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Prospects for the steady-state magnetic diagnostic based on antimony Hall sensors for future fusion power reactors

S. Entler[1], I. Duran[1], M. Kocan[2], G. Vayakis[2], M. Kohout[3], J. Sebek[3], P. Sladek[1], O. Grover[1], K. Vyborny[4]

[1]Institute of Plasma Physics of the CAS, Za Slovankou 1782/3, 182 00 Prague, Czech Republic
[2]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France
[3]Institute of Physics of the CAS, Na Slovance 1999/2, 182 00 Prague, Czech Republic
[4]Institute of Physics of the CAS, Cukrovarnicka 10/112, 162 00 Prague 6, Czech Republic

In the case of fusion devices with long pulses or continuous operation, conventional magnetic sensors, such as inductive sensors, have to be supplemented by steady-state magnetic field sensors. Therefore, the Hall sensors are considered as a part of the DEMO magnetic diagnostics. The paper reviews the present status of the DEMO steady-state magnetic field sensors based on the ceramics-metal Hall sensors with a sensing layer made of antimony. The mission of the Hall sensors and their operating requirements are summarized, and the design of the Hall sensor assembly is presented. Satisfactory results of initial tests of the sensors are presented.

Keywords: Magnetic diagnostics, steady-state, antimony, Hall sensor, sensor unit, controller, DEMO.

1. Introduction

Magnetic diagnostics are essential in today's tokamaks for determining the plasma position, stability, energy content and additional parameters critical for the safe operation of these devices. Conventional sensors, such as inductive pick-up coils, must be supplemented by steady-state magnetic sensors in devices with long pulse capabilities, as is the case of the ITER reactor [1]. It is known that the inductive sensors require integration, which leads to a reduction in measurement accuracy due to radiation-induced effects in the case of long steady-state pulses or continuous operation [2]. Therefore, the steady-state magnetic sensors will be an important part of the diagnostics of future fusion power reactors starting with the DEMO device.

The main difference in DEMO requirements with respect to ITER will be the higher ambient temperature at the sensor location (up to 350 °C, compared to up to 100 °C in ITER during normal operation and 220 °C during baking) and up to 1 - 4 orders of magnitude higher lifetime neutron fluence exposure depending on the sensor location [3][4]. The use of the ITER Hall sensors is not straightforward in DEMO, because their sensitive layer is made of bismuth with a melting temperature of 271.4 °C. Consequently, alternative sensing material solutions have to be sought.

The development of high-temperature Hall sensors based on a sensing layer made of gold has been described recently, for example in [4-6]. The gold sensors offer weak temperature dependence, however, their output voltage is very low due to the low Hall coefficient. Therefore, efforts had focused on other materials that have a higher Hall coefficient enabling higher sensor output voltage in comparison with gold.

As a suitable material, metalloid antimony was selected. Antimony has a Hall coefficient two orders of magnitude higher than gold and a sufficiently high melting temperature (Tab. 1). With the melting temperature of 631 °C, antimony satisfies the DEMO temperature-resilience requirement.

The aim of this paper is to describe the prospects for the steady-state magnetic diagnostic for the DEMO reactor based on the ceramics-antimony Hall sensors.

entler@ipp.cas.cz

Tab. 1 Hall coefficient at room temperature and melting temperature of selected metals [7].

	Hall coefficient [(-) mm^3/C]	Melting temperature [°C]
Bi	500	271
Sb	2	631
Cu	0.07	1 085
Au	0.05	1 064

2. Mission and operating conditions of the DEMO Hall sensors

The main mission of the presented Hall sensors is to measure the near-DC magnetic field along the poloidal contour of the vacuum vessel's inner and outer shells. Tangential and normal Hall sensors are designed to measure the local poloidal and radial components of the magnetic field, respectively [2].

The signals from the tangential sensors can be summed to produce plasma current measurements. The measurements of both the tangential and normal sensors can be used to reconstruct the plasma shape and position. Additionally, the tangential and normal sensors can be used to measure slow instabilities and local perturbations of the magnetic flux surfaces, including error fields and low harmonic modes, and locked modes, but not within their full frequency range [2]. For example, the final ITER bismuth Hall sensors diagnostics has an effective low-pass cut-off (-3 dB) at around 40 Hz due to complex signal processing.

The main sensor operating conditions and requirements in DEMO can be summarized as follows [3][4][8]:

- Static and dynamic magnetic fields.
- Operating temperatures of about 200 ºC (i.e. vacuum vessel operating temperature) in the case of the outer-vessel application and up to 350 ºC in the case of the inner-vessel application.
- High levels of the lifetime neutron fluence up to
- 2×10^{22} n/cm^2 in the case of the inner-vessel application.
- EM and mechanical loads, mechanical shocks during disruptions.

- Nuclear heating.
- Outgassing (exhaust to vacuum vessel or cryostat vacuum).
- High noise environment and spurious DC voltages.
- Far amplifying electronics (100-200 m).
- Measurement accuracy of about 0.1 % of the full measurement scale.
- No in-situ maintenance for the reactor lifetime.

3. Hall sensor design

The first series of the antimony Hall sensors suitable for DEMO used existing technologies developed for the ITER steady-state sensors. A sensor substrate was made of aluminum nitride ceramics with dimensions 6.4 mm x 6.4 mm in accordance with the ITER sensors. Aluminum nitride AlN, aluminum oxide Al_2O_3, or silicon nitride Si_3N_4 are considered for the DEMO application, and the final choice will be based on results of sensor radiation stability tests. The ceramic substrate with a thickness of several hundred µm is coated on both sides with a copper layer with a thickness of about 100 µm, and copper contact pads are etched on one side of the substrate [9].

The antimony sensitive layer with a thickness of several µm was deposited on the substrate by magnetron sputtering. The antimony layer was passivated and mechanically protected by a ceramic paste. Fig. 1 shows the manufactured sensor before passivation.

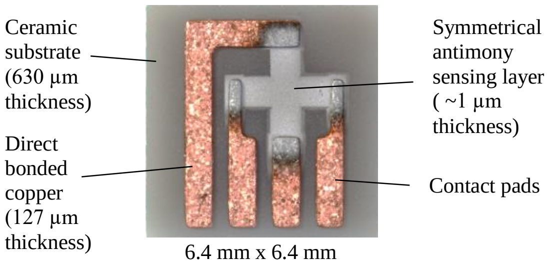

Fig. 1. Tested antimony Hall sensor (MA2 production batch).

An initial measurement of antimony sensor properties is presented in Figs. 2 and 3. The high magnetic field was measured in the Joint Laboratory for Magnetic Studies of the Institute of Physics of the Czech Academy of Sciences and the Charles University in Prague on the Physical Property Measurement System PPMS14 from the Quantum Design Company [10] allowing measurements at high magnetic fields in the range from -14 T to +14 T with a maximum field error of 12 mT [11]. The test was conducted at a constant temperature of 27 °C. The sensor sensitivity was measured in the Hall sensor laboratory of the Institute of Plasma Physics of the CAS (IPP) in a high-temperature vacuum oven at a constant magnetic field of 270 mT. The tested Hall sensors were manufactured by IPP within the production batches MA1 and MA2.
The behaviour of the antimony sensor is different from that of the ITER bismuth sensors tested previously [12][13]. The antimony sensing layer features a linear dependence on the magnetic field (Fig. 2) and a slightly nonlinear decreasing dependence of the sensor sensitivity on temperature (Fig. 3). In the range of the DEMO operating temperatures, the dependence on temperature can be approximated by a linear function. The tests also surprisingly showed a higher sensitivity of the antimony layer than expected. This result will be further explored.

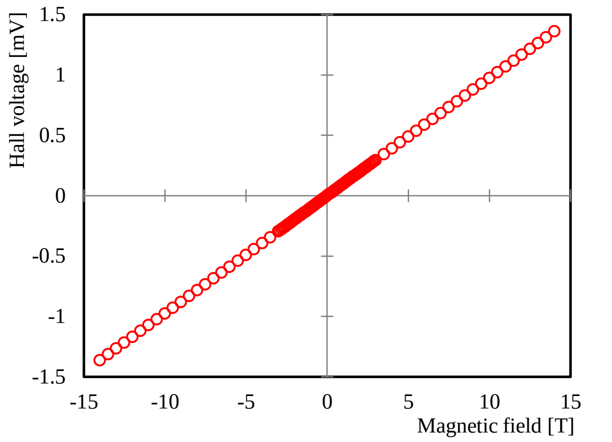

Fig. 2. Linear dependence of the antimony Hall sensor output voltage on the magnetic field (sensing layer thickness of ~1 µm, supply current of 4 mA).

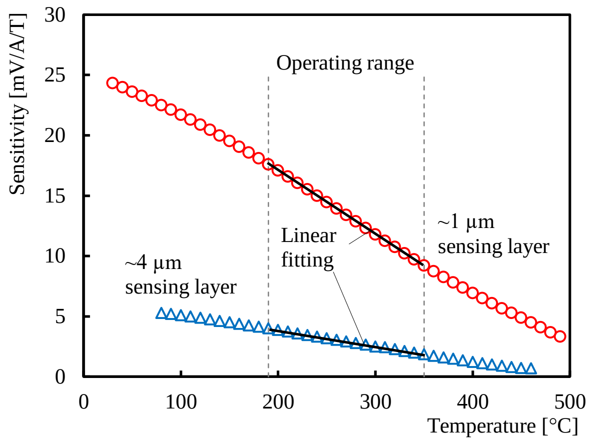

Fig. 3. Dependence of the antimony Hall sensor sensitivity on temperature in the case of ~1 µm and ~4 µm sensing layer thickness, respectively.

4. Sensor unit

The Hall sensor units protect Hall sensors from mechanical damage and provide means for attaching to the vacuum vessel. The design of the unit based on the ITER solution [8] is shown in Fig. 4. The unit may contain one or two Hall sensors to measure the tangential or/and normal component of the magnetic field.

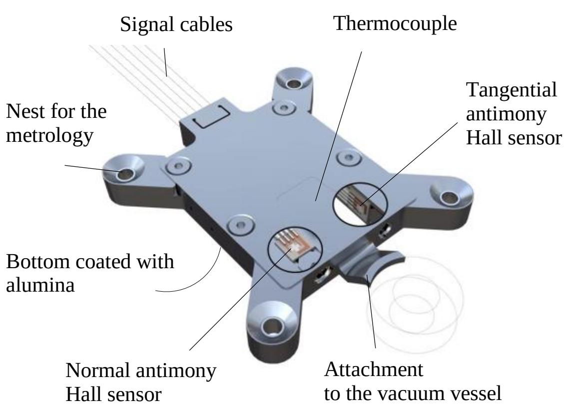

Fig. 4. ITER-like Hall sensors unit.

The unit is made of a stainless steel AISI 316 LN. The external dimensions of the unit are about 80 mm × 90 mm × 10 mm and the weight is ~0.1 kg. The small dimensions minimize thermal and EM loads and facilitate the positioning of the unit on the vacuum vessel surface. The single-point attachment of the unit to the vacuum vessel eliminates the stress due to the different thermal expansion of the unit and the vacuum vessel as well as the loop force [8].

Since the sensitivity of the antimony Hall sensors is temperature dependent, temperature measurement is integrated into the unit. The temperature of the sensors is monitored by an onboard Type N thermocouple located between both the sensors [8].

5. Signal processing

The sensor electronics play a key role in achieving high measurement accuracy in the noisy environment of fusion power reactors. The choice of the signal processing method is determined by the following factors:

- Measurements at the level of tens of nanovolts.
- Long (~100-200 m) distance between sensors and front-end electronics without preamplification.
- RF noise and spurious DC voltages interference.
- Temperature-dependent offset voltage.
- Interfering planar Hall voltage.

Advanced techniques, such as synchronous detection, current spinning technique, extensive offset reduction techniques, and use of cutting-edge IC elements for maximum stability and reliability, were applied to achieve satisfactory performance of the ITER Hall sensor diagnostics set (Fig. 5) [14]. For the DEMO application, the ITER electronics is being adapted to higher signal gain while maintaining measurement accuracy.

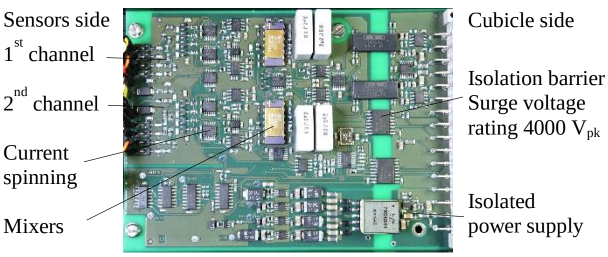

Fig. 5. ITER two channels fully-isolated high-amplification controller card integrating the synchronous detection and current spinning.

6. Cabling

The proper interconnection between the Hall sensor units and front-end electronics (controllers) plays an important role in making measurements possible and accurate. A critical parameter is the estimated interconnection distance ranging from 100 to 200 m (ITER 130-170 m). Location of signal amplifiers closer to the reactor is not possible due to the radiation and the heat load.

Symmetrical shielded twisted pairs should be used for signal transmission. The earthing points of the cable shielding are the sensor units inherently grounded on the vacuum vessel through the attachment. To avoid signal interference, the cable shielding should pass through the vacuum vessel and the cryostat feedthroughs to the controller. The controller cards are galvanically isolated with floating ground coinciding with the ground of the sensor units, i.e. the ground of the vacuum vessel (Fig. 6).

Thermocouple interconnections should use shielded thermocouple cables with shielding interrupted near the vacuum feedthroughs. The shielding inside the vacuum vessel and the cryostat should be grounded to the sensor unit and vacuum vessel respectively, and the shielding outside the cryostat should be grounded to the diagnostic room earthing (i.e. the ground of the sensor units is different from the ground of thermocouple reference units realizing a cold junction).

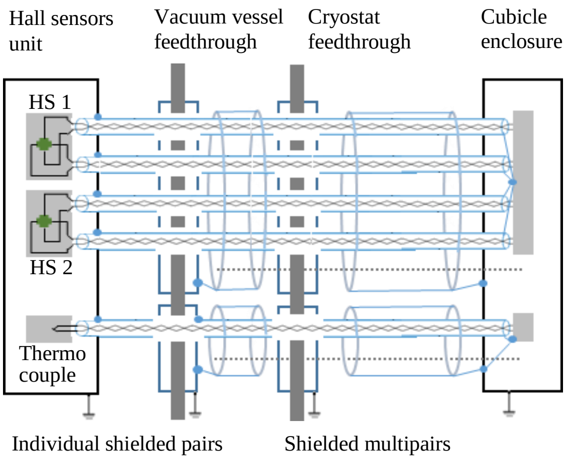

Fig. 6. The interconnection between the sensors unit and diagnostics room cubicle.

7. Sensor arrangement

In ITER, the primary measurements are provided by magnetic coils and the steady-state sensors provide only supplementary contributions for the magnetic measurements [2]. In the case of DEMO and subsequent fusion power reactors, the steady-state sensors may play also the primary role due to the need to accurately measure the magnetic field during several-hour pulses (DEMO1 2 hours) or continuous operation. Therefore, the initial arrangement of the DEMO Hall sensors was taken from the concept for the tangential and normal pickup coils based on simulations of magnetic control of the plasma shape [15]. The number of the Hall sensors is foreseen to be the same as the number of the pick-up coils [4].

The initial arrangement is summarized in Tab. 2. For comparison, the number of the Hall sensors in ITER is also shown. Each measurement sector will be instrumented with 30 inner-vessel and 68 outer-vessel Hall sensor units containing both the tangential and normal Hall sensors. The four instrumented vacuum vessel sectors are separated toroidally by 90 ° and form a quadruplex. The quadruplex will be rotated 45 ° relative to a quadruplex instrumented with the tangential and normal pick-up coils as shown in Fig. 7.

The presented arrangement is only a rough estimate, and the number of sensor units and their precise allocation will be subject of modelling and refinement being driven by the aim of achieving a minimum measurement error, coordination with the inductive sensors arrays and management of cable load.

Tab. 2 Initial arrangement of the DEMO Hall sensors diagnostics.

Tangential and normal sensors		ITER Hall sensors	DEMO Hall sensors
Inner vessel locations	Number of the poloidal locations	-	30
	Number of the tangential/normal sensors per vacuum vessel sector	-	30/30
	Number of the instrumented equispaced vacuum vessel sectors	-	4
	Total number of the tangential and normal sensors	-	240
Outer vessel locations	Number of the poloidal locations	60	68
	Number of the tangential/normal sensors per vacuum vessel sector	20/20	68/68
	Number of the instrumented equispaced vacuum vessel sectors	-	4
	Number of the instrumented vessel sectors with a poloidal offset	3	-
	Total number of the tangential and normal sensors	120	544

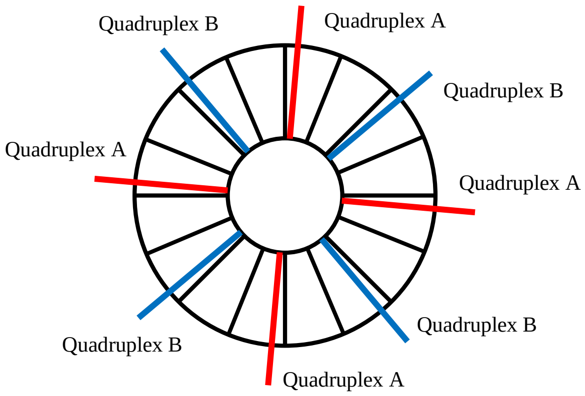

Fig. 7. Two quadruplexes of the vacuum vessel sectors instrumented with the tangential and normal magnetic sensors. The quadruplex A contains the pick-up coils, the quadruplex B contains the Hall sensors.

8. Testing plan

The long-term radiation tests of the sensors will be performed as soon as the sensor technology is optimized. Irradiation tests with a gradual increase of the neutron fluence will be carried out in the LVR-15 reactor of the Research Centre Rez or in another suitable experimental nuclear reactor.

Initial considerations were performed regarding the possibility to prepare the test of a few samples of the described Hall sensors within the ITER port plug structure where the neutron flux rate comparable to ITER in-vessel locations is expected. This experiment would offer a long-term test in a fusion reactor with the expected highest available fusion 14 MeV neutron load.

The high-temperature Hall sensors assembly will be also a part of the COMPASS-U tokamak diagnostics. The COMPASS-U tokamak will be built at the Institute of Plasma Physics in Prague and will work with a high magnetic field of up to 5 T and a first wall temperature of up to 500 °C [16].

9. Conclusion

The prospect of the DEMO magnetic diagnostic subsystem based on the ceramic-metal Hall sensors with the antimony sensitive layer for steady-state magnetic field measurements has been presented. The antimony Hall sensors feature linear dependencies on the magnetic field and temperature and significantly higher sensitivity compared to copper or gold sensors within the DEMO sensors operating range.

The presented design of the diagnostic set, including the antimony sensors, sensor units, and sensor controllers, utilizes the experience and technology gained in the development of the magnetic diagnostics for the ITER reactor and involves the application of the inner-vessel Hall sensors as well as outer-vessel Hall sensors. The initial tests of the thermal resistance of the sensors have been successful and as the next step, the radiation stability tests will be performed.

Acknowledgments

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