Investigation of stability of ITER candidate Hall sensors under neutron irradiation

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Hall sensors offer an attractive true non–inductive method of magnetic field measurements for fusion reactors. Their use for steady state magnetic diagnostics of ITER is presently limited by their questionable radiation and thermal stability. Issues of stable and reliable operation in ITER like radiation and thermal environment are addressed by the contribution. Recently, novel Hall sensors, compatible with temperatures up to 200°C, were developed and their radiation stability was tested at LVR–15 experimental fission reactor. Overview of the experimental set–up on LVR–15 reactor is given. Degradation of the sensor's sensitivity by several tens of percents was observed after neutron irradiation by the total neutron fluence of 2×10^{17} n/cm^2 in LVR–15. This level of neutron fluence is comparable to that expected to occur over the whole ITER life time for a sensor location just outside the ITER vessel. The in–situ recalibration techniques are expected to handle the observed degree of Hall sensors performance degradation in ITER environment.

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1 Introduction

The need for steady state magnetic field detectors for the future thermonuclear fusion reactor is evident. The primary magnetic diagnostics for ITER is based upon coils with the subsequent analogue integration. For pulse length 1000 s this approach becomes difficult. The possible solution is the use of Hall detectors that measure the absolute value of magnetic field directly. Typical semiconductor materials for a present day commercial Hall sensors are GaAs, InSb, InAs. The typical value of the Hall constant for these materials is from 1 mV/T to 1 V/T. The maximum operational temperature of commercial transducers is up to 150 °C. The main constrains connected with building the ITER steady state magnetic diagnostics system based on Hall sensors are:

– Stable and reliable operation of the sensors in the ITER radiation environment.

– Sensors must survive the elevated temperature of the ITER structure up to at least 220 °C (maximum allowance for baking).

The most pronounced objection against the use of Hall sensors in the reactor type tokamak is their vulnerability to radiation damage (esp. to the high neutron fluence). Neutrons (> 0.1 MeV) fluence rate of 5×10^{12} n/(cm^{2}s) is expected behind the ITER blanket for a possible maximum fusion power of 700 MW. Data on radiation stability of commercially available Hall sensors are sparse [1–3]. The special radiation hard Hall sensors based on InSb were developed and tested in the past [3–5]. Sensitivity of these sensors decayed by a few percents only at their ITER life time reference fluence of 2×10^{17} n/cm^2 which qualifies them for use on ITER from 'radiation hardness' point of view. However, survival temperature of these sensors is only up to 100 °C which is too low compared to the ITER requirement of 220 °C. Recently, novel Hall sensors compatible with temperatures up to 200 °C, were developed and their radiation stability was tested at LVR–15 experimental fission reactor to asses their performance in radiation environment.

2 Experimental arrangement

To asses the sensitivity of the tested Hall sensors in–situ in the irradiation channel of LVR–15 a complex experimental set–up had to be developed (see Fig. 1). In total, seven sensors were mounted in the cylindrical irradiation head made from aluminum. The test magnetic field was created by a calibration coil mounted within the irradiation head and driven by a power source of 320W. The coil driven by 8 A created the test magnetic field of 3.5 mT in the volume, where the Hall sensors were located. The test magnetic field was switched on/off by a PC controlled switch and its actual value was permanently measured and stored. The output voltage of the Hall sensors was monitored by multifunction data acquisition PC Board AD25HAL from AREPOC Ltd., Slovakia. The system offers 26 bits resolution, maximum error of 0.005 % and the noise level bellow 0.5 μV. Temperature within the irradiation head was measured at two location by PT–100 thermo resistors. The total neutron fluence accumulated was measured by a set of three activation foils made from Fe, Ni, and Co at three locations within the irradiation head. The irradiation head was inserted into the vertical channel of the LVR–15 reactor so that its leading edge was aligned with the top of the core region of the reactor. The irradiation was performed within a single 22 days long campaign. The reactor was operated at 9 MW of thermal output power.

3 Irradiation campaign

The output voltage from the Hall sensors was collected during the whole campaign with a sub–second time resolution and the temperature was sampled by 4

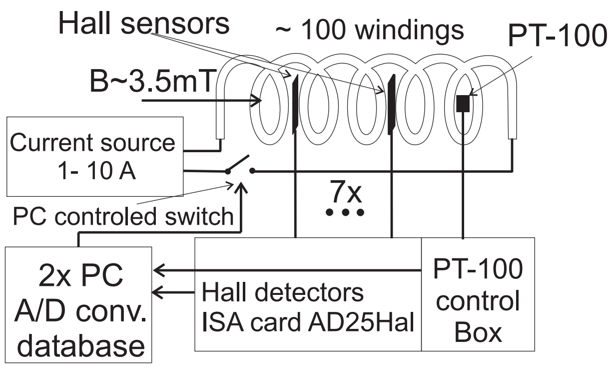

Fig. 1. Schematic set–up of the irradiation of the Hall sensors.

seconds/sample. The calibration magnetic field was periodically turned on and off with a pattern: 10s ON, 10s OFF to eliminate large temperature changes due to Joule heating from the calibration coil. The calibration magnetic field was measured with a sampling rate of 4 seconds/sample. The data record from sensor MSL4_05 is shown in the left panel of Fig. 2. Data plotted by red colour are taken during the time intervals when the calibration magnetic field was switched ON, while the blue denotes that there was no magnetic field during measurement. Detailed view of the several measuring cycles is shown in the right panel of Fig. 2. Unfortunately, due

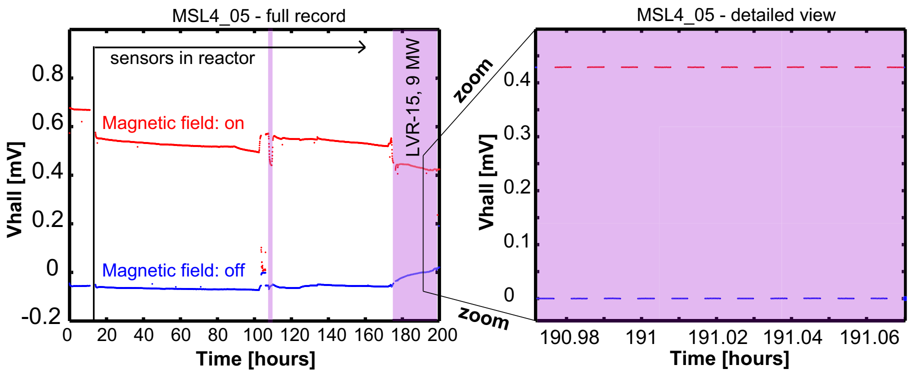

Fig. 2. Record of the MSL4_05 output voltage monitored during the irradiation campaign (left panel). Detailed view zoomed around 191 hour (right panel). Time interval when the reactor was running at 9 MW is denoted by purple colour.

to breaking of isolation of output leads for several tested Hall sensors, we were able to monitor output of only two Hall sensors in the course of irradiation. The two sensors are MSL4_05 based on material from solid solution of InAs and InSb and the MSL11_05 based on Galium nitrides. The other sensors were analyzed only after the execution of the irradiation campaign. In order to evaluate the change of sensors sensitivity in the course of irradiation, we have accounted for the change of sensors sensitivities due to temperature variations. The best results, in terms of lowest change of sensors output before the activation of reactor were obtained using coefficients of temperature dependence of sensor sensitivity 0.18 %/K in case of MSL4_05 and 0.1 %/K in case of MSL11_05. The resulting temporal evolutions of sensors sensitivities during irradiation are plotted in Fig. 3. The top panel shows irradiation

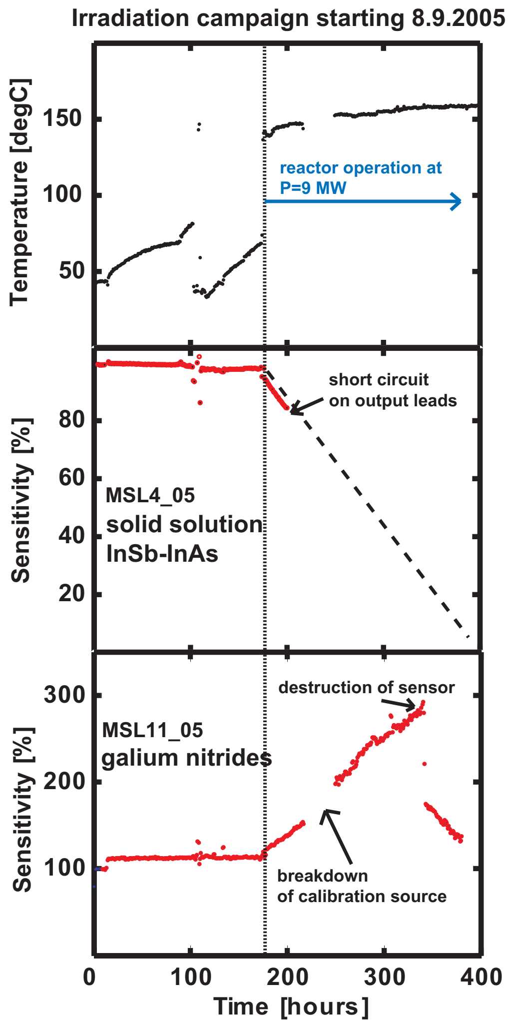

Fig. 3. Top panel – temperature of the irradiation head. Middle panel – temporal evolution of sensitivity of MSL4_05. Projected evolution after hour 200 (short circuit of output leads on irradiation head structure) is plotted by dashed line. Bottom panel – temporal evolution of sensitivity of MSL11_05 sensor.

head temperature evolution during irradiation. The start of reactor operation is denoted by solid line. The evaluated sensitivities of MSL4_05 and MSL11_05 are plotted in middle and bottom panels. The sensor MSL4_05 accumulated total neutron fluence of 6.7×10^{16} n/cm^2 (with a fraction of 4.6×10^{16} n/cm^2 of fast neutrons 0.1 MeV ÷ 20 MeV). At this fluence, which is about one fourth of the target ITER life time fluence (2.5×10^{17} n/cm^2), the sensitivity of MSL4_05 decayed by a little less than 20 %. Unfortunately, at this point, the short circuiting of MSL4_05 output leads occurred that disabled further monitoring also of this sensor. The sensitivity of MSL11_05 was followed up to 'destruction' at 2.7×10^{17} n/cm^2 (with a fraction of 1.9×10^{17} n/cm^2 of fast neutrons), which is slightly above the target ITER life time fluence. The sensitivity of the sensor reached almost 300 % of pre–irradiation value at that point. Significant noise level and large offset voltage are drawbacks of this sensor up to now.

4 Post irradiation analysis

All the sensors were taken out from the irradiation head after the 22 days long campaign and further analyzed. The total neutron fluence accumulated was up to 4.5×10^{18} n/cm^2. After the full campaign, contacts of all sensors output leads were lost inside the sensors bodies. Significant damage of the sensors sealant was seen (see Fig. 4). Because, all the sensors were tested before irradiation under temperatures up to 200 °C without any impact on their neither functionality nor appearance, the possible reasons for observed loss of contacts are:

- Radiation induced deterioration of sensors sealant and consequent breaking of contacts due to mechanical stresses. This hypothesis is supported by the fact that the most pronounced sealant damage was seen for the most inner sensors that were subject to highest radiation doze.

- Combined effect of elevated temperature and radiation on the sensors sealant. Those sensors that accumulated the highest neutron fluence were subject to highest radiation heating.

- Mechanical damage during a complicated installation of the irradiation head inside the channel and its dismounting after the campaign.

- Local exceeding of 200 °C temperature limit inside the sensors due to localized radiation heating. This statement is based on the rather similar look of the sensor's sealant for sensors taken out of the reactor with such sealant exposed to temperature higher than 200 °C. Although, the possibility of such high local overheating seems not to be probable as it would require temperature differences of around 100 °C or more within the irradiation head, it can not be fully excluded. Clearly, temperature monitoring in thermal contact of each individual irradiated Hall sensor would be very beneficial for interpretation of future follow up experiments.

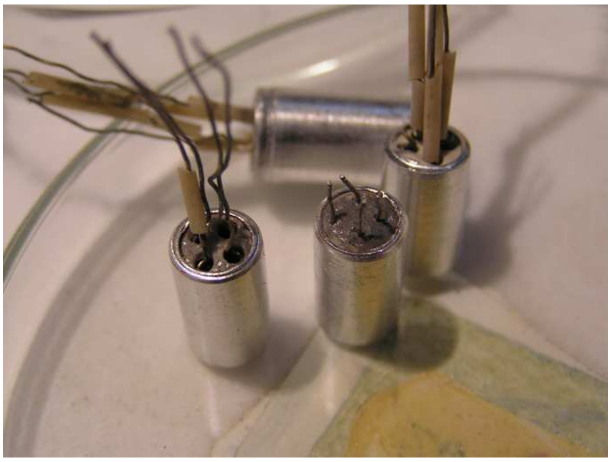

Fig. 4. Sensors taken out from the irradiation head after the full 22 days long irradiation campaign.

5 Summary

Set of candidate Hall probes compatible with temperature up to 200 °C was developed, manufactured, and tested on LVR–15 fission reactor. A fully automated PC based system for periodic in–situ calibration of the Hall sensors during irradiation in the LVR–15 fission reactor channel was developed and put in operation. It features high precision, high level of automation and remote control possibility via internet which is particularly important when operated in radiation environment of fission reactors. A set of 7 Hall sensors was irradiated within a 22 days long campaign with a total accumulated neutron fluence up to 4.5×10^{18} n/cm^2 which is 20 times more than the target ITER life time fluence. Loss of electrical isolation during installation of the irradiation head inside the reactor allowed on–line monitoring of output for only two sensors during the irradiation. The output of MSL4_05 (InAs–InSb) was monitored up to 6.7×10^{16} n/cm^2. At this fluence, which is about one fourth of the target ITER life time fluence, the sensitivity decayed by a less than 20%. The second sensor MSL11_05 (galium nitrides) was followed up to 'destruction' at 2.7×10^{17} n/cm^2 which is slightly above the target ITER life time fluence. The sensitivity of the sensor reached almost 300 % of pre–irradiation value at the point of 'destruction'. Although, the in–situ recalibration techniques are expected to handle the observed degree of Hall sensors performance degradation in ITER environment, further optimization of tested materials composition is desirable to provide stronger confidence in their long term reliable operation on ITER. The post irradiation analysis of all seven sensors was done after their removal from the irradiation head. Apparent damage of the sensors sealant was found particularly for sensors that were subject to highest radiation doze.

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References

[1] G. A. Wurden et al.: *Steady–State Position Control for the Tokamak Physics Experiment (TPX)*, 62–940825–LANL, Nov. 1997.

[2] J. F. Baur et al.: *Radiation Hardening of Diagnostics for Fusion Reactors*, GA–A16614, Dec. 1981.

[3] I. Ďuran et al.: *Stability of the Hall sensors performance under neutron irradiation*, poster P2–66, published in E–proceedings of 12th International Congress on Plasma Physics, 25–29 October 2004, Nice, France at: http://hal.ccsd.cnrs.fr/ccsd–00001781.

[4] I. Bolshakova et al.: IEEE Transactions on Applied Superconductivity, **12** (2002) 1655–1658.

[5] I. Bolshakova et al.: *Stable Semiconductor Magnetic Field Sensors Under Dozes of High Radiation*, 30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 2003, ECA Vol. 27A, P–4.68.