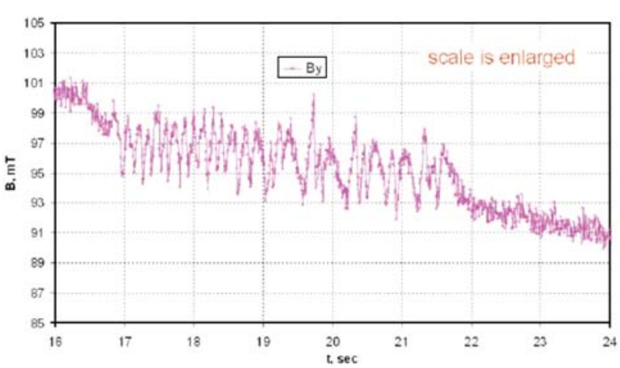

Fig. 6. The pulse discharge fragment in the experiment #34085.

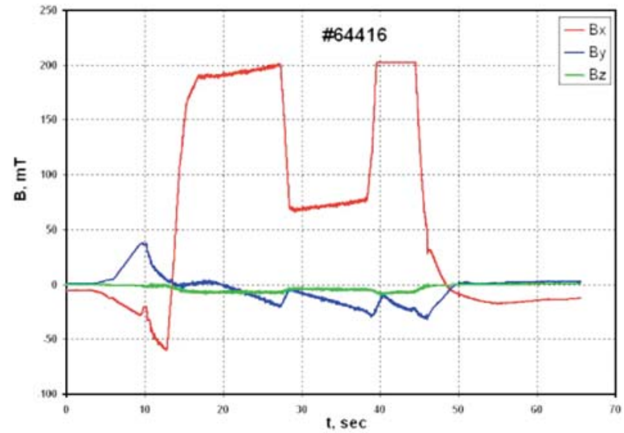

Fig. 7. The results of magnetic field measurement at JET tokamak, where B_x is vertical, B_y is horizontal, and B_z is toroidal components (plasma pulse #64416).

These measurements showed that magnetic diagnostics instrumentation based on galvanomagnetic Hall transducers allows to measure even a fine structure of quasi-stationary magnetic field in contrast to the inductive transducers, in which the short-term changes of magnetic field are averaged due to the integration of the coil's output voltage.

At JET reactor, during the experiments on magnetic field measuring using our specially created Hall sensor-based device, the 3D-probe was located ex-vessel on the P3U poloidal field coil of the machine. The results of the three orthogonal components B_X, B_Y, B_Z measurements during the experiment #64416 at JET reactor are shown in Figure 7.

The experiments at TORE SUPRA and JET tokamaks were performed for the first time and illustrated the availability of the proposed Hall sensor design solutions for the measurement of the quasi-stationary magnetic field as well for the measurement of its fine structure. Presently, the investigations of the ex-vessel magnetic field at JET tokamak, which is a test bed for the future ITER, are continued. The preparation for the in-vessel experiments at TORE SUPRA tokamak is also in progress.

4. CONCLUSION

The Hall sensor-based devices are multifunctional instruments for the magnetic field measuring under irradiation conditions. They meet the requirement toward the intelligent measuring devices, since they possess the functions

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of self-diagnostics and auto-correction of transduction function.

Primary transducers of magnetic field are based on the radiation-hard semiconductor sensors, the signals of which under the neutron irradiation $F = 10^{18}\,\mathrm{n \cdot cm^{-2}}$ are subject to minor changes of just several percents, which can be corrected under irradiation conditions.

The method for devices' stabilization is based on the test measuring method using the synchronous detection and high-precision microconverters. The test magnetic field is generated around the Hall sensors by means of the copper microsolenoid, that parameters of which are stable under the irradiation.

New algorithm of transduction function correction, which is based on the frequency separation of differential and integral signal components, was developed.

The accuracy of magnetic field measuring under neutron irradiation equals to 0.1%, the range of magnetic field to be measured is ± 5 T.

Developed sensor devices can supplement the existing system of thermonuclear reactors' magnetic diagnostics so that to improve the magnetic field measuring accuracy under irradiation conditions. Contrast to the measuring pick-up coils, the developed sensor devices make it possible to measure magnetic fields in a wide frequency range from DC magnetic fields to hundreds kHz.

The developed Hall sensor-based devices have been successfully applied to the measurement of the magnetic field pulses at the European thermonuclear reactors TORE SUPRA (France) and JET (Great Britain).

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