Comparative measurements of plasma position using coils, Hall probes, and bolometers on CASTOR tokamak

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Plasma position on CASTOR tokamak is measured by several systems based on different experimental methods. Vertical and horizontal plasma displacements are deduced from data of 4 Mirnov coils spaced poloidaly by 45°. Output of the Mirnov coils is routinely used as an input for automatic feed–back control of plasma position on CASTOR. Independently, we used an array of 16 Hall sensors, which measure the required magnetic field directly. Additional information on plasma position is obtained from two arrays of bolometers that measure horizontal and vertical profile of plasma radiation. Principle design of the all used diagnostics is given. Comparison of horizontal and vertical displacements deduced using various experimental methods is presented.

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1 Introduction

Czech **A**cademy of **S**ciences **TOR**us (CASTOR) is a small tokamak with a circular cross section ($R_0 = 0.4$ m, $a = 0.085$ m, $B_\Phi \approx 1.2$ T , $I_p < 12$ kA). The quasi stationary phase of the discharge is about 20 ms long. Plasma position is monitored and feed–back stabilized during the full discharge length. There are indications of systematic downward shift of plasma column as deduced from arrays of Langmuir probes [1]. In contrast, the standard magnetic plasma position diagnostic shows systematically a rather centered plasma position. Recently, a new diagnostic tools become available (bolometers, Hall sensors) which have potential to provide additional information on plasma position on CASTOR.

2 Magnetic measurements of the plasma position

Magnetic sensors distributed poloidaly around the plasma column are used to determine the position of current channel in tokamaks. The distribution of the plasma current follows the distribution of plasma density and temperature. Therefore, the magnetic sensors provide information about position (movement) of the plasma column itself. The stability of the plasma column is in tokamaks given by Grad–Shafranov equation for asymmetric tokamak configuration [2]. Solving this equation it is possible to derive analytic expression for vertical Δ_V and horizontal

$\Delta_{\rm R}$ plasma fluid displacement [3]:

$$\Delta_{\rm V} = \frac{B_2}{2B_0} b \,, \tag{1}$$

$$\Delta_{\rm R} = \frac{B_1}{2B_0} b - \frac{1}{2} \left[ln \frac{b}{a} - 1 + (\Lambda - \frac{1}{2}) \left(1 + \frac{a^2}{b^2} \right) \right] \frac{b^2}{R_0} \,, \tag{2}$$

where,

$$\Lambda = \left(\frac{B_1}{2} - \bar{B}_V \right) \frac{R_0}{B_0 b} - \ln \frac{b}{a} + 1 \,,$$

$$a = a_L - \left({\Delta_R}^2 + {\Delta_V}^2 \right)^{\frac{1}{2}} \,,$$

$B_1 = B_\theta(\pi) - B_\theta(0), B_2 = B_\theta(-1/2\pi) - B_\theta(1/2\pi), B_0 = \mu_0 I_p / 2\pi b$, and $\mu_0 = 4\pi \times 10^{-7}$ H/m. $I_{\rm p}$ is a plasma current, R_0 is the major radius, $B_\theta(\theta)$ is the poloidal magnetic field, θ represents poloidal angle, $a_{\rm L}$ is radius of circular limiter, b is radius of the Mirnov coils ring and $\bar{B}_{\rm V}$ is an averaged vertical magnetic field along the torus.

2.1 Brief overview of CASTOR standard magnetic diagnostic

The magnetic field system consists of iron core, copper shell and active coils. Copper shell, 10 mm thick, encompasses the vacuum chamber at inner radius of 117 mm. Plasma position is measured by using set of four Mirnov coils, two toroidal loops, Rogowski coil and saddle coil, see Fig. 1. Rogowski coil, wounded outside the shell, is used for measurement of the plasma current $I_{\rm p}$. The sensitivity of Rogowski coil is 0.49 cm^2, density of turns is $n = 3 \times 10^3$ m^{-1}. Two toroidal loops detect the

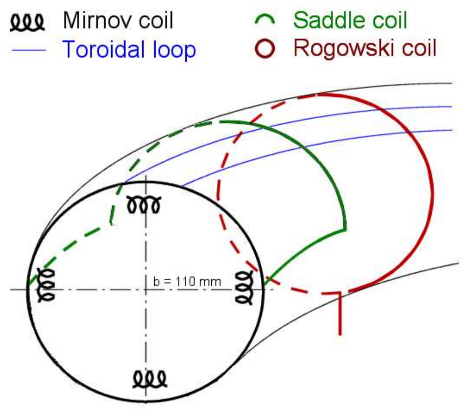

Fig. 1. Schematic diagram of CASTOR standard magnetic diagnostics.

toroidally averaged vertical magnetic field $\bar{B}_{\rm V}$. They are placed at radii 302.5 mm and 647.5 mm. Total measured area is approximately 1.02 m^2. Poloidal magnetic field B_θ is measured by four Mirnov coils. They are placed inside the vacuum chamber in the shadow of limiter at minor radius b. They consist of 97 turns each. The sensitivity of each coil is approximately 35 mV/mT, inductance is 13.7 H. The same support carries one saddle coil which have 8 turns and a sensitivity of 1.5×10^3 mV/mT. It measures local vertical magnetic field B_{V} at Mirnov coils cross–section.

2.2 SK ring

Additional new diagnostic that can be used for plasma position measurements is SK ring. It is the full poloidal ring of 16 magnetic coils, 16 Hall sensors and 96 Langmuir probes uniformly distributed around the whole poloidal circumference. All the sensors are aligned to measure the poloidal component of magnetic field B_θ. Langmuir probes made from molybdenum wire are at the radius of 87 mm. Each one has 0.5 mm in diameter and the tip extends 1 mm over the steel ring. Each of the magnetic coils has 97 turns and total active area around 35 cm^2. They are located at radius of 95 mm.

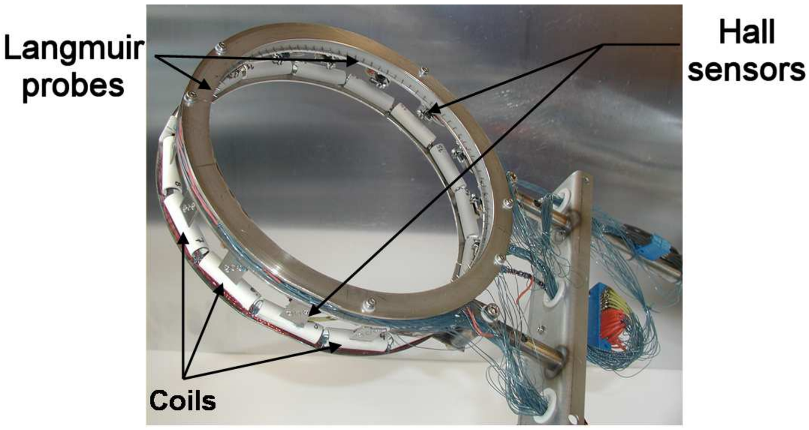

Fig. 2. SK ring – full poloidal array of 16 Hall sensors, 16 coils, and 96 Langmuir probes.

2.2.1 Hall probes on SK ring

Proper integration of Mirnov coils signals to obtain the absolute level of magnetic field turns out to be a rather difficult task on CASTOR because of various drifts and pick–ups of other magnetic field components and noise. Therefore, it becomes attractive to use Hall effected sensors, which can measure absolute value of magnetic field directly. Low cost commercially produced Hall sensors type Allegro A1322LUA, installed at radius of 95 mm, are used on SK ring. These sensors are linear output sensors. Their operating temperature is $-40\,^\circ$C to $150\,^\circ$C, frequency range $0 \div 30$ kHz, nominal sensitivity 31.25 ± 1.56 mV/mT and supply voltage 5 V.

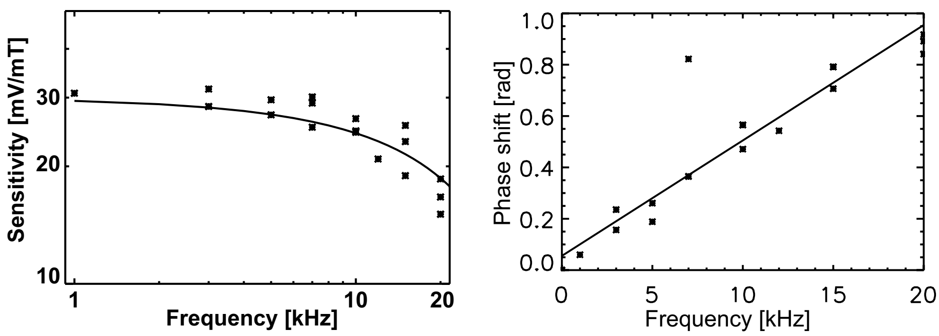

Fig. 3. Amplitude and phase characteristics of the A1322LUA Hall sensor.

We performed absolute calibration of those sensors in the frequency range $1 \div 20$ kHz. The resulting amplitude and phase characteristics are on Fig. 3. The frequency characteristic of the sensor is at 30 mV/mT reasonably flat in frequency range from 1 up to 10 kHz. The phase is linearly increasing up to 20 kHz with the frequency. This response is satisfactory for monitoring of plasma position, which changes on CASTOR time scales slower than 100 µs.

Measurements of the poloidal magnetic field B_θ are complicated by cross-talk with toroidal magnetic field B_Φ. It is because the Hall sensors can not be aligned perfectly perpendicular to the B_Φ. Note that the amplitude of the desired quantity B_θ amounts to only $1 \div 2\,\%$ of the background magnetic field B_Φ. The toroidal magnetic field pick–up $B_{\Phi p}$ must be removed in order to determine the value of the B_θ. It is done by performing vacuum field shot with charging only toroidal field coils, where $B_{\Phi p}$ is directly measured. Consequently, we subtract $B_{\Phi p}$ from the data measured during plasma discharge to obtain B_θ.

3 Estimation of plasma position by bolometers

Additionally, we have applied the non–magnetic method for estimation of plasma position, bolometry. Bolometry deduce plasma position from the profile of radiation emitted by plasma. Bolometers on CASTOR are two arrays with 16 and 19 AXUV diode detectors. The first AXUV array is located at the bottom side of the tokamak at the distance of 267 mm from a plasma center. The second AXUV array is placed at the low field side at the distance 342 mm from a plasma center. Typically, the two types of radiation profiles are observed on CASTOR. The first one is parabolic and the position of plasma center is identified with the maximum of radiation profile. The second one is hollow profile and the position of plasma center is identified with the local minimum of plasma radiation in the core region of CASTOR tokamak.

4 Results

On CASTOR, plasma displacements Δ_V and Δ_R are determined from standard magnetic diagnostic data (see Fig. 1) during the plasma discharge via analog electronic circuits, which realize eq. 1, 2. Output of these circuits are two signals U_{vert}, U_{rad} proportional to Δ_V and Δ_R. To obtain the displacements in absolute units, following equations are used:

$$\Delta_V = -43.3\ U_{vert}/I_p \qquad [\mathrm{mm, V, kA}]\,, \tag{3}$$

$$\Delta_R = -33.3\ U_{rad}/I_p \qquad [\mathrm{mm, V, kA}]\,. \tag{4}$$

Overall accuracy of displacements determination using this method is ± 3 mm [4]. Additionally, we evaluated plasma displacements using Hall sensors on SK ring instead of Mirnov coils.

For this purpose, we have numerically evaluated Equations 1, 2, where we have used data from Hall sensors for B_θ. The desired plasma position on CASTOR is predefined before each shot by switches R and Z. The R switch controls the horizontal position and can be varied from 1 to 5. Z switch controls vertical plasma position and can be varied from 0 to 12. In order to cover the full operational space of CASTOR, we have performed approximately 100 shots (#31231 to #31331) with all combinations of plasma position control switches. The resulting comparison of plasma position deduced from standard diagnostic and using numerical evaluation of Hall sensors is plotted in the Fig. 4. We observed qualitative agreement between displacements deduced from Hall sensors and standard diagnostic both in horizontal and vertical directions. Concerning magnitude of the horizontal displacement (left panel of Fig. 4), the standard diagnostic claims centered plasma position but, with unreasonably low spread of data $\pm$ 0.2 mm. Note, the estimated precision of this system is 3 mm. This finding puts in doubt the value of conversion coefficient in Equation 4 and suggest that it should be at least by a factor of 10 higher. The horizontal displacement deduced from Hall sensor data is about 6 mm toward the low field side of the torus. Additional finding is that the horizontal plasma position is rather constant independent on setting of R control switch. Concerning the magnitude of the vertical displacement, it is underestimated by the standard diagnostic compared to Hall sensors by a factor of two. Assuming that the Hall sensors provide the correct information on plasma displacement, this suggests need of revision of conversion coefficient also in Equation 3.

Additionally, we compared the plasma displacements deduced from magnetic measurements to those deduced from vertical and horizontal profiles of plasma radiation measured by bolometers during the same series of discharges. We chose the results of Hall sensors to represent the magnetic measurements. Comparison of vertical displacement deduced from both methods is shown in the Fig. 5. There is a clear linear trend between output of both methods which proves the relation between the location of maximum of the vertical plasma radiation profile and the plasma position. Although, this relation is linear as it is seen from Fig. 5, it is far from expected identity relation. Additionally, we found very low correlation

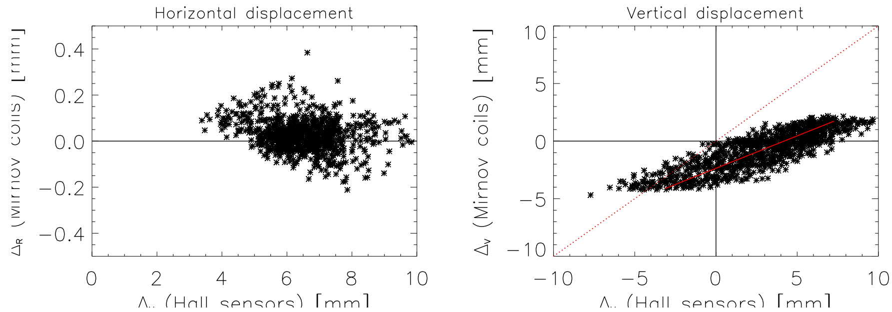

Fig. 4. *Left panel*: Comparison of horizontal plasma displacement Δ_{R} deduced from standard magnetic diagnostic and from Hall sensors. *Right panel*: Comparison of vertical plasma displacement Δ_{V} deduced from standard magnetic diagnostic and from Hall sensors. The solid red line shows the linear fit of the data. Red dotted line denotes the target ideal case when both diagnostics provide the same results.

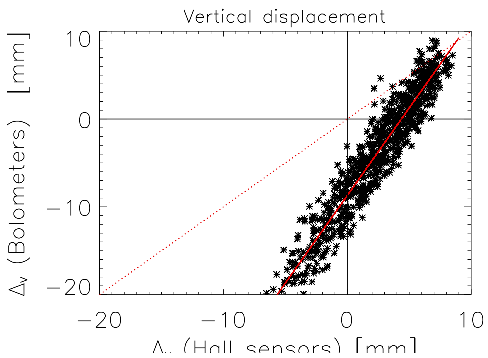

Fig. 5. Comparison of vertical plasma displacement Δ_{V} deduced from the Hall sensors and from the bolometers. The solid red line shows the linear fit of the measured trend. Red dotted line denotes the target ideal case when both diagnostics provide the same results.

between horizontal displacements deduced from horizontal plasma radiation profile and from magnetic measurements. Possible reason for the observed discrepancies is rather low resolution of bolometric arrays of 10 mm and 11 mm combined with uncertainties in determination of local extreme of often observed double peaked radiation profiles. In case of magnetic measurements, the exact location of sensors and their centering around the axis of tokamak chamber are the main sources of uncertainties.

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