Stability of the Hall sensors performance under neutron irradiation

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A principally new diagnostic method must be developed for magnetic measurements in steady state regime of operation of fusion reactor. One of the options is the use of transducers based on Hall effect. The use of Hall sensors in ITER is presently limited by their questionable radiation and thermal stability. Issues of reliable operation in ITER like radiation and thermal environment are addressed in the paper. The results of irradiation tests of candidate Hall sensors in LVR-15 and IBR-2 experimental fission reactors are presented. Stable operation (deterioration of sensitivity bellow one percent) of the specially prepared sensors was demonstrated during irradiation by the total fluence of 3 10^{16} n/cm^2 in IBR-2 reactor. Increasing the total neutron fluence up to 3 10^{17} n/cm^2 resulted in deterioration of the best sensor's output still bellow 10% as demonstrated during irradiation in LVR-15 fission reactor. This level of neutron is already higher than the expected ITER life time neutron fluence for a sensor location just outside the ITER vessel.

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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 analog 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.

The Hall effect was first observed in 1879 by E.H. Hall at the Johns Hopkins University. Take a slab of conductor or semiconductor material (see Fig. 1) and drive a constant current I_H along it. Then, immerse the slab into a magnetic field B that points along the slab normal. A voltage U_H appears between the remaining two faces of the slab. This, at the time of its discovery a very puzzling observation, is called Hall effect. It's precise treatment is rather complicated and involves quantum mechanics. Here it will be described from the viewpoint of classical electrodynamics only. The current I_H driven through a N type semiconductor or conductor is carried by electrons. Electrons moving with velocity v are affected by the external magnetic field B and see a Lorentz force $F=q(E+v\times B)$. This force causes the electrons to drift toward one side of the Hall plate which establishes an electric potential U_H as depicted in Fig. 1. For P type semiconductors, the situation is similar, only the polarity of the Hall voltage U_H being reversed. The voltage U_H is given by the equation $U_H=k_H\, I_H\, B \sin(\alpha)$, where α is the angle between B and I_H and k_H is the Hall coefficient. k_H depends on the semiconductor material chosen, on the slab area facing B, and also on temperature. For measurement of the magnetic field, it is desirable to keep

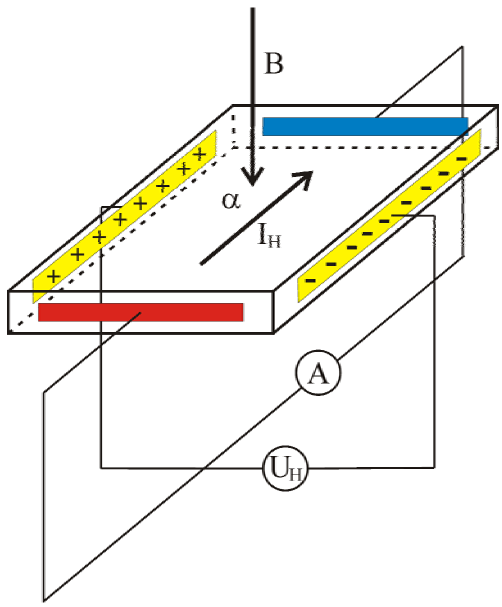


Figure 1: Principal scheme of Hall detectors based on a N type semiconductor.

I_H and $\sin(\alpha)$ constant, therefore, it is possible to introduce a Hall constant $k = k_H I_H \sin(\alpha)$. Consequently, the measured quantity U_H, is directly related to the external magnetic field B by:

$$U_H = k\,B \qquad \text{Eq 1.}$$

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 1V/T. The driving currents I_H range from a few mA to a few hundreds of mA. The maximum operational temperature of commercial transducers is up to 185 °C.

The main constrains connected with building the ITER steady state magnetic diagnostics (SSMD) 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)

Other requirements appear to be readily achievable by the present day technology.

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

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 fluxes). Neutrons (>0.1 MeV) flux density of ~ 5×10^{12} n/(cm^{2}s) is expected behind the ITER blanket for a possible maximum fusion power of 700 MW. The issue is not as critical as it is for other semiconductor elements as transistors for example. The reason is that the physics of transistor is in fact a physics of junction between two types of semiconductors while the Hall effect is a volume process in a single type of a semiconductor. The basic mechanism of radiation damage is rather simple. The incident neutrons increase the density of the free charge carriers within the volume of the Hall sensor through ionization of semiconductor material. The electric field $\boldsymbol{E}=(0,-E_y,0)$ generated by the Hall effect across the semiconductor inserted into magnetic field $\boldsymbol{B}=(0,0,B_z)$ is given by $\boldsymbol{E}=\boldsymbol{B}\times\boldsymbol{v}$. The free charge carriers within the semiconductor material are forced to move with velocity $\boldsymbol{v}=(v_x,0,0)$ by external circuits. The velocity $\boldsymbol{v}$ is related to the current density $\boldsymbol{j}$ driven by these circuits by $\boldsymbol{j}=ne\boldsymbol{v}$, where e is electric charge of the single free charge carrier in the semiconductor and n is density of the free charge carriers in the semiconductor material. Combining previous equations one obtains:

$$E_y = \frac{1}{ne} B_z j_x \qquad \text{Eq. 1}$$

When using the Hall sensors for measurement of magnetic field, the j_x is kept constant. Consequently, the Hall electric field generated across the Hall sensor is inversely proportional to the density of free charge carriers. Therefore, any ionization process within the sensor decreases its sensitivity. The improved radiation stability of the Hall sensors is achieved by using semiconductor material with high concentration of free charge carriers n thus, minimizing the relative impact of ionizing radiation. But, as the sensors from high n semiconductors has low sensitivity (~ 1 mV/T), there is an apparent trade-off between radiation stability and sensitivity of the sensors. Another option is the use of the micro-crystals with a good crystalline structure doped by special impurities as Te or Se. The good crystalline structure is important to increase capacity of the crystal for radiation induced damage, while still maintaining reasonable performance. The additional dopants can act also as "healing agents" that correct defects in the crystal grating caused by ionizing radiation. Still additional option how to compensate the impact of radiation is to employ the in situ recalibration techniques, already demonstrated in [1]. Placing the Hall sensor into miniature solenoid driven by known oscillating current offers possibility to recalibrate the sensor any time during its operation. Degradation of the sensor can be compensated by increasing the Hall sensor control current I_H.

The existing data on the Hall sensors irradiation tests are sparse and sometimes inconsistent. According to LakeShore Cryogenics, Inc. published also in [2] the 3-5% decrease in sensitivity of highly doped InAs Hall sensors (the most „radiation-hard") was observed after irradiation by 10^{15} n/cm^2. That would imply a substantional decrease in sensitivity after a few tens of seconds of a single ITER discharge for sensor location just behind blanket. On the other hand, according to [3], the treshold for 'significant damage' to a Hall sensor is in the range 10^{16}-10^{19} n/cm^2. That would mean the time range comparable to the ITER fluence life time (4700 hours) in the most optimistic case. The recent experiments [4] proved the stability of special radiation hard Hall sensors within 0.04% under neutron irradiation of total fluence of 10^{15} n/cm^2.

Temperature stability of present commercial Hall transducers

Although, the properties of many commercially available Hall transducers approach or directly satisfy the requirements for ITER steady state magnetic diagnostics (SSMD), it is unfortunately not the case as far as their maximum allowed temperature is concerned. The ITER requirement is that the sensors must survive temperature excursions up to ~ 220 °C. The most of the commercial transducers operate up to 100 °C. There are a couple of options in the range up to 150 °C. Within the knowledge of the authors there are only a few commercial sensors exceeding this limit. Maximum "storage temperature" was offered by the transducer HS-100 (F.W. Bell, USA) surviving up to 190 °C.

2. Motivation

The aim of our work was to determine the influence of neutron irradiation of the ITER relevant total fluence on the sensitivity of a set of candidate Hall probes. The sensitivity of the Hall sensors is to be measured in-situ during the whole irradiation process. Irradiation tests were proposed in the fission light water research reactor LVR-15 (10 MW) placed in Nuclear Research Institute in Řež. This aim had to be obtained following the steps:

- Identification and obtaining the set of candidate Hall probes.
- Design and manufacturing of the hardware for test irradiation in the horizontal BNCT beam line of LVR-15 reactor (irradiation head with possibility of on-line calibration of the sensors, fully automatic data acquisition system).
- Preliminary irradiation tests in the horizontal BNCT beam line of LVR-15 reactor (low neutron flux).
- Design and manufacturing of the hardware for main irradiation near the core of the LVR-15 reactor (irradiation head with possibility of on-line calibration of the sensors, temperature monitoring inside the irradiation head, fully automatic data acquisition system).
- Irradiation tests of the eight candidate Hall probes within the reactor core of LVR-15.
- Data analysis and preparation of report.

3. Experimental set-up

The LVR-15 is light-water moderated and cooled tank nuclear reactor with forced cooling. The fuel type IRT-2M enriched to 36% and a combined water-beryllium reflector are used. The basic reactor characteristics are:

- maximum reactor power	10 MW
- maximum thermal neutron flux in the core	1.5×10^{18} n/m^{2}s
- maximum fast neutron flux in the core	3×10^{17} n/m^{2}s
- maximum total neutron flux in the core	3×10^{18} n/m^{2}s
- total neutron flux at the end of the BNCT beam	1×10^{13} n/m^{2}s

The reactor is equipped with the following experimental facilities:

- high-pressure water loops

- vertical channels for material testing (rigs)
- vertical irradiation channels
- pneumatic rabbit system for short-time irradiation
- nine horizontal channels (beam tubes)
- thermal column
- hot cells

The experimental campaigns of LVR-15 reactor are organized in 20 days cycles of permanent operation followed by 10 days of switched off state. The reactor is operating usually from September till the end of June.

BNCT channel

The first stage of irradiation took place in the reactor epithermal horizontal channel routinely used for Boron Neutron Capture Therapy (BNCT) – treatment of patients with cancer. The nominal neutron flux densities in the BNCT horizontal channel are as follows (BNCT core configuration):

Neutron energy	Neutron flux density [cm^{-2} s^{-1}]
thermal	$(1.12 \pm 0.05) \times 10^8$
<0.5eV, 10keV>	$(6.98 \pm 0.27) \times 10^8$
above 10 keV	$(6.94 \pm 0.40) \times 10^7$

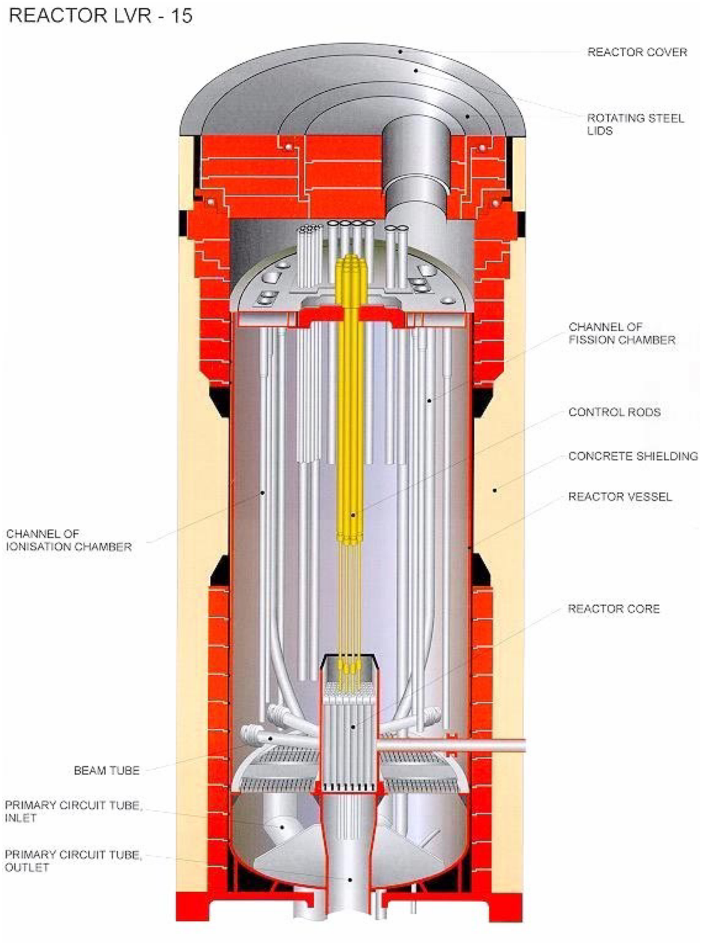


Figure 2: Schematic layout of the LVR-15 reactor, side view

The full spectrum of the neutron flux is shown in the Fig.4.

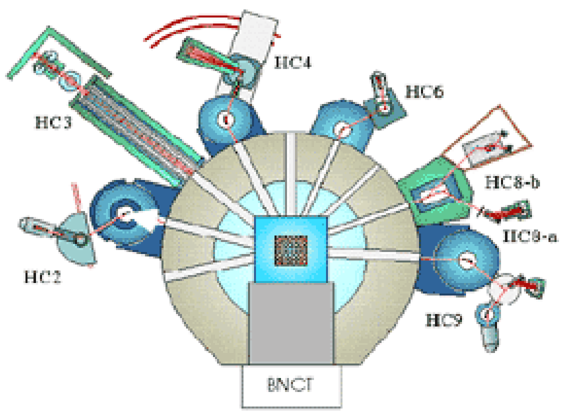


Figure 3: Schematic layout of the distribution of the LVR-15 horizontal channels. BNCT channel is shown in the lower part of the picture. The reactor core is depicted in the central part.

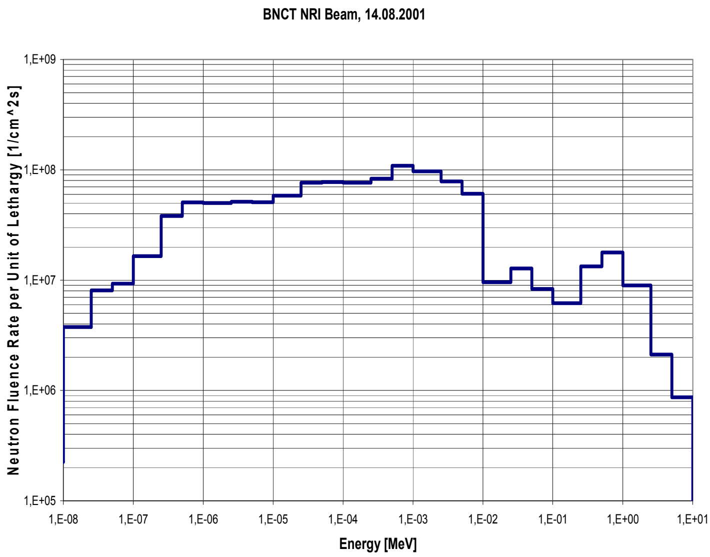


Figure 4: Nominal spectrum of the neutron flux density in the BNCT channel

The vertical channels – the reactor core

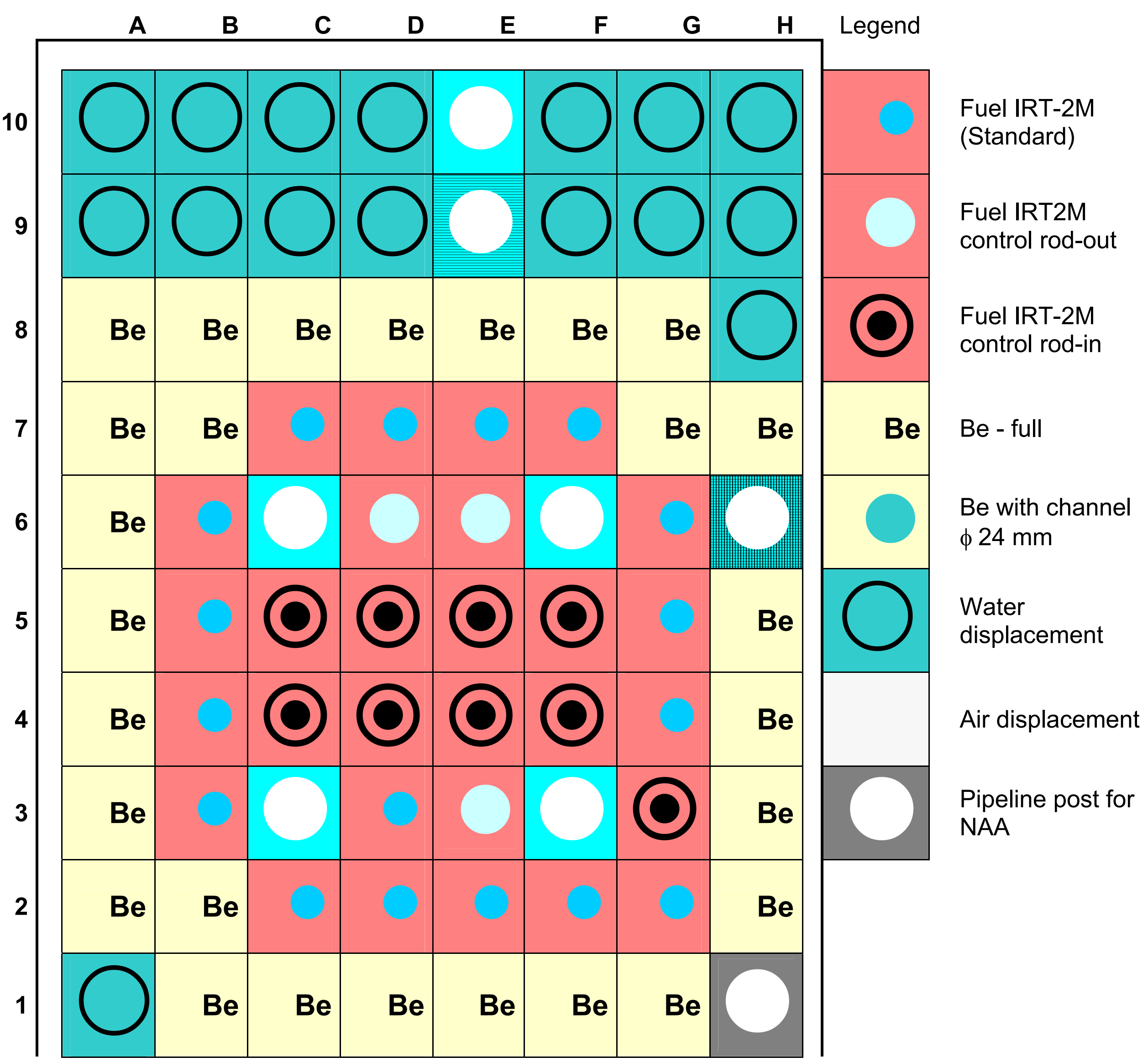
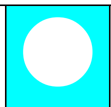
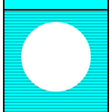
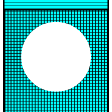
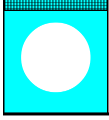


Figure 5: Schematic set-up of the reactor core zone – top view. Top right panel – explanation of various symbols. Bottom right panel – parameters of four types of vertical irradiation channels.

Irradiation channel	Fluence rate E>1.0 MeV ($m^{-2}s^{-1}$)	dpa rate (s^{-1})	Gamma heating in steel (W/g)
	1,60E+16	2,26E-09	0,7
	3,20E+16	4,53E-09	1,2
	1,70E+17	2,41E-08	1,9
	4,38E+17	6,20E-08	3,2

The standard set-up of the LVR-15 core region is depicted in the Fig. 5. The fuel rods in the central segment of the core region are surrounded by berilium reflector modules. Four types of vertical irradiation channels are shown with the basic parameters stated. These values apply to the horizontal mid-plane of the core region. The berilium reflector module at location H6 was removed and the new dry irradiation channel for Hall sensors was inserted instead as marked in Fig. 5. The full spectrum of neutron radiation within the core region is plotted in the Fig. 6.

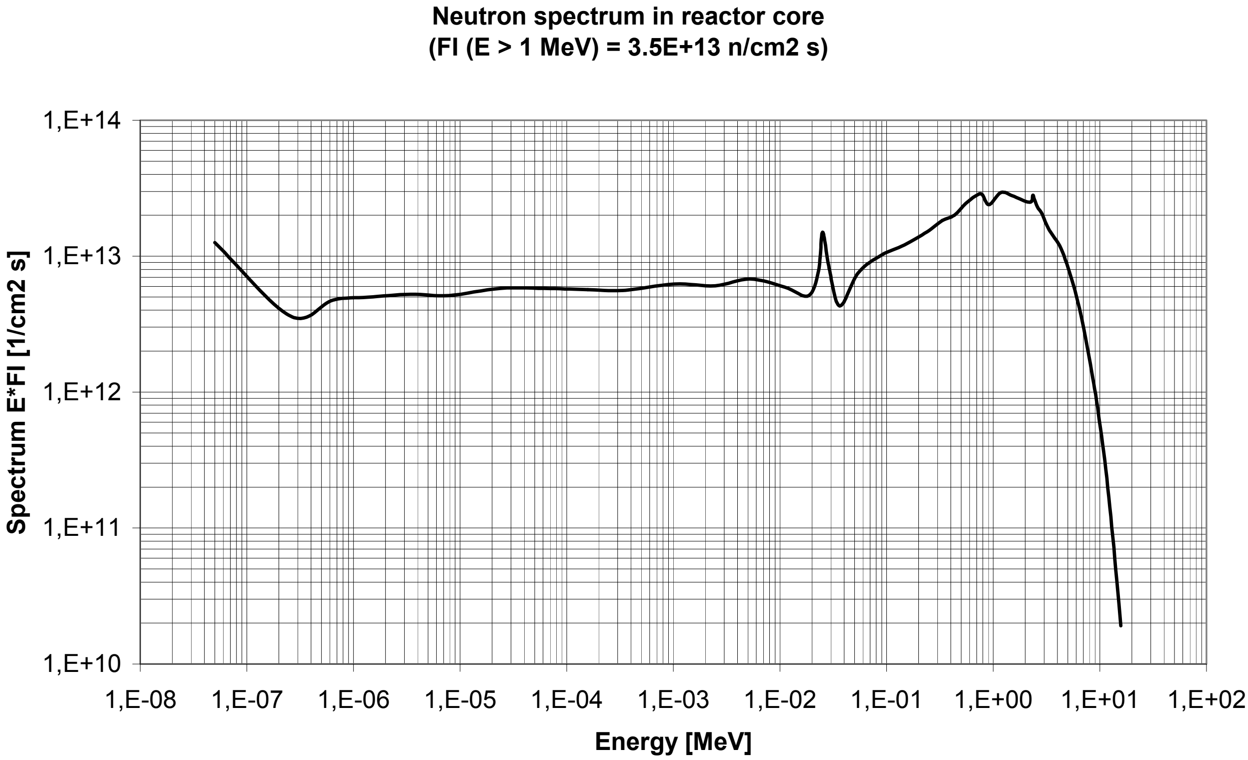


Figure 6: Spectrum of neutron radiation in the core of LVR-15 reactor.

Candidate Hall sensors

The following set of Hall sensors was chosen for the irradiation tests. The most typical semiconductor materials and doping levels for commercial Hall sensors are included.

Type	Manufacturer	Material	Sensitivity [mV/T]	Max. control current [mA]	Max. operation temperature[°C]
MSL-1	MSL, Lviv, Ukraine	InSb	15	40	100
MSL-2	MSL, Lviv, Ukraine	InSb	6	40	100
MSL-3	MSL, Lviv, Ukraine	InSb	10	50	100
MSL-4	MSL, Lviv, Ukraine	InSb	10	75	100
HGT-3010	Lakeshore, USA	InAs bulk, highly doped	10	100	100
HGT-3030	Lakeshore, USA	InAs, bulk low doped	100	100	100
HS-100	F.W. Bell, USA	InAs thin film	240	30	185
GH-800	F.W. Bell, USA	GaAs bulk	1000	5	175

Table 1: Set of candidate Hall sensors chosen for irradiation tests.

Other hardware

Multifunction data acquisition PC Board AD25HAL from AREPOC Ltd., Slovakia has been purchased to control and collect data from the Hall sensors during irradiation. The AD25HAL basic features are as follows:

Programmable input resolution:	20-26 bits
Maximum error:	0.005% of reading
Number of analog inputs:	8 differential
Input range:	0-10V unipolar or ±5V bipolar
Programmable gain:	1-128
Input resistance:	> 100MΩ
Typical noise:	< 0.5 μV

As AD25HAL board provides only single current source to drive the Hall sensors, additional current sources has been manufactured to be able to drive all 8 sensors simultaneously. The PT-100 temperature sensor together with control electronics has been purchased to allow for temperature monitoring inside the irradiation head during measurement. The output voltage of the temperature sensor was stored by a PC oriented DAQ system. Power source of 320W, 0-30V, 0-10A has been purchased to drive the calibration solenoid inside the irradiation head. The PC-controlled switch was used to switch on/off the current to the calibration coil in pre-defined time intervals. Typically, we have used the pattern 5 minutes - ON, 55 minutes – OFF. Two irradiation heads for measurements in the horizontal and vertical channels have been designed and manufactured. Next picture shows the schematic experimental arrangement of the irradiation experiment. The whole system is fully

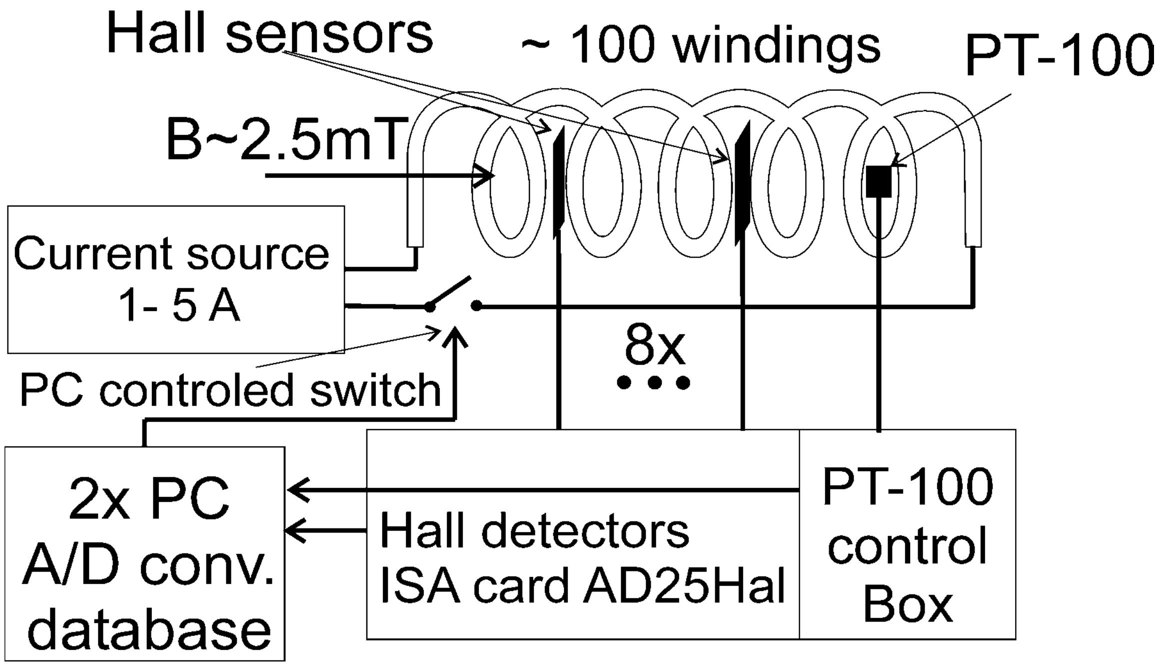


Figure 7: Schematic set-up of the irradiation of the Hall sensors.

automated allowing periodic calibration of the Hall sensors in predefined time intervals during the whole irradiation cycle (~ 20 days).

4. Results - irradiation in the horizontal channel

The arrangement shown in fig.7 was first tested on the table without presence of any radiation by a 3 day run. Then, the irradiation head was placed into horizontal irradiation channel (BNCT). The single Hall sensor GH-800 (expected to be the most vulnerable to neutron radiation) was irradiated for about 27 days in total. The total neutron fluence accumulated by sensor during this time interval, measured by activation monitors is summarized within the table 2.

Computed total fluence (activation monitors + SAND code)			
energy groups		Fluence (cm^{-2})	Fluence rate ($cm^{-2}.s^{-1}$)
(0.0, 0.398 eV)	thermal	1.53E+13	6.56E+06
(0.398 eV, 10 KeV)	epithermal	1.01E+14	4.33E+07
(10 keV, 0.1 MeV)		3.05E+12	1.31E+06
(0.1 MeV, 20 MeV)	Fast	8.14E+12	3.49E+06
Total		**1.27E+14**	**5.47E+07**

Table 2: Total neutron fluence received by GH-800 sensor during the 27 day irradiation in the BNCT horizontal channel.

The reactor was operated with thermal power of 9 MW. The calibration solenoid was driven by the 5 Amperes creating the calibration magnetic field of about 2.5 mT. The output voltage from the GH-800 sensor was collected with sampling rate of 9 seconds/sample. The output voltage of the temperature sensor mounted inside the irradiation head was collected only on a day to day basis during this experimental run. The later, very low temporal resolution, appeared to be not sufficient for correct data interpretation due to strong temperature dependence of the GH-800 output. To account for the temperature dependencies, the temperature in the reactor hall, measured once per hour, was used.

The main aim of this preliminary irradiation run in the horizontal channel was to test the whole set-up during a long-term run in the environment as close to the final irradiation in the reactor core as possible. The importance of temperature monitoring in the irradiation head with comparable temporal resolution to the sensor's output voltage was recognized.

No radiation induced degradation of the sensor sensitivity was observed after irradiation of GH-800 sensor by total neutron fluence of 1.27×10^{14} cm^{-2}. This fluence corresponds to about 8 seconds of ITER burn for a sensor location behind the blanket and to about 3 ITER shots (each 3000 seconds long) for a sensor location outside the vessel.

Moreover, a container with additional ~ 20 various Hall sensors produced by MSL Lviv laboratory was simultaneously irradiated by the same total neutron fluence as the irradiation head. Properties and radiation induced changes of these sensors will be analyzed later on by MSL Lviv team.

5. Results - irradiation in the vertical channel.

A new irradiation head (of the same type as used for horizontal BNCT channel) was designed and manufactured for irradiation and in-situ calibration of up to eight Hall sensors in the vertical dry channel of the LVR-15 reactor. The 9 meters long vertical channel (duralumin tube) was manufactured. The irradiation channel was covered by cadmium thermal neutron shielding to increase fast/thermal neutron fluence ratio. Additional current sources were manufactured to provide supply for all the 8 sensors. Additional data acquisition channels were provided to allow monitoring of temperature in the irradiation head and other relevant quantities as calibration current etc. with a good temporal resolution of a few seconds.

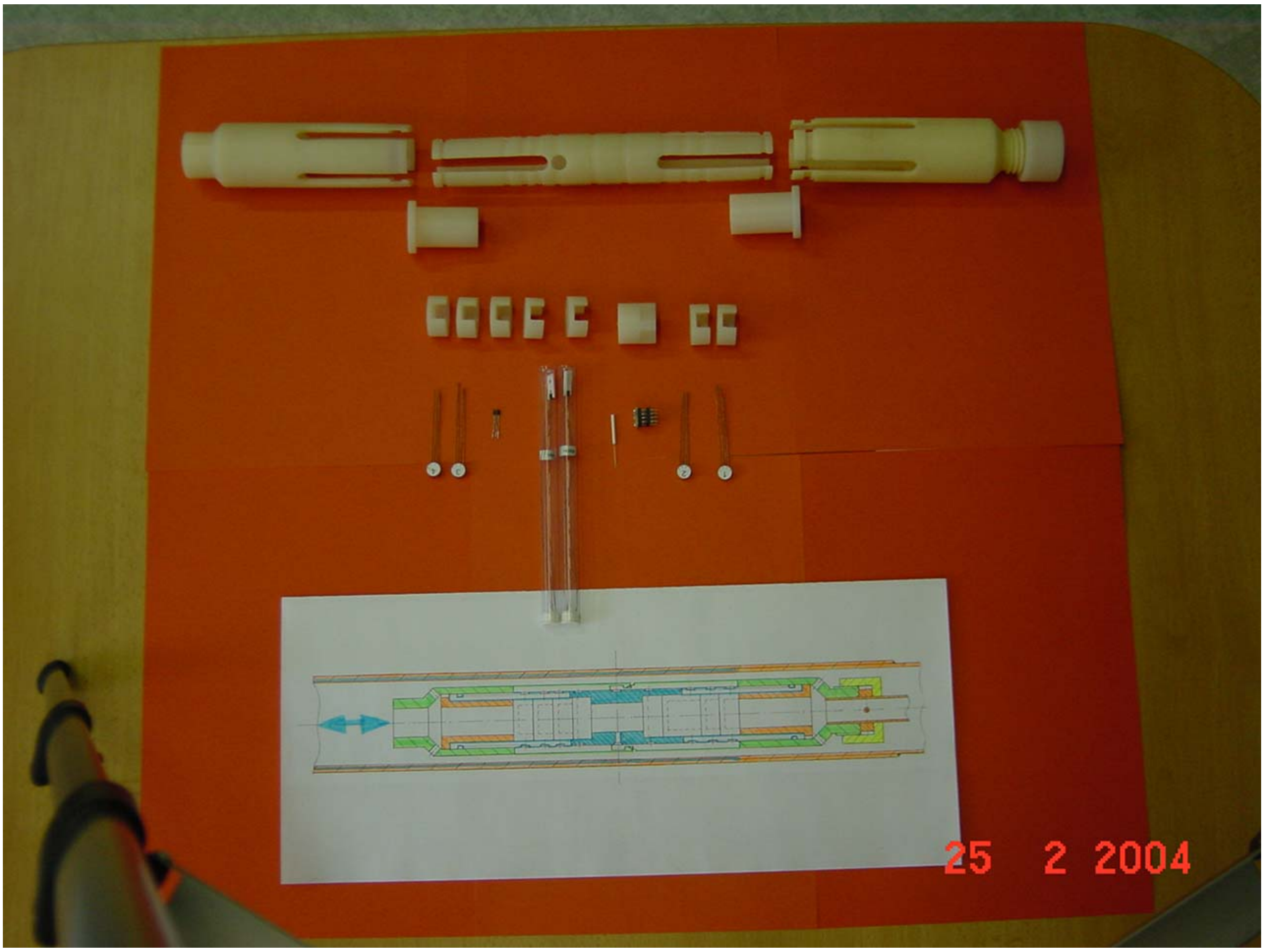


Figure 8: Set-up of the irradiation head before mounting of the Hall sensors and winding of the calibration coil.

The preliminary tests proved, that it is not possible to place the irradiation head directly in the middle of the reactor core to maximize neutron fluence rate. The maximum allowed temperature of the most of the sensors (100 °C) would be exceeded in this case due to radiation heating. The test was done by placing of the equivalent mass of the same material as used for manufacturing of the irradiation head into the reactor core. The melting of this "mock-up" showed that the temperature clearly exceeded 200 °C there.

	Position above the core bottom [cm]	Fluence rate E>1.0 MeV [$cm^{-2}s^{-1}$]	Gamma heating in steel [W/g]	Heating by [K]
Core mid-plane	30	1,70E+13	1,90	**150**
20 cm above core top	80	5,00E+11	0,50	**39**
30 cm above core top	90	1,00E+11	0,19	**15**

Table 3: Dependence of the neutron fluence rate and gamma heating on the position above the reactor core.

As a result, the irradiation head with 8 Hall sensors was installed so that the most inner Hall sensor was located 50.5 cm and the most outer 64.5 cm above the reactor core mid-plane. The length of the whole irradiation head is 20 cm. Irradiation channel is actively cooled by surrounding water to 20 °C

during the reactor start-up phase and to 50 °C during the flat-top operation. The temperature rise in the irradiation head due to radiation heating should be well acceptable for these locations as shown in the table 3.
The irradiation lasted for the total number of 20.8 days. The reactor was operated at 8.4 MW thermal power output. Its operation was interrupted during this campaign from safety reasons for 3.5 days due to malfunction of certain support systems. Although, the total accumulated neutron fluence during this campaign was measured by activation foils mounted within the irradiation head, the evaluation of these measurements requires some time lag after the irradiation head is removed from the reactor. As the results are not available yet, we use the values for neutron fluence rate from previous measurements where the reactor was operated at similar output power. These measurements were done at three certain positions above the reactor core base line. These data were extrapolated to the actual positions of the Hall sensors, assuming exponential fall off of the flux rate from the top of the reactor core.

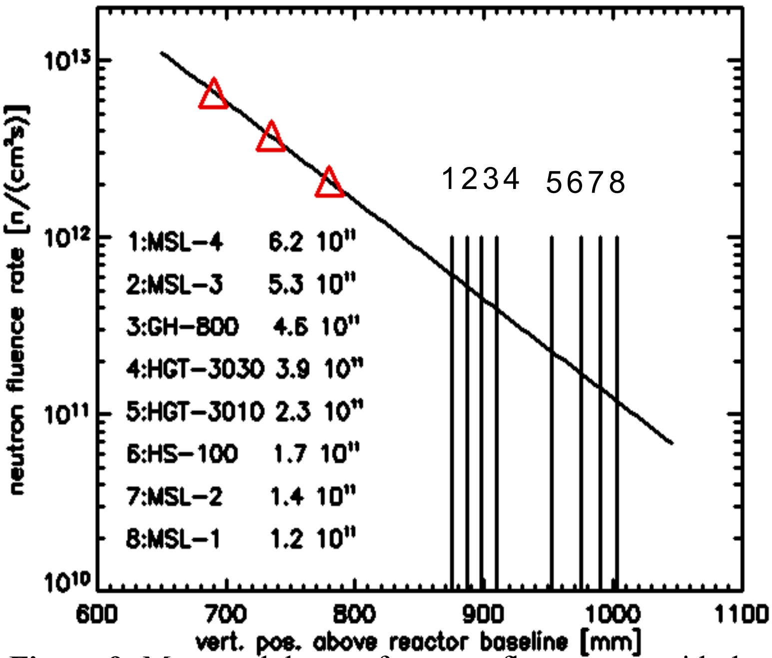


Figure 9: Measured decay of neutron fluence rate with the distance from the reactor core. Measured values are plotted by red triangles. The exponential fit is plotted by solid line. Position of each Hall sensor during irradiation is denoted. The values of fluence rate at respective position of each sensor are stated in n/cm^{2}s.

Type of Hall sensor	Total fluence [n/cm2]
MSL-1	2.5×10^{17}
MSL-2	3.0×10^{17}
MSL-3	1.1×10^{18}
MSL-4	1.3×10^{18}
HGT-3010	4.8×10^{17}
HGT-3030	8.4×10^{17}
HS-100	3.6×10^{17}
GH-800	9.8×10^{17}

Table 4: The total neutron fluence accumulated by each Hall sensor during the whole 20.8 days long irradiation campaign.

The output voltage from all eight Hall sensors was collected during the whole campaign with a time resolution 2.5 seconds/sample and the temperature was sampled by 1-3 seconds/sample (see fig. 11). Data plotted by red color are taken during the time intervals when the calibration magnetic field of 2.5 mT was switched ON, while the blue denotes that there was no magnetic field during measurement. Detailed view of the three measuring cycles is shown in the figure 10. The output of the sensor HGT-3010 was chosen as an example. The calibration magnetic field was switched ON periodically for 5 minutes (red data points) followed by 55 minutes of no magnetic field (blue data points). The difference between red and blue data is the response of the Hall sensor to the applied calibration magnetic field. The heating of the irradiation head caused by current flowing through the calibration solenoid is seen on the temperature trace in the top panel of the figure 10.
The full records of the output voltages of all Hall sensors through the irradiation campaign are shown in the figure 11. The color scheme is the same as in figure 10 – blue – no magnetic field, red – applied

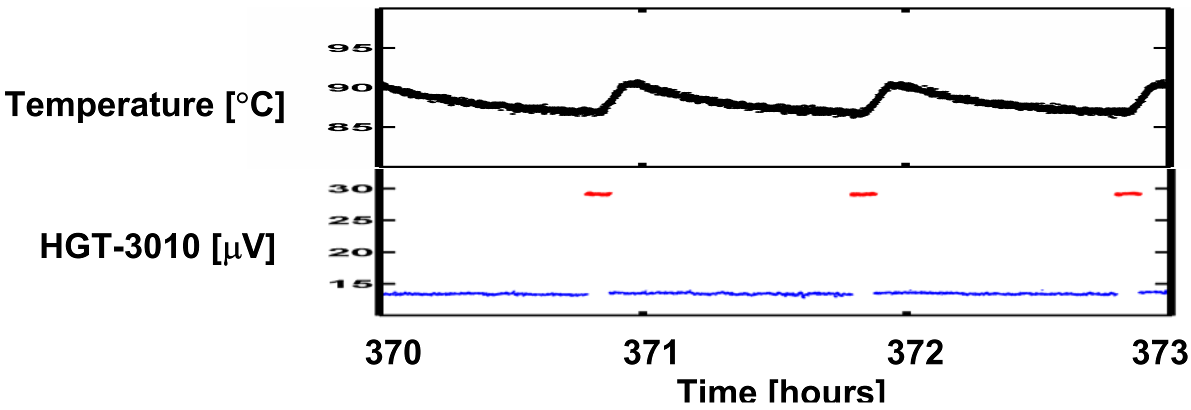


Figure 10: Detailed view of the three measuring cycles during the irradiation campaign. Upper panel - temperature in the irradiation head. Lower panel – output voltage of the HGT-3010 Hall sensor without (blue) and with (red) applied calibration magnetic field of 2.5 mT.

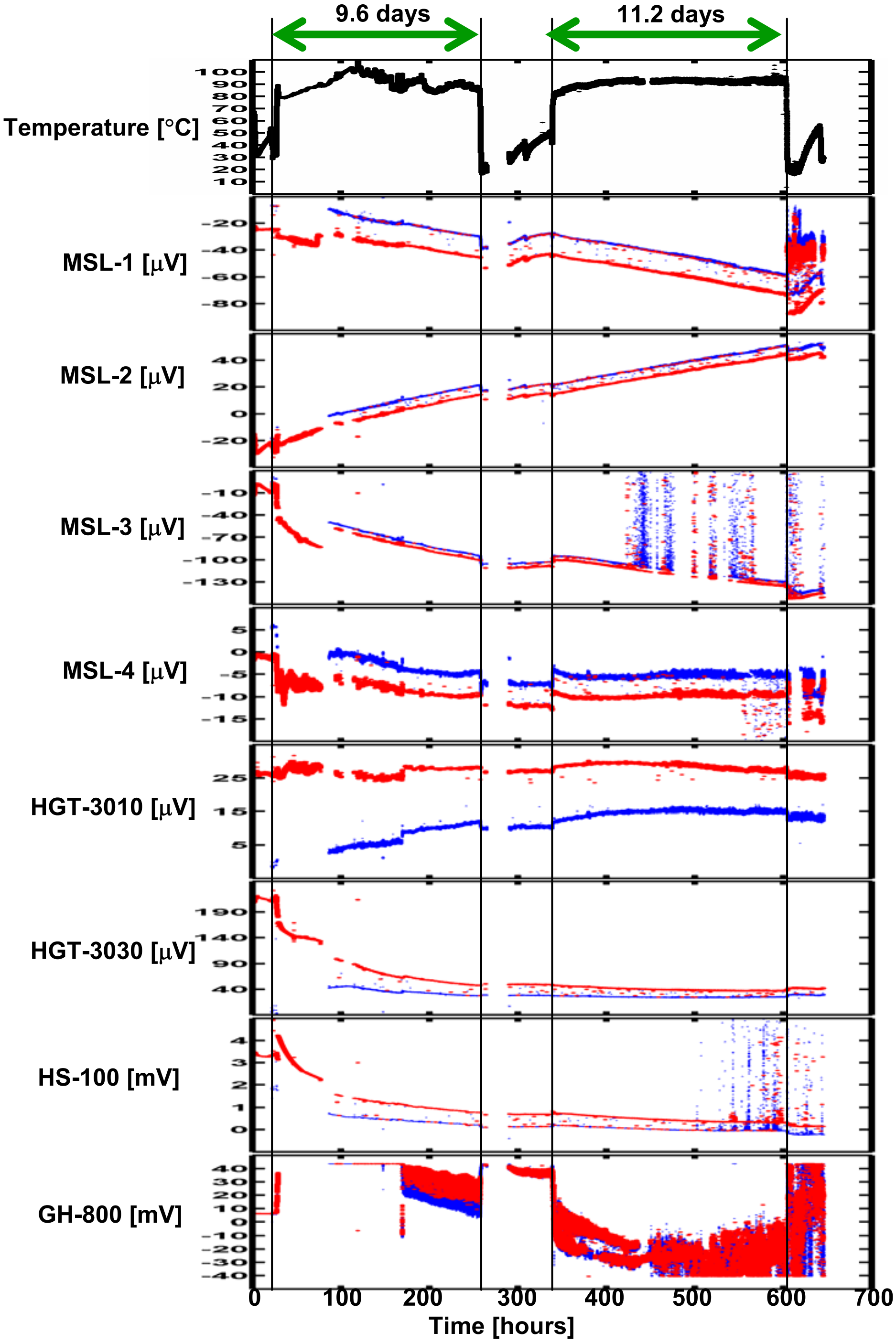


Figure 11: Top panel - temporal evolution of the temperature in the irradiation head during the whole irradiation campaign. Remaining panels – output voltage of all 8 irradiated Hall sensors with applied calibration magnetic field (red data points) and at zero magnetic field (blue data points). The brake in irradiation due to the temporal shut down of the reactor is seen after approximately 9.6 days of irradiation. The bursty behaviour of measured data seen for example on sensor MSL-3 after approx. 450 hours of irradiation is cause by deterioration of output cables insulation and consequent intermittent short circuit events.

calibration magnetic field of 2.5 mT. The periods of reactor operating at full power in this campaign - 8.2 MW are demonstrated in the top panel of the figure 11 by elevated temperature close to 100 °C. The fully automated PC controlled switch for periodic switching of calibration magnetic field was put in operation after approximately two days of irradiation. The calibration magnetic field was ON, during the first days of the experiment except of a short period before the reactor start-up as it is seen in full data records plotted in the figure 11. As the temperature gradually exceeded the upper allowed limit of 100 °C, the PC controlled switch was included in the calibration circuit to limit the heating of the irradiation head by current flowing through the calibration solenoid. Additionally, the air cooling of the irradiation head was introduced after the break in reactor operation. Combination of these two approaches proved to be efficient to stabilize temperature around 90 °C during the second half of the irradiation campaign for a given reactor output power and position of the irradiation head above the reactor core (see upper panel of figure 11). After approximately 450 hours of the campaign, the deterioration of the input and output cables of some Hall sensors manifested itself by intermittent short-circuits and consequent bursts in the measured data as it is seen e.g. in the data

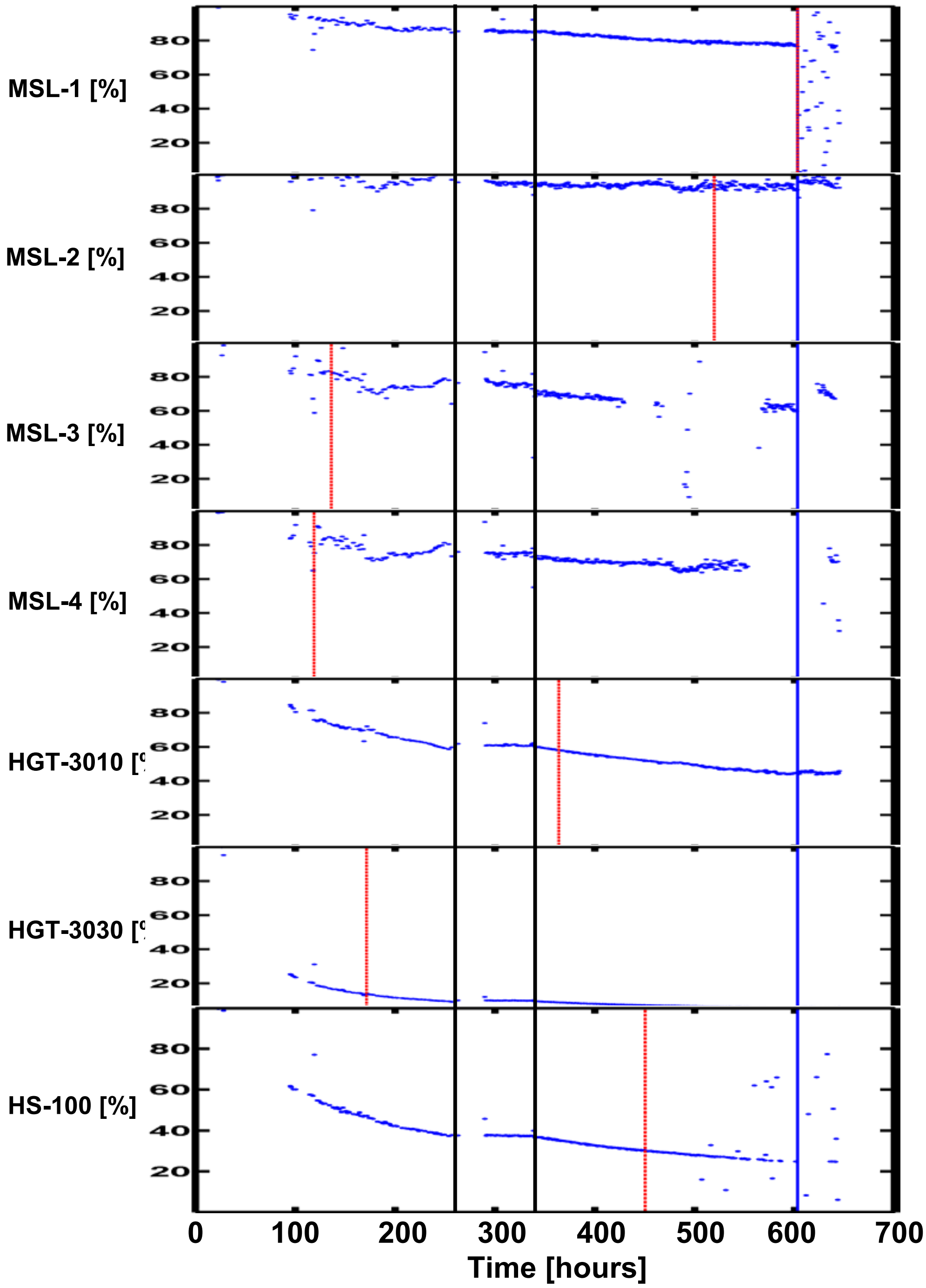


Figure 12: Gradual deterioration of Hall sensors sensitivities during the irradiation campaign. The sensitivity of each sensor is plotted in per-cents of original pre-irradiation value. The red vertical lines denote the time when the reference neutron fluence of 2.5×10^{17} cm^{-2} was reached. Black vertical lines denote the intermediate reactor shut-down during the campaign, and the blue vertical line denotes the end of the irradiation campaign.

record of the sensor MSL-3. The data from the sensor GH-800 are shown only for completeness as it was destroyed soon after the reactor start-up.

The summary of the temporal evolution of the sensitivity of sensor is given in the figure 12. Gradual deterioration of sensitivity with irradiation is observed for all sensors. Because of different position of each sensor above the reactor core, the total neutrons fluence accumulated at the end of campaign is different for each sensor. The reaching of a nominal neutron fluence of 2.5×10^{17} cm^{-2} is marked by red line in the figure 12. Missing or scattered data in the later phase of the campaign correspond to the periods affected by short-circuiting of Hall sensor leads. The following table presents the essence of the experimental results obtained – total accumulated fast neutron fluence, deterioration of the sensitivity after irradiation by 2.5×10^{17} neutrons/cm^2, and remaining sensitivity after the whole campaign for each tested Hall sensor .

Type of Hall sensor	Total fast neutron (E>1 MeV) fluence accumulated [n/cm^{-2}]	Remaining sensitivity after irradiation by fast neutron fluence of 2.5×10^{17} cm^{-2} (in % of original values).	Remaining sensitivity after irradiation by the total fast neutron fluence (in % of original values).
MSL-1	2.5×10^{17}	**77 %**	77 %
MSL-2	3.0×10^{17}	**94 %**	93 %
MSL-3	1.1×10^{18}	**82 %**	62 %
MSL-4	1.3×10^{18}	**85 %**	70 %
HGT-3010	4.8×10^{17}	**58 %**	44 %
HGT-3030	8.4×10^{17}	**13.8 %**	5.6 %
HS-100	3.6×10^{17}	**30.2 %**	25 %
GH-800	9.8×10^{17}	**destroyed**	destroyed

Table 5: Summary of the irradiation experiment: type of the sensor, total accumulated fast neutron fluence, deterioration of the sensitivity after irradiation by 2.5×10^{17} neutrons/cm^2, and remaining sensitivity after the whole campaign.

All sensors except the GH-800 proved to be operational after irradiation by fast neutron fluence of the order of 10^{17} - 10^{18} cm^{-2}. This level of fluence is comparable or higher than the ITER life time fluence at the considered locations of the steady state magnetic sensors. Beneficial effect of higher doping of the Hall sensors semiconductor material for radiation hardness is demonstrated by better stability of the LakeShore sensor HGT-3010 (highly doped) compared to the HGT-3030 (low doping). The best results were achieved by the set of four sensors manufactured by MSL Lviv Laboratory. The sensitivity of the best sensor from this set, MSL-2, remained stable (within 10%) during the whole irradiation campaign. Such deterioration of the sensor's sensitivity can be well handled by in-situ recalibration techniques if properly applied. Testing of such approaches combined with further optimization of the sensors composition, especially, to make them compatible with the ITER thermal environment is underway.

6. Summary of the results obtained

- Set of candidate Hall probes was identified. None of the sensors presently available is fully compatible with the ITER thermal environment – survival temperature to be at least 200 °C.
- A fully automated PC based system for periodic in-situ calibration of the Hall sensors during irradiation in the LVR-15 fission reactor channels was developed.
- The system was tested with a single Hall sensor GH-800 which was irradiated in the BNCT channel for 30 days in total. The total neutron fluence of 1.28×10^{14} cm^{-2} was accumulated. No radiation induced deterioration of the sensor's sensitivity was observed.

- New irradiation head and additional hardware was used for simultaneous irradiation of eight Hall sensors in the vertical channel of LVR-15, allowing monitoring of sensors sensitivity during irradiation. Eight sensors were irradiated by a fast neutron (E>1 MeV) fluence of 2.5×10^{17} cm^{-2} during a single 20.8 days long campaign. The total neutron fluence achieved for each sensor vary due to the different position of each sensor above the reactor core ranging from 2.5×10^{17} cm^{-2} to 1.3×10^{18} cm^{-2}.
- All sensors except GH-800 remained operational after irradiation by the total neutron fluence exceeding that expected to occur over the whole ITER lifetime at location outside the vessel. Some sensors survived irradiation by the total fast neutron (E>1MeV) fluence comparable to the ITER life time fast neutron fluence expected inside the vessel and stayed operational with their sensitivity decayed only by a few tens of percents. These findings encourage further optimization of the sensor's composition and investigation of possible in-situ recalibration techniques.

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