Measurement of safety factor using Hall probes on CASTOR tokamak

K. Kovařík, I. Ďuran

Czech Academy of Sciences, Ass. EURATOM/IPP.CR, Czech Academy of Sciences,
Za Slovankou 3, 182 00 Praha 8, Czech Republic
e-mail: kovarik@ipp.cas.cz

I. Boshakova, R. Holyaka, V. Erashok

Magnetic Sensor Laboratory, Lviv Polytechnic National University,
Lviv, Ukraine

Received 15 May 2006

Hall sensors offer an attractive true non–inductive method of magnetic field measurements for fusion devices. However, there is only limited experience in using of these sensors in such demanding environment (high heat loads, radiation, and electromagnetic noise). Recently, a combined magnetic probe was developed for CASTOR tokamak, which contains 3 Hall sensors and 3 coils arranged to measure all three components of magnetic field approximately in a single point of space. The probe is compatible with in–vessel use well in confinement region of CASTOR. It is fully controlled by multi–functional electronic system that drives the Hall probes, amplifies their output signals, performs the A/D conversion and stores the measured data on PC. The bandwidth of the system is up to 200 kHz. Design of the system and its implementation on CASTOR is reviewed. Results obtained using this diagnostic on CASTOR tokamak is presented. Radial profile of the poloidal magnetic field is used to deduce radial profile of safety factor.

PACS: 52.25.Jm
Key words: plasma, tokamak, safety factor, hall probe

1 Introduction

Future fusion devices and particularly fusion power plants based on magnetic confinement must operate in steady state regime. Long discharges imply quasi static magnetic fields that are difficult to measure with present day inductive methods (i.e. magnetic loops) with satisfactory precision. The sensitivity of inductive methods decreases with decreasing frequency of the measured magnetic field. Additionally, the proper integration of measured time derivative of the magnetic field over the long time intervals ($> 1\,000$ s) becomes very difficult due to integrators drifts. Therefore, a new non–inductive methods compatible with the harsh environment of future fusion devices (high radiation and thermal loads) must be developed and tested. Some aspects of operation of non-inductive methods can be tested already in present day machines as they offer similar configuration of magnetic fields and also some environmental constrains as vacuum and elevated temperature. One possible approach to measurement of static magnetic fields is the use of galvanomagnetic devices based on Hall effect. We applied a new magneto metric system based on a 3D Hall probe head for in–vessel measurements of magnetic field vector in the CASTOR tokamak ($R = 0.4$ m, $a = 0.085$ m, $B_\phi \approx 1.2$ T , $I_\mathrm{p} < 12$ kA).

1.1 Hall effect sensors

This magneto metric technique is generally widespread offering a wide range of commercially available transducers. However, not many measurements in fusion devices were done up to now, except those reported in [1–4]. Output voltage U_H of any Hall effect sensor can be expressed as:

$$U_\mathrm{H} = h I_\mathrm{H} B \sin\alpha \; , \tag{1}$$

where h is a constant depending on type of material, its geometry, and temperature; I_H is the control current driven through the sensor, α is an angle of the measured magnetic field $\mathbf{B}$ with respect to the plane of the sensor. The sensitivity of present day Hall transducers varies but in general, it is rather small ($1 \div 1\,000$) mV/T depending on material and construction. As a result, the Hall voltage must be amplified before A/D conversion and storage. To minimize the pick–up of spurious voltages, it is necessary to use low noise amplifiers and to place them as close to the transducer as possible. The survival temperature of the commercial Hall sensor is up to 150 °C, which is not sufficient for most of the fusion devices where the vacuum chamber is conditioned to 200° C or more. Identification of a new materials compatible with such temperatures and also radiation is the area of active research.

1.2 Safety factor

Safety factor q is one of the key parameters describing the stability of the plasma in tokamak. The meaning of this dimensionless parameter is the number of toroidal turns it takes a magnetic field line to make a single full poloidal turn. For tokamak with large aspect ratio ($R/a \gg 1$) and circular cross–section, it is given by following formula:

$$q = \frac{r}{R}\frac{B_\mathrm{T}}{B_\theta} \; , \tag{2}$$

where r is radial coordinate along the minor radius, R is major radius, B_T is toroidal magnetic field and B_θ is poloidal magnetic field. As q has clearly a radial dependence, it is convenient to express its value at the boundary of the plasma confinement region called separatrix using the measured quantities as B_T and plasma current I_p

$$q(a) = \frac{2\pi}{\mu_0}\frac{a^2}{R}\frac{B_\mathrm{T}}{I_\mathrm{p}} \; . \tag{3}$$

Assuming the constant R and B_T, the radial profile of q inside the plasma confinement region is given only by radius r and radial profile of B_θ. Radial dependence of B_θ is determined by radial profile of plasma current density $j(r)$. Current density profile is a quantity, that is very difficult to measure in fusion devices, therefore, the following formula is usually used for its approximation:

$$j\left(r\right)=j\left(0\right)\left(1-\frac{r^2}{a^2}\right)^p\ , \tag{4}$$

where p is so called "peaking factor" that determines the steepness of the profile. Typical values of this parameter in fusion plasmas are 1÷3. The previous considerations lead to the following profile of q within the plasma confinement region [5]:

$$q\left(r\right)=q\left(a\right)\frac{r^2}{a^2\left(1-\left(1-\frac{r^2}{a^2}\right)^{p+1}\right)}\ . \tag{5}$$

Radial profile outside the plasma column but still within the radius of toroidal field coils have a simple parabolic dependence:

$$q\left(r\right)=q(a)\frac{r^2}{a^2}\ . \tag{6}$$

2 3D Hall probe on CASTOR

The magnetic probe head was constructed to measure magnetic field vector in quasi–single–point of space inside the confinement region of CASTOR tokamak (see Fig. 1). It consists of 3 perpendicular Hall sensors and 3 perpendicular coils mounted within a dural casing. The dural structure of the probe head is covered by MACOR ceramic cap to protect it from direct contact with the plasma. Electronic box that control and drive the probe head is placed in a distance of approximately 3 meters from the probe head on the top floor of CASTOR tokamak. The measured data, pre-processed, conditioned, and digitized by electronics box, are transferred via RS232 interface to PC where they are stored and further analyzed. The operational parameters of the 3D Hall probe are given in following table (Tab. 1). Before the start of the experimental campaign, we have aligned the 3D probe head so that one Hall sensor is oriented toroidaly, and the other two are oriented horizontally and vertically. In case of ideal alignment of the probe head, there is a simple relation

Fig. 1. Left panel: schematic layout of the probe head and distribution of sensors with dimensions. Middle panel: photo of the probe head from outside. Right panel: probe head fixed on the manipulator together with the control electronics box.

Outer size of the probe head	20 × 20 × 25 mm
dynamic range	± 5 T
precision	$\leq 0.1\%$
bandwidth	up to 200 kHz
maximal temperature	100 °C

Table 1. Main parameters of 3D Hall probe

at the top of the torus between the cartesian and cylindrical coordinates, and as a result, toroidal sensor measures B_{T}, horizontal sensor measures B_θ and vertical sensor B_r. Because of large disproportion between the magnitudes of these fields on CASTOR ($B_{\mathrm{T}} \sim 1$ T, $B_\theta \sim 20$ mT, $B_r \sim 5$ mT) and limited mechanical rigidness of CASTOR vacuum vessel, the perfect alignment of the probe is impossible and the cross–talk between individual components must be accounted for, as it is discussed in the section 2.1.

2.1 Experimental results

Example of the magnetic field vector measurement in a CASTOR discharge #29674 is given in Fig. 2. First, let us discuss the figures contained on the left side of Fig. 2. Here, temporal evolutions of raw signals measured by the 3 perpendicular Hall sensors converted into absolute units are shown. The left top panel shows the temporal evolution of toroidal magnetic field having the sinusoidal shape and reaching the peak value of 1.1 T. The middle panel shows temporal evolution of signal from horizontal magnetic field sensor. The measured data are a clear superposition of a three signals of different origin:

1. B_θ – which is the target quantity to be measured,
2. αB_{T} – which is the cross–talk from the toroidal magnetic field caused by imperfect alignment of the Hall sensor perpendicularly to the B_{T},
3. $\alpha dB_{\mathrm{T}}/dt$ – which is an inductive pick–up of B_{T} caused by imperfect alignment of the Hall sensor and the intrinsic loop of non zero area formed by the Hall sensor itself.

The same superposition of the signals occurs also in case of vertical Hall sensor, where the misalignment of the probe head is even more pronounced. Here, the output signal is superposition of B_r, βB_{T}, and $\beta dB/dt$. The coefficients α and β are proportional to the angles by which the probe head is turned out of the ideal alignment. In order to eliminate components of the measured signals proportional to the B_{T} cross–talk, we performed discharge with charging only toroidal field coils without initiating plasma. In this case, the output of the horizontal and vertical sensor was proportional only to the cross–talk from B_{T}. Subtracting this cross–talk from data measured in standard CASTOR plasma discharge, we obtained desired

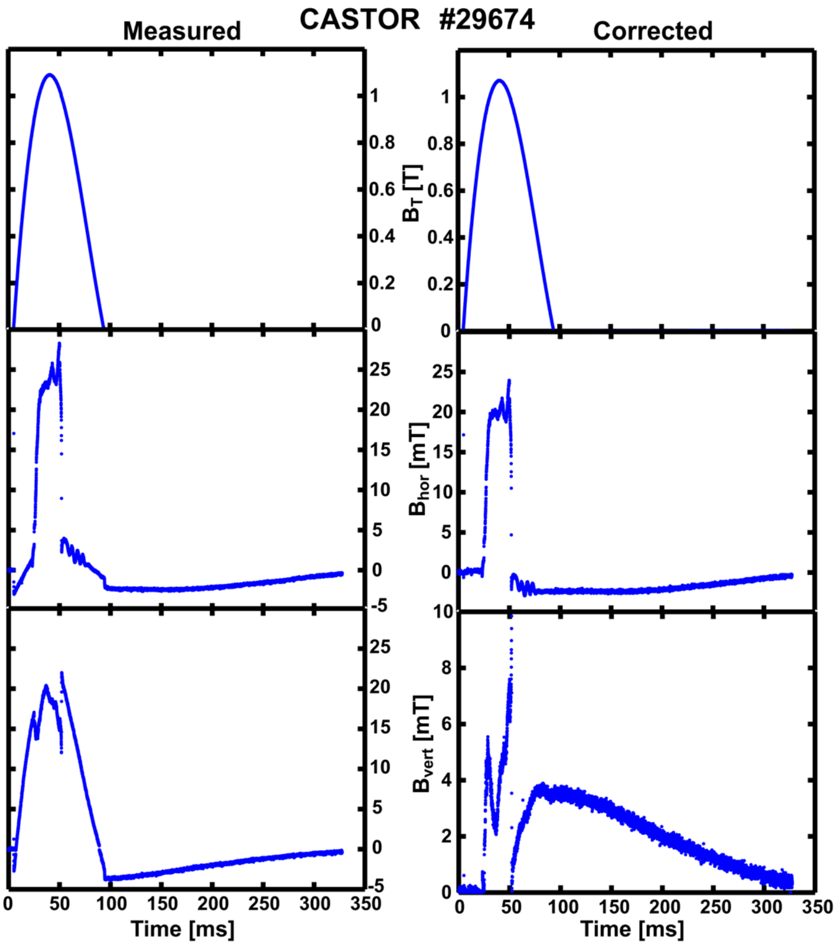

Fig. 2. Left panel – temporal evolution of measured magnetic field components at the top of the CASTOR torus (discharge #29674). The leading edge of the 3D Hall probe was located 76 mm from the plasma center. Right panel – the same data after removal of inductive pick–up and cross–talk from B_{T}.

time evolutions of B_θ and B_r. The resulting temporal evolutions after application of correction procedure are plotted on the right side of Fig. 2. The shape of the B_θ follows the temporal evolution of plasma current as expected reaching the amplitude up to 20 mT. Interesting observation is the presence of significant magnetic field of a few militeslas up to 300 ms after the termination of plasma discharge. This magnetic field is supposed to be caused by eddy currents induced in the tokamak chamber after the termination of discharge. This observation has a practical implication for the integration of magnetic coils data on CASTOR. Usually, it was assumed that after termination of B_T there are no remaining magnetic fields. This assumption was used to fix the zero level of the integrated coils output. In the light of present findings, the zero field state on CASTOR occurs only 250 ms after the termination of B_T.

2.2 Radial profile of safety factor

Additionally, we have performed the series of shots to measure radial profile of B_θ and consequently profile of safety factor q. The 3D Hall probe was moved radially on a shot to shot basis up to $r = 60$ mm. The global plasma parameters in the beginning of stationary phase of discharge were reproducible for all probe positions namely plasma current $I_p \in 9 \div 9.5$ kA and line averaged plasma density $n_e \in (1 \div 1.2) \times 10^{19}\,\mathrm{m}^{-3}$. Measured radial profile of B_θ is shown in the left panel of Fig. 3. The maximum of the B_θ profile is located at $r = 69$ mm which we identify with the position of plasma separatrix. As a result, in the discussed shot series, the plasma was shifted down by 8 mm and consequently the minor radius was reduced to 77 mm. We used the measured radial profiles of B_θ and B_T to compute q profile using Equation (2), see right panel of Fig. 3. The measured data were fitted by theoretical formulas (5, 6) with a peaking factor p being the free parameter. The value of edge safety factor was computed using Equation (3). In confinement region, the best agreement between modeled and measured q profile was reached for relatively low peaking factor of $p = 0.6$. In scrape-off layer, some discrepancy between expected and measured q profile is seen for larger radii $r > 85$ mm. It is caused by measured decrease in toroidal magnetic field for these radii which is not taken into account in theoretical expression.

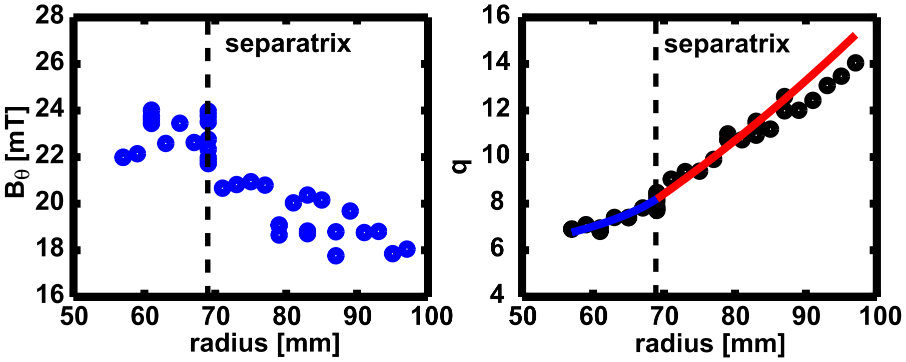

Fig. 3. Left panel: radial profile of B_θ. Right panel: radial profile of safety–factor. Solid line shows the theoretically expected q profile.

3 Conclusion

A new magnetic probe diagnostic based on Hall sensors was put in operation on CASTOR. The magnetic field vector was measured well within the plasma confinement region. Errors of the measurement caused by imperfect alignment of the probe head were analysed and corrected. Significant remaining magnetic field up to 5 mT due to eddy currents persists in the tokamak chamber up to 300 ms after the termination of discharge. Radial profile of the magnetic field factor was measured on a shot to shot basis up to $r = 60$ mm. Measured profile of q is consistent with theoretical expectations assuming the downward shift of the plasma column by 8 mm and rather flat current density profile with the peaking factor of 0.6.

This research has been supported by the grant KJB100430504 of Grant Agency of Academy of Sciences of the Czech Republic.

References

[1] I. Ďuran et al.: Rev. Sci. Instrum. **73** 3482 (2002).

[2] V. Coccorese et al.: Rev. Sci. Instrum. **75** 4311 (2004).

[3] I. Ďuran et al.: *Magnetic field measurements using the galvanomagnetic devices on Tore Supra and CASTOR tokamaks*, proceedings of 32nd EPS Conf. on Plasma Phys., Tarragona June 27 – July 1, ECA **29C** (2005).

[4] Yuhong Liu et al.: Rev. Sci. Instrum **76** 93501 (2005).

[5] I. Ďuran: *Fluktuations of magnetic field on CASTOR tokamak*, diploma thesis FNSPE CTU, Praha (2003).