EUROFUSION WPJET1-PR(15) 12972

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Preprint of Paper to be submitted for publication in Nuclear Fusion

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Abstract

The paper discusses radiation-resistant sensors and their magnetic measuring instrumentation resulting from R&D activities that were carried out in the framework of an international collaboration. 3D probes with Hall sensors have been successfully tested in European reactors TORE SUPRA and JET. Notably, long-term operation of sensors and ancillary equipment has been demonstrated over the period of 5 years (2009-2014) on JET. Testing in neutron fluxes in nuclear research reactors shows sensors performance under the conditions of high neutron fluences (>10^{18}n/cm^2). The conducted studies have confirmed the long-term operation of the developed magnetic measuring sensors in ITER-relevant conditions and the promising qualities of these development products for DEMO.

Introduction

Tokamaks require accurate measurement of magnetic fields to ensure operation of the device and interpretation of other diagnostic signals. Present day machines employ largely quite reliable inductive transducers [1] based on pick-up coils with integrators for measuring the magnetic topology. Inductive transducers satisfactorily perform their function in the existing reactors where magnetic field pulses last a few dozen seconds at most. The increase in the pulse duration up to 3600 s in the new generation of reactors, as it is expected in ITER, leads to a significant drop in the accuracy of integration. Moreover, high neutron fluxes are capable of stimulating radiation-induced signals in the integrators, which are also a cause of the decreasing accuracy of the measurements [2].

We have suggested complementing the system of customary pick-up coils with 3D probes comprising semiconductor Hall sensors. Unlike the inductive transducers, they have no restrictions in terms of pulse duration, and provide sufficient accuracy, when applied for measuring high-frequency and constant magnetic fields alike. This makes them a promising option for the measurement of steady-state magnetic fields in new generation reactors characterized by high pulse duration.

However, commercially available semiconductor sensors are not applicable under high radiation conditions intrinsic to thermonuclear fusion reactors.

Radiation-resistant semiconductor sensors and magnetic measuring instrumentation have been designed, and their long-term performance in the conditions of fusion reactors have been demonstrated, owing to the efforts of an international research collaboration supported by projects of CRDF (Civilian Research & Development Foundation) and STCU (Science & Technology Center in Ukraine).

This paper expounds on the major approaches to the implementation of magnetic-measuring instrumentation for measuring steady-state magnetic fields in ITER-relevant conditions, and 5-year testing of such instrumentation prototype on JET (Joint European Torus) over the years 2009-2014.

Radiation-Resistant Magnetic Field Sensors

The developed measuring instrumentation employs Hall sensors based on semiconductor III-V materials InSb and InAs with high mobility of charge carriers as primary magnetic field transducers. A significant amount of studies dedicated to increasing radiation resistance of these materials have been conducted in order to create radiation resistant sensors [6]. These studies have shown that irradiation of indium-containing semiconductors with neutrons lead to the generation of fast-neutron-induced radiation defects of donor and acceptor nature in such materials. Simultaneously, slow, intermediate and resonance neutrons cause transmutation of indium into stannum, which serves as a donor impurity in these semiconductors.

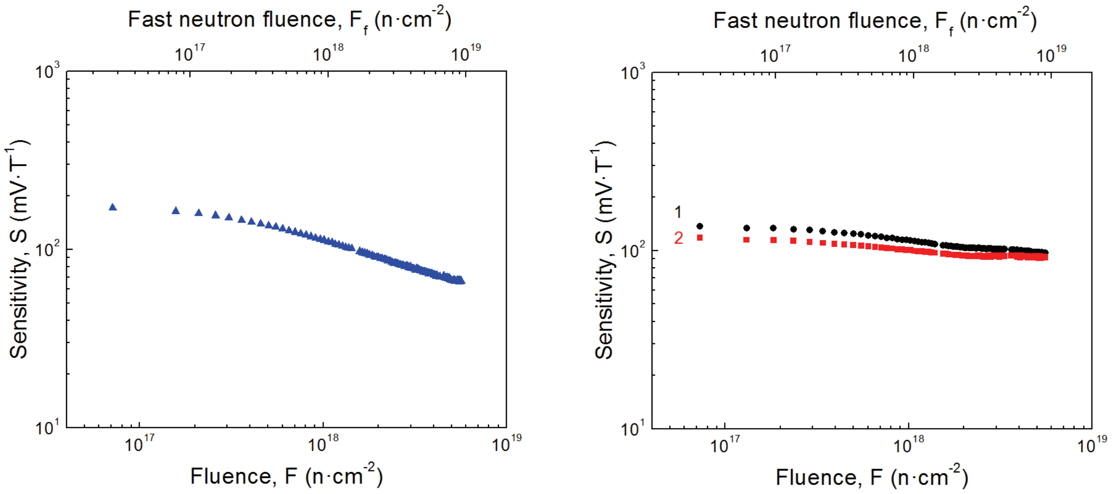
However, the energy band structure is different for indium arsenide and antimonite, which manifests in their different behavior under ionizing radiation. Therefore, these materials would require separate approaches to their parameter stabilization in radiation conditions. In indium antimonite, the radiation stability of the parameters is achieved through a balance between acceptor-type radiation defects and donors generated due to transmutation of indium. In indium arsenide parameter stabilization of the irradiated material is possible at the optimum concentration corresponding to the Fermi level pinning in the conduction band.

In order to achieve high radiation resistance of the sensor materials, methods of chemical doping and radiation modification have been applied. However, ensuring sufficient resistance of sensors in the radiation environment of tokamaks requires also taking into account the energy spectrum of neutrons in each specific sensor location in the reactor. According to revised estimations by M. J. Loughlin [7], the locations of steady-state sensors in ITER in various reactor areas are characterized by neutron fluence ranging from 10^{16}n·cm^{-2} to $1.3\cdot10^{18}$n·cm^{-2}.

InSb/i-GaAs and InAs/i-GaAs heterostructures obtained using the methods of molecular-beam epitaxy (MBE) [8] and MOC-hydride epitaxy [9,10] have been used in manufacturing the sensors for the developed magnetic measuring instrumentation. The developed technologies for growing 100 nm thick nano-scale layers allowed increasing the sensitivity of sensors made from heavily doped materials. Additionally, merely 20-30 nm thick buffer layers were used to cut back on the mismatch between crystalline lattice parameters of the work layer and the substrate.

Sensor samples were tested for radiation stability of their parameters in neutron fluxes in nuclear research reactors IBR-2 in Dubna, LVR-15 in Řež, and WWR-M in Gatchina. Dedicated instrumentation has been created for experiments in nuclear reactors. The instrumentation was placed in a reactor channel and allowed conducting online measurements of the sensor parameters during irradiation [4].

Figure 1 shows results of the last experiments on sensors irradiation in nuclear reactor IBR-2 in October 2014. Testing was carried out up to high fluences $F=6\cdot10^{18}n\cdot cm^{-2}$ that are considerably higher than the maximum fluence of$1.3\cdot10^{18}n\cdot cm^{-2}$ in the locations foreseen for steady-state sensors in ITER over 25 years of ITER life-time. Initial carrier concentration in all three tested sensors was not considerably different ($1.8\cdot10^{18}n\cdot cm^{-3}$; $2.0\cdot10^{18}n\cdot cm^{-3}$ and $2.4\cdot10^{18}n\cdot cm^{-3}$). However technological characteristics of the buffer layer creation can be a reason of this difference. Nonetheless, it is expected that stabilization of irradiated sensor parameters will be higher at initial carrier concentrations close to the optimum concentration $(3\div1)\cdot10^{18}n\cdot cm^{-3}$.



(a) **(b)**

Fig.1. InAs nanoscale sensors sensitivity irradiated up to fluence $F=6\cdot10^{18}n\cdot cm^{-2}$: (a) initial carrier concentration $n=1,8\cdot10^{18}n\cdot cm^{-3}$; (b) initial carrier concentration $n=2,0\cdot10^{18}n\cdot cm^{-1}$ (curve 1) and $n=2,4\cdot10^{18}n\cdot cm^{-3}$(curve 2)

The tests conducted in nuclear reactors have confirmed the sensors' operability in neutron fluxes up to the highest fluences exceeding the level of maximum radiation load expected in steady-state sensors' locations in ITER.

3D measurement of magnetic field vector component in TORE SUPRA and JET reactors

Magnetic-measurement instrumentation (MMI) has been developed on the basis of radiation-resistant sensors and was used for magnetic field vector component measurement in TORE SUPRA and JET reactors. Examples of measurement in specific experiments on plasma confinement in these reactors are shown in Figure 2. They demonstrate the Hall sensors ability to effectively measure both high-frequency and steady-state magnetic fields.

MMI contains 3D probes comprising Hall sensors, an electronic unit and software. MMI is based on the periodic in-situ calibration method. The method relies on the periodic measurement of signal induced by the test magnetic field of the integrated magnetic measuring transducer that contains 3 orthogonally aligned Hall sensors. The test magnetic field is generated near the Hall sensor with a suitable actuator – a tiny solenoid made of copper wire.

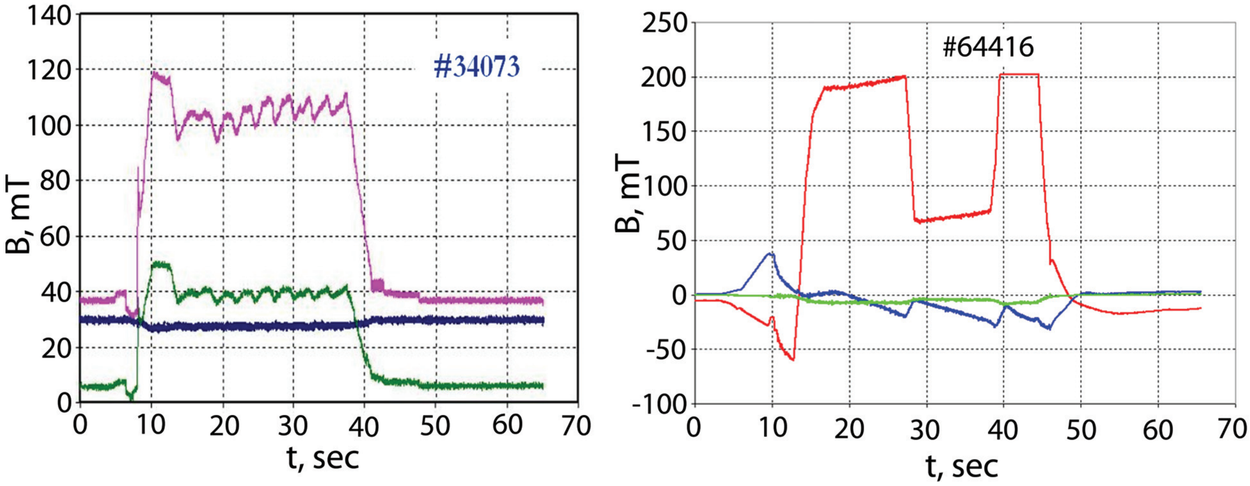


Fig. 2. 3D measurement of magnetic field vector component in European fusion reactors: (a) –TORE SUPRA reactor: experiment on plasma confinement № 34073; (b) –JET reactor, experiment on plasma confinement № 64416.

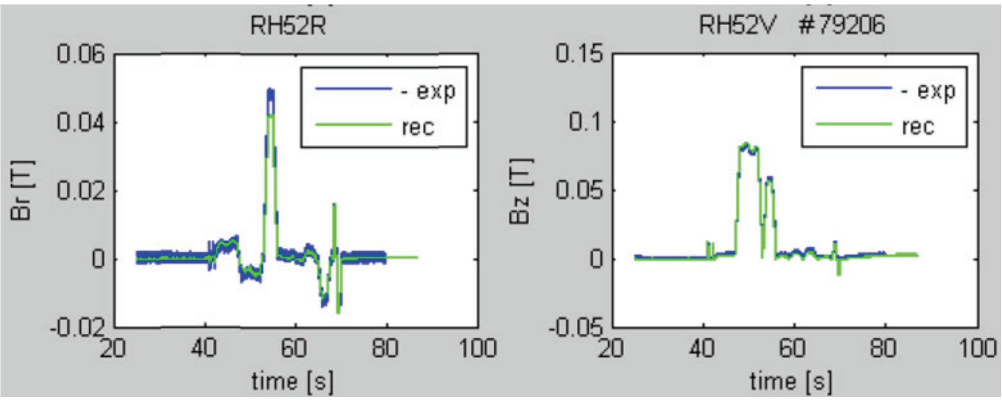
Noise-immune methods of signal processing are used for filtering the test magnetic field signal from general signal generated by the reactor magnetic field. Notably, the magnitude of the reactor magnetic field can exceed that of the microsolenoid test field by several orders. E.g. the value of test field can amount to 5 mT, while toroidal magnetic field at ITER can reach upwards of 5 T, i.e. a thousand times as much. Synchronous signal detection is a key to zeroing in on such weak test fields with high accuracy. The value of the test magnetic field being independentof the accumulated radiation dose is of principal importance. It is known that magnetic field induction relies only upon the geometric parameters of the microsolenoid, number of winds and supply current. None of these parameters depends upon radiation, and therefore even if the parameters of the wire the microsolenoid is made of change under radiation, the value of the test magnetic field will remain stable.

Experimental Evaluation of Long-Term and Stable Magnetic Sensor Operation

In 2009 during JET session C27 six sets of magnetic-measuring system with 3D Hall probes (i.e. 18 radiation-resistant Hall sensors in total) were mounted ex-vessel on JET fusion reactor. Electronic units were placed a few meters away from the probes. Signals were passed along about 100 m of cables to the acquisition room.

Special significance had the evaluation of the accuracy of MMI periodic in-situ calibration based on periodic measurement of sensor signals, generated by test magnetic field of the measuring transducer's microsolenoids.

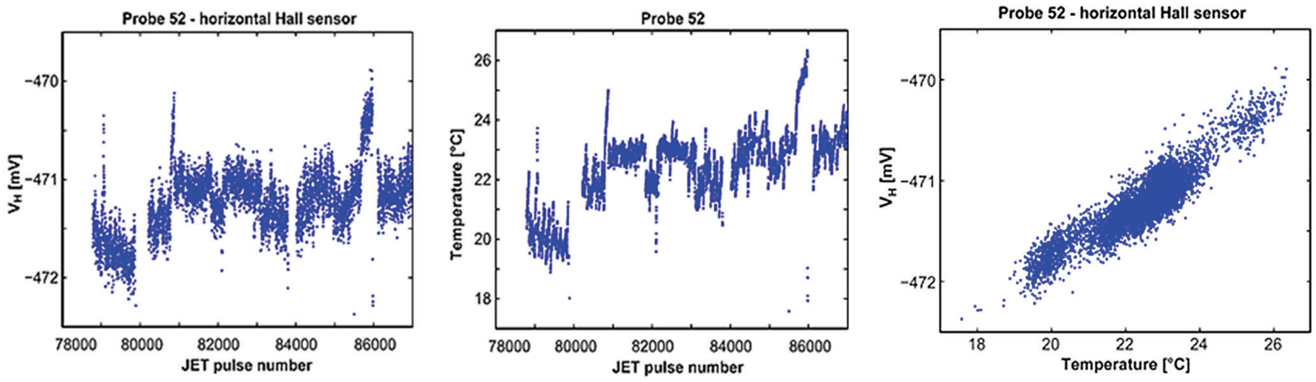
MMI instrumentation installed in 2009 presently operates in online measurement mode, and feeds the data on magnetic field into JET database. An example of magnetic field measurement results obtained with MMI (exp) and through model calculations (rec) is plotted in Fig. 4. Model calculations using the signals of pick-up coils included into the system of magnetic diagnostics employed on JET was performed for the spatial locations of MMI 3D probes. The figure shows good correspondence between experimental and calculated results. However, as it has been noted, unlike pick-up coils, MMI allows measuring however long pulses of magnetic field, which is going to have crucial importance in magnetic diagnostic systems of future generation reactors, ITER in particular [5].



(a) (b)

Fig.3. Comparison of model calculation (rec) experimental and magnetic field measurement (exp) with 3D probe №52: (a) – Br radial field, (b) – Bz vertical field.

In 2014 we evaluated the performance stability of all Hall sensors that were installed on JET over the 5 year period, which amounts to over 8000 JET pulses. First of all, all Hall sensors in 6 sets of 3D probes have been operating with reliably high precision over the whole 5 year period. Further we demonstrate in detail the data evaluation used for the sensors set, using three sensors of 3D probe #52 as an example. The measured response of Hall sensor to the calibration magnetic field after subtraction of offset of amplifiers is plotted in Figure 4(a). The temperature inside the #52 probe for each calibration cycle is shown in Figure 4(b), the temperature dependence of Hall voltage range - in Figure 4(c).



(a) (b) (c)

Fig.4. Evaluation of horizontal sensor stability in 3D probe №52 as a function of plasma pulses quantity: (a) – Hall voltage range generated by calibration magnetic field; (b) – sensor temperature; (c) – temperature dependence of Hall voltage range.

Already Figure 4 clearly demonstrates that the changes of sensors' sensitivity in 3D probe #52 over the period of 5 years of operation on JET are small and there is no visible trend of continuous degradation or repeated instability or failures. Short periods, where the data are missing, correspond to the JET commissioning discharges in between experimental campaigns where the GMI was not operated. Further, the spread of the probe temperatures during calibration is rather low, i.e. from 18 ºC to 26 ºC. Finally, it is apparent, that the changes of the Hall voltage correlate very well with temperature evolution leading to correlation coefficient of 0.91.

The temperature dependence of Hall voltage generated by the certain magnetic field is linear following:

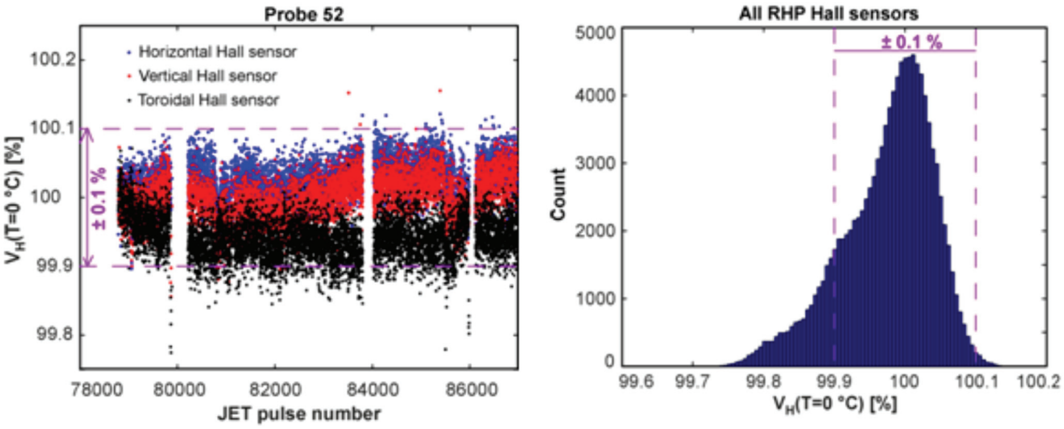
$$\mathbf{V_H\ (T)=VH\ (T=0^\circ C)[1+\alpha T]} \qquad (1)$$

where T is sensor's temperature and α is the temperature coefficient of the Hall voltage.

We used the method of the minimization of the cross correlation coefficient between VH and T records to obtain appropriate value of α coefficient leading to $\alpha = 4.99\times10^{-4}$ ºC-1.

Finally, in order to assess the long term stability of performance of Hall sensors installed on JET, we plot the V_H(T=0 ºC) normalized by the initial value of this voltage and multiplied by 100 for each of the three Hall sensors contained within the probe #52, see Figure 6 (a).

Practically all values of V_H(T=0 ºC) for all 3 Hall sensors contained within the probe #52 are within ± 0.1 % of the initial values. A certain desensitization trend, amounting to approximately 0.05 %, of the sensitivity is observed only for the toroidal sensor during the first months of its operation on JET. Such trend is observed also for a few additional Hall sensors in the other probe heads, however, upon closer inspection it was concluded that this decrease can be rather attributed to non-ideally compensated temperature dependence (slight nonlinearity) than to temporal degradation of sensor properties.



(a) (b)

Fig. 5. The full record of V_H(T=0ºC) for horizontal, vertical, and toroidal Hall sensors (a) and histogram (b) of the V_H (T=0ºC) including calibration data from all 18 GMI Hall sensors over the full time interval of 5 year of their operation on JET

Figure 5(a) shows the statistical distribution of V_H(T=0ºC) from all 18 GMI sensors accumulated over the full investigated time interval of approximately 5 years of their operation on JET. Again, it is found, that the bulk of the calibration data fall within ± 0.1 % of their initial values (Figure 5(b)). The slightly skewed distribution toward decreased sensitivity is rather caused by non-ideal compensation of temperature dependence of the sensor's sensitivities than to a real temporal degradation of sensors properties.

Conclusions and outlook

The developed radiation-resistant semiconductor sensors of magnetic field have received experimental evaluation as they were tested in nuclear research reactors, and demonstrated their high performance under conditions of high-fluence neutrons several times as high as the maximum neutron fluence in steady-state sensor locations in ITER reactor.

We have determined all optimum parameters of the magnetic field radiation-resistant sensors which allow conducting measurements in radiation environment without periodic sensor recalibration that considerably simplify magnetic-measuring instrumentation without decreasing measurement accuracy.

The task of development and testing of ITER-relevant tools for measuring steady-state magnetic fields that would satisfy the radiation and temperature conditions of thermonuclear fusion reactors has been solved. Magnetic measuring instrumentation with 3D Hall sensors has successfully undergone testing in European reactors TORE SUPRA and JET. Thereby the sensors and instrumentation have shown long-term operability over the period of 5 years on JET.

Making use of radiation-resistant sensors, two new methods for measuring tokamak magnetic fields have been developed jointly with the JET team, which made subject to European patents. The first one concerns the method of in-situ calibration that applies the signals of pick-up coils customarily used in tokamaks. It allows increasing precision and reliability of JET and ITER magnetic fields measurements. This method is patented in the UK (patent GB 2427700) [11]. The second method concerns the minimization of the sensor's residual voltage offset, and allows enhancing reliability and precision of low residual magnetic fields measurements in metal constructions of JET and ITER alike. This method [12] is a subject of European Patent application № 10858732.0 of 18.04.2013. Implementation of these methods in JET, which are also useful for ITER, is being considered.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission and U.S. CRDF Global. This work was also part-funded by the RCUK Energy Programme under grant EP/I501045, the Czech Science Foundation GAP205/10/2055, STCU project #3988 and U.S. Civilian Research & Development Foundation (CGP Project UKP2-7111-LV-13). The authors gratefully acknowledge use of facilities and instrumentation supported by the University of Wisconsin Materials Research Science and Engineering Center (DMR-1121288).

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