Magnetic measurements using array of integrated Hall sensors on the CASTOR tokamak[a)]

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We have performed the first tests of "integrated" Hall sensors (IHSs) in a tokamak in-vessel environment. IHS combines the sensing element together with the complex electronic circuitry on a single small chip. The on-chip integrated circuits provide stabilization of the supply voltage, output amplification, noise suppression, and elimination of temperature dependencies. Eight IHSs of A1322LUA type produced by Allegro MicroSystems, Inc. were mounted on a stainless steel ring symmetrically encircling the CASTOR plasmas in poloidal direction 10 mm outside the limiter radius. IHSs were oriented such that they measure the horizontal and vertical magnetic fields. We found out that these sensors qualify for in-vessel use of small to middle sized fusion devices where the radiation is not an issue and the temperature below 150 °C can be guaranteed. The main advantages over the traditional pickup coils are the smaller size and more straightforward interpretation of output without the need of rather cumbersome integration and drift removal procedure associated with the use of inductive loops. We successfully exploited the sensors for determination of vertical plasma displacement on CASTOR. This new diagnostic helped us to shed more light into long term observed discrepancy on CASTOR between vertical plasma displacement as deduced by standard magnetic and by nonmagnetic diagnostics (Langmuir probes, bolometers). © *2008 American Institute of Physics.* [DOI: 10.1063/1.2971209]

I. INTRODUCTION

As the discharges became longer in large tokamaks, the evaluation of B from its measured time derivative has become increasingly difficult because the integration needs a precise determination of possible offsets in the preamplifiers. Advancements in semiconductor technology hand in hand with a broad spectrum of industrial applications have driven development of new types of Hall sensors for magnetic measurements in recent years. A particular advancement is the availability of "integrated" Hall transducers, where the sensing element together with the complex electronic circuitry is integrated on a single small chip with characteristic dimension of a few millimeters. The on-chip integrated circuits provide stabilization of the supply voltage, output voltage amplification, signal conditioning in order to suppress the high frequency noise, and elimination of temperature dependence of the sensor's output. Because of the widespread industrial use of such sensors, their cost is rather low (of the order of 1 Euro/piece).

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II. RESULTS

We have performed the first tests of this type of Hall sensors in a tokamak in-vessel environment on CASTOR tokamak (R/a=0.4/0.085 m, I_p=10 kA, B_T=1 T, n_e =10^{19} m^{-3}). The eight Hall sensors of A1322LUA type produced by Allegro MicroSystems, Inc. were mounted on a stainless steel ring symmetrically encircling the CASTOR plasma in poloidal direction 10 mm outside the limiter radius (see Fig. 1). The Hall sensors were oriented such that they measure the horizontal and vertical magnetic fields at four locations (top, bottom, high field side, and low field side). The special adjustable holders were used in order to ensure proper alignment and consequently to minimize the crosstalk from the toroidal magnetic field B_T. A traditional magnetic pickup coil was fixed nearby each Hall sensor for reference and also for envisaged magnetohydrodynamics studies. The Hall sensors have a nominal sensitivity of 31.25 mV/mT and dynamic range of ±80 mT. The peak-to-peak noise level is below 1 mT. The output bandwidth specified by the manufacturer is 30 kHz and it is limited by the built-in internal feedback capacitor.[1] According to the results of our calibration, we have performed in the frequency band of 0–20 kHz, the sensors feature reasonably flat frequency response in the range from dc to 10 kHz as shown in the left panel of Fig. 2. The operating temperature range is from –40

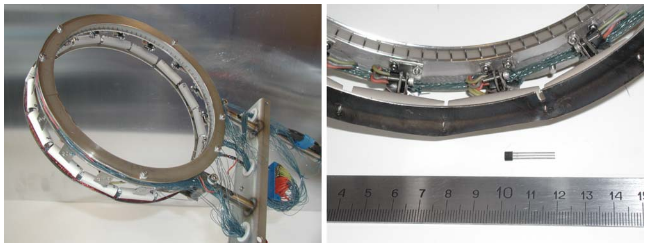

FIG. 1. (Color online) The ring of up to 16 Hall sensors, 16 coils, and 96 Langmuir probes before its installation on CASTOR tokamak (left panel). Detailed view of the Hall sensors attachment systems with a single Hall sensor shown before its installation onto the ring (right panel).

to 150 °C. A supply voltage of 5 V is needed to drive each Hall sensor. In the quiescent state (no magnetic field), the output voltage is ideally equal to one-half of the supply voltage. An increasing south-pole magnetic field will increase the voltage from its quiescent value. Conversely, an increasing north-pole field will decrease the voltage from its quiescent value. Figure 2 right panel demonstrates the typical evolution of the sensor output voltage during CASTOR discharge (red trace) and during vacuum field discharge where only toroidal field coils were energized (blue trace). It is apparent that mechanical holders of the Hall sensors do not allow perfect alignment of the sensors parallel to the B_T. However, thanks to the good stability of the misalignment of the sensors within each experimental day, it is possible to measure contribution from B_T before actual plasma experiments, and subtract it from measured data numerically.

We exploited the above described system of eight Hall sensors to get further insight into vertical plasma position measurement on CASTOR. In previous years there was observed a systematic disagreement between CASTOR vertical plasma position measurements using the standard approach of a pair of magnetic coils placed at the top and at the bottom, inside the vacuum vessel, and other available diagnostics (rakes of Langmuir probes, bolometers).[2] The differential signal of the coils pair is used to drive the CASTOR vertical plasma position feedback system.[3] The vertical plasma position deduced by this method is rather centered for most of the CASTOR operating regimes. On the contrary, measurement of separatrix position performed by a radial rake of Langmuir probes suggests significant downward shift of the plasma column. In these experiments the radial rake of Langmuir probes is introduced into the CASTOR edge plasmas from the top and the separatrix position is identified with the measured location of maximum in floating potential profile.

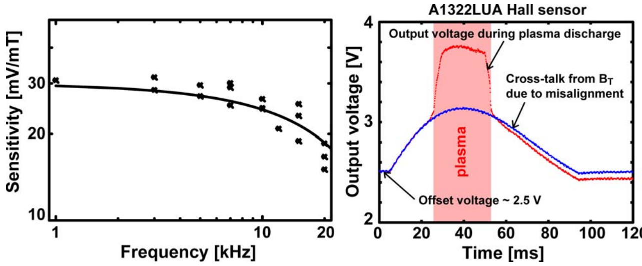

FIG. 2. (Color online) Left panel: calibration curve of the Allegro A1322LUA sensors in the frequency band of 0–20 kHz. Right panel: demonstration of typical output voltage of the sensor taken during CASTOR discharge (red) and voltage proportional to B_T measured by the sensor due to its imperfect orientation parallel to B_T (blue).

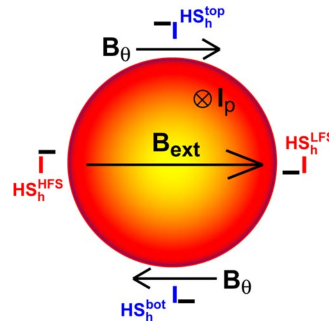

FIG. 3. (Color online) Schematic layout (not in scale) of the location and arrangement of Hall sensors HS_h^{top}, HS_h^{bot}, HS_h^{HFS}, and HS_h^{LFS} (denoted by solid bars) which were used to determine vertical plasma position. Each Hall sensor measures magnetic field perpendicular to its plain. Directions of plasma induced poloidal magnetic field B_θ at the top and bottom of the CASTOR and of an additional magnetic field induced by other tokamak circuits B_{ext} are given.

We explain the observed discrepancy by the fact that the differential signal of the coil pair is affected by additional horizontal magnetic field B_{ext} generated by other sources apart of the plasma current (see Fig. 3). Sources of such additional magnetic field are currents through the vertical plasma position control coils, stray fields from the tokamak primary winding or additional currents induced in the stainless steel tokamak chamber. Figure 3 shows schematically the distribution of Hall sensors mounted on the ring and directions of the measured magnetic fields. The vertical displacement of the plasma current channel from the centered position in a tokamak with circular cross section is proportional to the differential signal of horizontal magnetic fields (induced by plasma current) measured at the top and at the bottom of the torus B_θ^{top}, B_θ^{bottom} as[2]

$$\Delta_v = \frac{\pi b^2}{\mu_0 I_p}(B_\theta^{top} - B_\theta^{bottom}), \tag{1}$$

where b denotes the radial distance of the magnetic sensors from the geometric center of the tokamak chamber and I_p stands for the plasma current. The "standard approach" used also on CASTOR identifies B_θ^{top} with the output of the top Hall sensor HS_h^{top} (or integrated output of the top coil, not shown in Fig. 3) and B_θ^{bottom} with the output of the bottom Hall sensor HS_h^{bottom} (or integrated output of the bottom coil). However, in the case of the presence of any additional external horizontal magnetic field, the situation is different. In this case, the signal of the top magnetic sensor is proportional to the sum of B_θ^{top} and B_{ext} while the signal of bottom magnetic sensor is proportional to the difference of B_θ^{bottom}-B_{ext}. As a result, the differential signal of the top and the bottom magnetic sensors is

$$U_{dif}^{top\text{-}bottom} \approx (B_\theta^{top} - B_\theta^{bottom} + 2B_{ext}). \tag{2}$$

Clearly, this signal is offset compared to the real vertical plasma displacement by quantity proportional to the actual magnitude of B_{ext}. The response of the internal magnetic sensors to currents in the tokamak windings was measured by performing a series of vacuum field shots where individual tokamak windings were energized without producing plasma. It was found that horizontal magnetic fields from the tokamak primary windings as high as 4 mT and those from vertical plasma position feedback system as high as 7 mT in opposite direction are recorded by the sensors inside the tokamak chamber. This demonstrates that the vertical plasma position feedback system provides enough capacity to compensate the stray fields from the primary windings; however, more magnetic measurements are needed as an input to the feedback system to correctly evaluate and consequently control the plasma vertical position.

We took advantage of the Hall sensors distribution in CASTOR, where the B_{ext} is directly measured by Hall sensors measuring horizontal magnetic field on the high field side and low field side of the tokamak chamber HS_h^{HFS} and HS_h^{LFS}, respectively (see Fig. 3). Thanks to the rather good spatial homogeneity of B_{ext} across the poloidal cross section, which we verified experimentally, we can subtract the B_{ext} from the output of the top and bottom Hall sensors HS_h^{top}, HS_h^{bottom}. It is clearly seen in Fig. 4 (left panel) that a rather good agreement was achieved in determination of plasma vertical displacement between magnetic diagnostic (Hall sensors) and rake of Langmuir probes after elimination of signal proportional to B_{ext}. Figure 4 (right panel) presents example on how the dependence of the vertical plasma displacement on setting of the Z switch changes after application of above described correction. The Z switch (positions 0–12) is a knob on the CASTOR vertical plasma position control system used to predefine the desired vertical plasma position before each CASTOR shot.

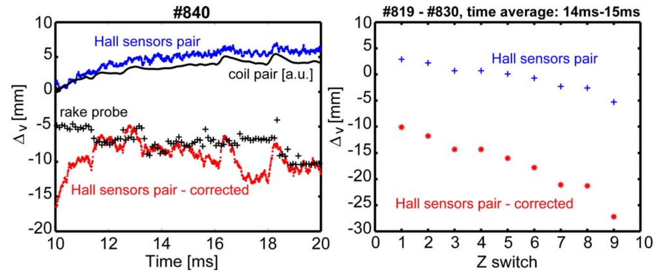

FIG. 4. (Color online) Left panel: comparison of vertical plasma displacement evolutions deduced from a coil pair (black line), Hall sensors pair (blue), Hall sensors pair corrected for presence of B_{ext} (red), and rake of Langmuir probes (black +). Right panel: vertical plasma displacement as a function of hardware CASTOR feedback system switch Z obtained as the simple differential signal of a pair of Hall sensors (blue) vs the same differential signal but corrected for presence of B_{ext}.

ACKNOWLEDGMENTS

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