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Measurement of magnetic field using array of integrated Hall sensors on the CASTOR tokamak

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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). We have performed the first tests of this type of Hall sensors in a tokamak in-vessel environment on CASTOR tokamak (R/a=0.4m/0.085m, I_p=10kA, B_T=1T, $n_e=10^{19}m^{-3}$). The 8 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. 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 cross-talk from the toroidal magnetic field. A traditional magnetic pick-up coil was fixed nearby each Hall sensor for reference and also for envisaged MHD studies. The sensors have a nominal sensitivity of 31.25 mV/mT and dynamic range ±80 mT. The peak-to-peak noise level is below 1mT. The bandwidth specified by the manufacturer is 30 kHz, however, the reasonably flat frequency response was achieved only in the range DC-10 kHz. The operating temperature range is from -40°C to 150°C. A supply voltage of 5V is needed to drive each Hall sensor. More details on operational aspects of these Hall sensors can be found in [1].

We exploited the above described system of 8 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

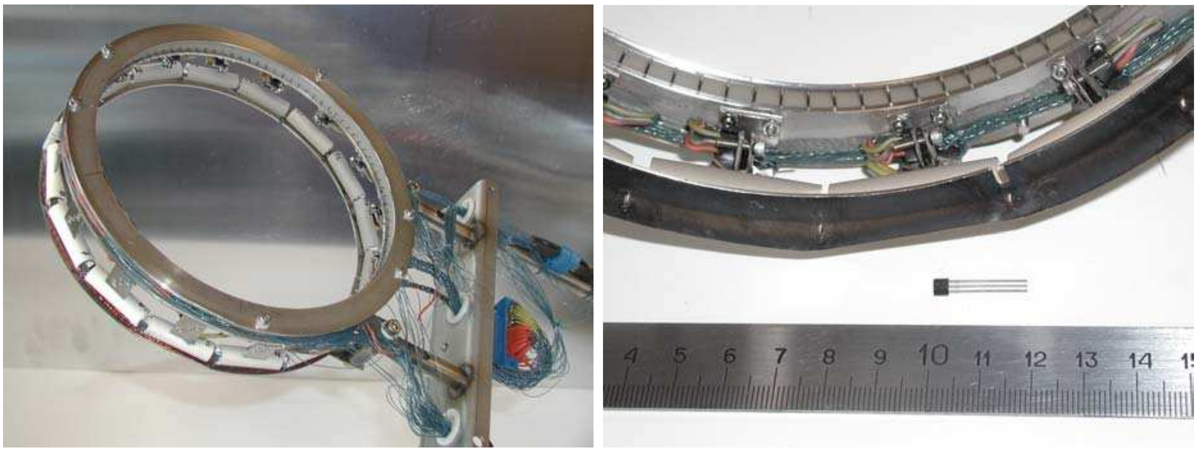

Figure 1: The ring of up to 16 Hall sensors, 16 coils and 96 Langmuir probes before its installation on CASTOR tokamak (left pannel). Detailed view of the Hall sensors attachment system with a single Hall sensor shown before ts installation on the ring (left pannel).

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 feed-back system [3]. The vertical plasma position deduced by this method is rather centred for most of the CASTOR operating regimes. In 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.

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 figure 2. 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 2 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 cantered 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 [3]:

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

where, b denotes the radial distance of the magnetic sensors from the geometric centre of the tokamak chamber and I_p stands for the plasma current. The 'standard approach' used also on

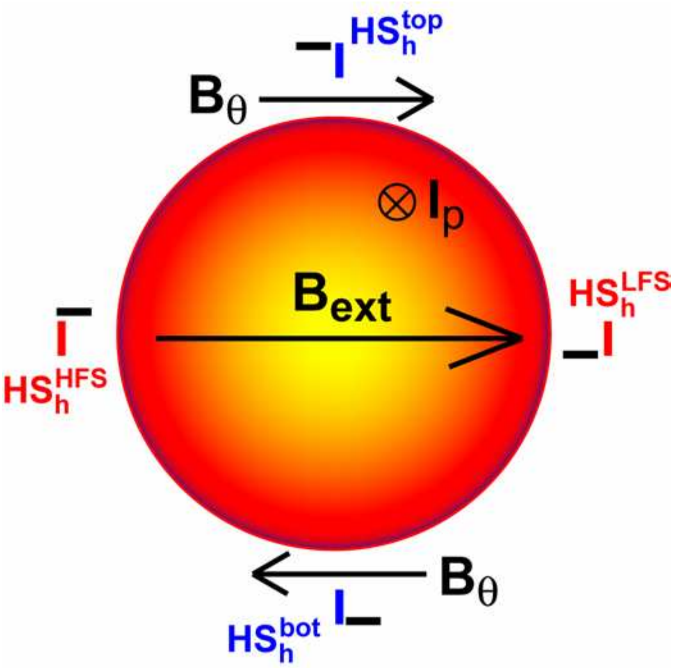

Figure 2: Schematic layout (not in scale) of the location of Hall sensors and directions of horizontal magnetic fields that are used to deduce vertical plasma position.

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. 2) and B_θ^{bottom} with the output of the bottom Hall sensor HS_h^{bottom} (or integrated output of the bottom coil – not shown in fig. 2). However, in case of the presence of any additional external horizontal magnetic, 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:

$$U_{dif}^{top-bottom} \approx \left(B_\theta^{top} - B_\theta^{bottom} + 2B_{ext}\right)$$

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 feedback system as high as 7 mT in opposite direction are recorded by the sensors inside the tokamak chamber. This demonstrates that the vertical 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 figure 2.). Thanks to the 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

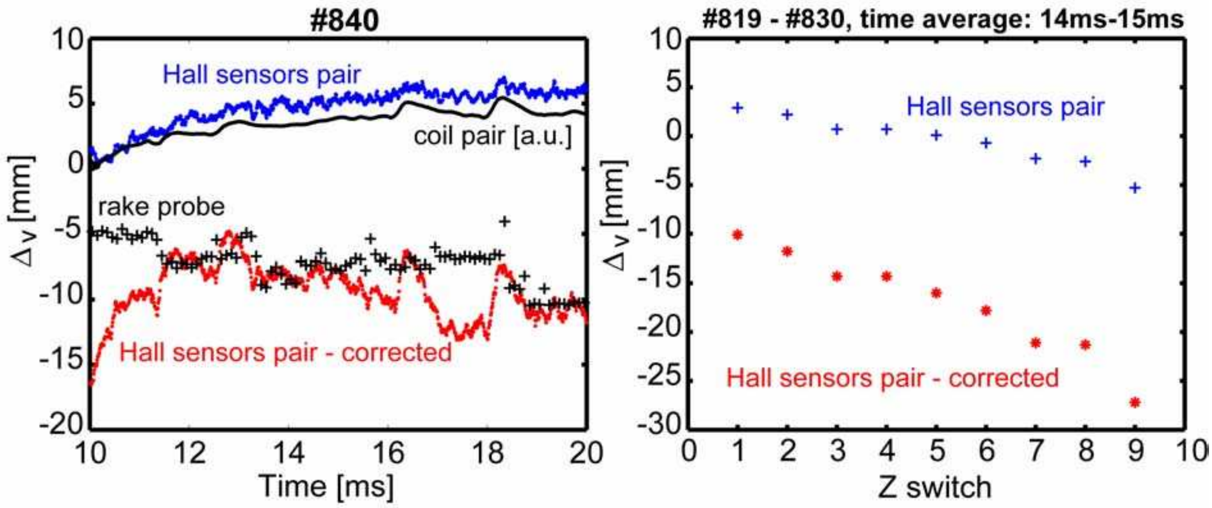

Figure 3: Left panel: comparison of vertical plasma displacement evolutions deduced from a coil pair (black line), Hall sensors pair (blue), Hall sensors pair corrected for presence of B_{ext} (red), and rake of Langmuir probes (black +). Right panel: vertical plasma displacement as a function of hardware CASTOR feedback system switch Z obtained as the simple differential signal of a pair of Hall sensors (blue) versus the same differential signal but corrected for presence of B_{ext}.

HS_h^{top}, HS_h^{bottom}. It is clearly seen in figure 3 (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 3 (right panel) presents example, 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 pre-define the desired vertical plasma position before each CASTOR shot.

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References

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