Novel advanced Gundestrup-like probe for the measurements of flows and edge plasma parameters in TEXTOR

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Novel advanced Gundestrup-like probe for the measurements of flows and edge plasma parameters in TEXTOR

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A novel advanced Gundestrup-like probe head for local measurements of equilibrium and fluctuating plasma parameters in the plasma edge of TEXTOR is described. This probe assembly enables us to simultaneously determine the toroidal and poloidal plasma flows, the ion saturation current, density, electron temperature, floating potential, as well as their fluctuating properties. An improved analytical probe model is used to correctly relate the ratio of the ion saturation currents measured at the upstream and downstream collecting surfaces to the plasma flow. The probe is mounted on a fast reciprocating manipulator resulting in a high radial resolution of the profiles. A unique feature of the fast probe is the electrical linear motor drive which allows predefining any wave form of the radial position. The high speed of the probe drive reduces the exposure time which enables us to measure several radial profiles within a single discharge deep inside the last closed flux surface. We describe the first experimental results of flow, radial electric field, ion density, and temperature profiles measured in the plasma edge of TEXTOR. In order to verify the accuracy of these measured quantities we compare the measured radial electric field with the one calculated from the single ion momentum balance equation.
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I. INTRODUCTION

A wealth of information on boundary plasma profiles, fluctuations, turbulence, and turbulence driven cross-field transport can be provided using electric probes. Among several diagnostics to measure the plasma flow velocity, a Mach probe[1] is a very simple tool to obtain the ion acoustic Mach number (M_i), defined by the ratio of the plasma flow velocity to the ion acoustic velocity. A Mach probe consists typically of two oppositely facing collectors insulated from each other and aligned with the magnetic field. The ratio (R) of the measured upstream ($I_{\mathrm{sat,up}}$) and downstream ion saturation currents ($I_{\mathrm{sat,down}}$) yields the Mach number parallel to the magnetic field.[2] In order to determine also the perpendicular Mach number, additional collectors inclined with respect to the magnetic field are necessary. Such an array of collectors, poloidally distributed over the probe's circumference, is generally known as a "Gundestrup" probe.[3] In Sec. II A we present a novel advanced Gundestrup-like probe head which consist of two Gundestrup arrays at different radial positions and a four-Langmuir-probe array mounted on the flat end of the head. This probe is capable of measuring the density, temperature, and floating potential in tokamak edge plasmas. In addition, the ion saturation currents collected by the Gundestrup arrays can be used to infer the speed and direction (poloidal and toroidal) of flowing plasmas.

Fast reciprocating probe assemblies have been installed on several tokamaks, stellarators, and reversed field pinch machines.[4–9] The fast movement is often obtained by means of a pneumatically or hydraulically driven piston which offers speed but a poor control of the acceleration, dwell time, and radial position. A versatile fast reciprocating and rotating probe system has recently been installed at the midplane of TEXTOR. The use of this fast reciprocating probe system enables us to measure several radial profiles within a single discharge deep inside the last closed flux surface (LCFS). The probe drive will be described in Sec. II B.

In order to test the sensitivity of the probe, measurements of the plasma edge parameters have been performed in TEXTOR in two different plasma regimes: in Ohmic plasmas and in edge ergodized plasmas, imposed by the dynamic ergodic divertor (DED), where changes to the rotation profiles due to the enhanced radial conductivity are expected. The DED, installed at TEXTOR, is a set of 16 coils, wrapped

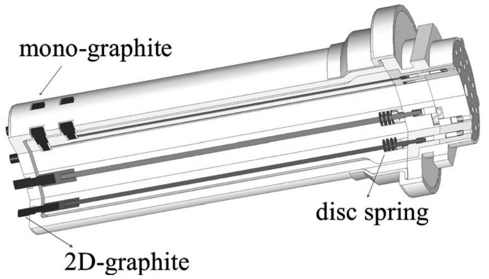

FIG. 1. The Gundestrup-like probe head consisting of two arrays separated radially, both with eight flat collectors distributed poloidally and a four-Langmuir-probe array mounted on the flat end of the head.

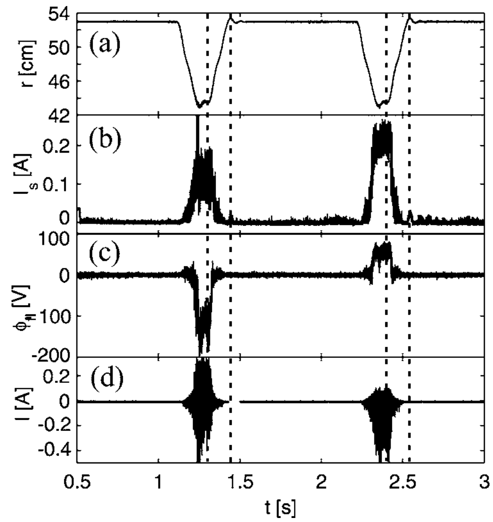

FIG. 2. Temporal evolutions (No. 99777) of (a) radial position of the probe (b) I_s from one top Langmuir pin (c) ϕ_{fl} from another top pin (d) current collected from one side flat collector pair.

around the vessel at the high field side and creates a perturbation field resonant with the $q=3$ surface.[10,11] The dynamical operation of the DED coils results in a rotation of the magnetic field pattern and hence of the plasma itself. In Sec. III we present the first experimental results of the new probe diagnostic on TEXTOR carried out before and during DED operation. Furthermore, the reliability of the probe model is demonstrated by comparing radial profiles of flows and edge plasma parameters with the single ion momentum balance equation. Finally, we summarize in Sec. IV.

II. PROBE

The probe assembly consists of two main components: the probe head and the probe drive.

A. Probe head design

The Mach probe head described here has a total of 20 collectors which can simultaneously obtain a large variety of edge plasma parameters. The probe consists of two sets of monographite collectors located at two different radial positions (radially separated by 1 cm). Each set consists of eight flat collectors poloidally distributed around the circumference of the head as shown in Fig. 1. The ion saturation currents of each collector pair, of which one faces the upstream while the other faces the downstream direction with respect to the magnetic field, are used to infer the speed and direction of flowing edge plasmas together with the electron temperature. In addition, a four-Langmuir-probe array is mounted on the flat end of the cylindrical probe head facing the plasma. The saturation current and floating potential, collected by two cylindrical top pins, are used to determine the electron density n_e, the radial electric field E_r, and the properties of turbulence as well. The top pins are made of two-dimensional (2D) graphite, a low Z material with a high thermal conductivity and a better resistance, compared to monographite, to resist the high temperatures originating at the front surface of the probe head. A boron nitride body (also low Z) electrically insulates each top and side collector from one another. The body consists of internal and external housings which are fixed at the back of the probe using a stainless steel ring. Such a probe design enables easy access for disassembly and replacement of any part of the probe head. The probe assembly is mounted on a fast reciprocating manipulator which has recently been installed on the TEXTOR tokamak.

B. Probe drive

A fast scanning and rotatable probe system was designed to provide local plasma edge parameter profiles with high temporal and spatial resolutions. The linear movement is a two-stage mechanism starting from an initial position of the probe within the exchange port allowing for easy physical access. First the probe is slowly (0.3 m s^{-1}) moved to its standby position at 530 mm (close behind the limiter) where there is no exposure to the plasma. Once this position is reached, a fast (up to 2 m s^{-1}) reciprocating linear motion reaching as far as 170 mm into the plasma can be triggered. A unique feature of the fast probe drive is the use of two ac servo electrical motors which allows predefining any wave form for the radial position. The fast linear drive is numerically controlled and has the flexibility of providing the user to change the three main parameters, which are the (1) radial position (any penetration depth between 1 and 170 mm in 1 mm steps with a mechanical repetition accuracy of ±0.1 mm), (2) dwell time (up to 10 s with 1 ms increments), and (3) speed (up to 2 m s^{-1} with 1 mm s^{-1} increments). Furthermore, these types of motors offer a reliable performance at maximum acceleration (90 m s^{-2}). In addition to the linear movement, the probe system is designed to simultaneously rotate a probe at variable frequencies with a maximum of 3 Hz. However, no rotating probe measurements have been performed yet. Figure 2(a) represents the temporal evolution of the radial probe position. Two strokes were programmed to reciprocate the probe from 53 to 43 cm with a velocity of 0.8 m s^{-1} and a dwell time of 50 ms. These settings were found to be a good compromise in limiting the exposure time of the probe head and still gathering enough data in order to be successfully analyzed. Note that a small "over shoot" occurs which is immediately (<40 ms) countered by a reversed velocity bringing the probe back to 43 cm where it remains during the dwell time before returning to its initial position.

III. OPERATION AND RESULTS

The discharge parameters are major radius $R_0=1.73$ m, magnetic field $B_T=1.9$ T, plasma current $I_p=280$ kA, and

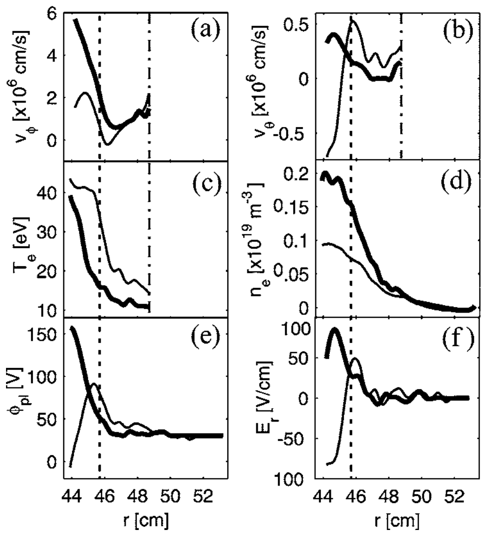

FIG. 3. Radial profiles (No. 99777) of the (a) toroidal flow v_ϕ, (b) poloidal flow v_θ, (c) electron temperature T_e, (d) electron density n_e, (e) plasma potential ϕ_{pl}, and (f) radial electric field E_r before (thin line) and during (thick line) DED. The vertical dashed line marks the position of the LCFS. The dashed-dotted line indicates the end of the reliability of the Gundestrup data.

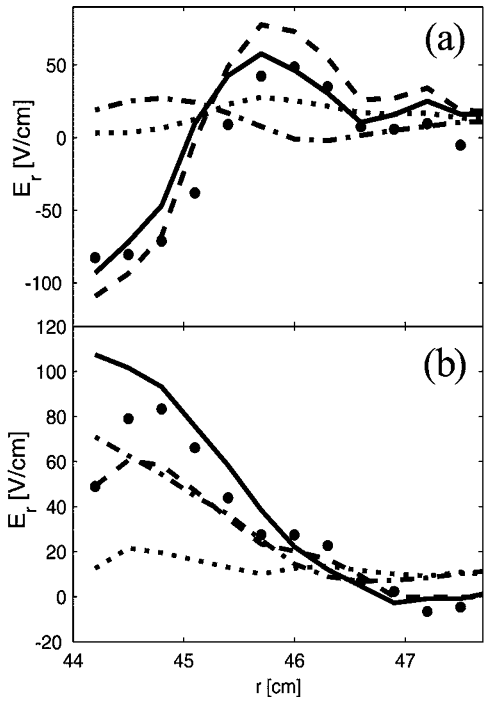

FIG. 4. Comparison of $E_{r,\mathrm{calc}}$ (solid line) calculated with the radial ion momentum equation and the measured $E_{r,\mathrm{meas}}$ (filled circles) before (a) and during (b) DED. $E_{r,\mathrm{calc}}$ consists of $|\nabla_r p_i/en_i|$ (dotted line), $-v_\theta B_\phi$ (dashed line), and $v_\phi B_\theta$ (dashed-dotted line).

line-averaged density $\bar{n}_{e,0}=1.5\times 10^{19}\ \mathrm{m}^{-3}$. The DED has been operated with poloidal/toroidal mode number of 6/2 and is switched on at $t=1.6$ s reaching its flat top phase at $t=2$ s for a period of 1 s. The DED target plate is located at $r=47.7$ cm and the plasma was shifted 2 cm inwards which gives a radial position of the LCFS of $r=45.7$ cm. The saturation current I_s and floating potential ϕ_{fl} time traces measured by two top Langmuir pins, when reciprocating the probe before and during DED operation, are shown in Figs. 2(b) and 2(c), respectively. The current (I) of one Gundestrup collector pair, connected as a double probe and swept with a 200 Hz triangular voltage (V) of amplitude of ±200 V, is plotted in Fig. 2(d). The data are digitized at 40 kHz to obtain a sufficient amount of data points per sweep in the I-V characteristic. The upstream and downstream ion saturation currents and the electron temperature T_e are obtained by fitting a nonlinear function of the form $I=-I_{\mathrm{sat,up}}\{[1-\exp[-(V-V_{\mathrm{fl}})/T_e]]/[R+\exp[-(V-V_{\mathrm{fl}})/T_e]]\}$ with $R=I_{\mathrm{sat,up}}/I_{\mathrm{sat,down}}$ and $V_{\mathrm{fl}}=V(I=0)$.

A one dimensional fluid probe model is used for determining both the toroidal v_ϕ and poloidal v_θ flow velocities from the probe data.[12,13] Here, an improved analytical expression relates the plasma flow to the measured ion saturation currents collected at the upstream and downstream collecting surfaces of the probe. The dashed lines in Fig. 2 indicate the two time periods which are used to determine the edge radial profiles plotted in Fig. 3.

The spatial resolution of the flow and T_e profiles is determined by the frequency of the applied voltage (200 Hz) and by the velocity of the probe. For a velocity of 0.8 m s^{-1}, the probe moves 4 mm during one sweep; therefore the spatial resolution of the double probe measurements varies from 4 to 8 mm, depending on the number of sweeps (one or two) which are used in the data analysis. A higher resolution can be achieved by increasing the sweep frequency or decreasing the probe velocity to the detriment of less data points per $I(V)$ fit and longer exposure of the probe to the plasma. The radial extent (outwards) of the flow and T_e profiles is limited by the signal to noise (S/N) ratio. In the scrape-off layer (SOL) the saturation current drops strongly, producing a high (S/N) ratio. In exchange for some loss in spatial resolution, we averaged over two sweeps (one period) in order to improve the (S/N) ratio. Therefore, reliable profiles were obtained up to 48.7 cm which is 3 cm into the SOL. The radial profiles of v_ϕ, v_θ, and T_e before (thin line) and during DED (thick line), are shown in Figs. 3(a)–3(c), respectively.

Figure 3(d) shows the ion density n_i profiles which are directly calculated from $I_s=0.5A_sZ_ien_i[k(T_i+T_e)/m_i]^{0.5}$ (assuming $T_i\approx T_e$) where T_i is the ion temperature, Z_ie and m_i are the electric charge and mass, respectively, and A_s is the front tip collection area. The radial electric field is calculated from the negative derivative of the plasma potential defined as $\phi_{\mathrm{pl}}=\phi_{\mathrm{fl}}+2.5T_e$. Typical profiles of plasma potential and radial electric field are shown in Figs. 3(e) and 3(f).

Hence, we have determined all the quantities associated with the radial force balance equation

$$E_r=\nabla_r p_i/n_iZ_ie - v_{\theta,i}B_\phi + v_{\phi,i}B_\theta, \tag{1}$$

where $p_i=n_iT_i$ is the ion pressure, and B_θ and B_ϕ are the poloidal and toroidal magnetic fields. Therefore, we are able to verify the accuracy of our measurements by comparing the measured radial electric field $E_{r,\mathrm{meas}}$ with $E_{r,\mathrm{calc}}$ calculated from (1). Figure 4 shows the relative contribution of each term to $E_{r,\mathrm{calc}}$ and illustrates the comparison with $E_{r,\mathrm{meas}}$. Note that the absolute values of the diamagnetic term are plotted. In both cases the magnitude of the diamagnetic term is comparable and its contribution to $E_{r,\mathrm{calc}}$ negligible. Since

B_θ is one order of magnitude smaller than B_ϕ, the poloidal velocity term should be much larger than the toroidal one for similar v_ϕ and v_θ. Indeed, in the Ohmic case the v_ϕ term remains small and contributes little (but is not negligible) to $E_{r,\mathrm{calc}}$. Here, the electric field is mainly the result of the $\bar{E}_r \times \bar{B}$ driven poloidal flow. However, during DED, very high toroidal velocities (order of magnitude higher than v_θ) were measured which result in a v_ϕ term comparable to the v_θ term. Nevertheless, we found that in both cases, before and during DED, the radial profiles of all these quantities are consistent with the first order radial single ion momentum balance equation. The $E_{r,\mathrm{calc}}$ is in good quantitative agreement with the measured radial electric field which supports the accuracy of our measurements and the underlying probe model used.

IV. SUMMARY

The design of a new advanced Gundestrup-like probe head was described. A fast reciprocating probe system for high spatial resolution measurements is presented. First results of probe measurements, before and during DED operation, are shown and cross-checked with the radial force balance equation. In conclusion, it is shown that the measurements of flows and edge plasma parameters in TEXTOR with the presented probe diagnostic are reliable and accurate. It will provide useful data for DED characterization studies and further improvements of probe modeling.

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[1] H. Othsuka *et al.*, Plasma Phys. Controlled Fusion **20**, 749 (1978).
[2] I. H. Hutchinson, Phys. Fluids **30**, 3777 (1987).
[3] C. S. MacLatchy, C. Boucher, D. A. Poirier, and J. Gunn, Rev. Sci. Instrum. **63**, 3923 (1992).
[4] N. Asakura, S. Tsuji-lio, Y. Ikeda, Y. Neyatani, and M. Seki, Rev. Sci. Instrum. **66**, 5428 (1995).
[5] J. G. Watkins *et al.*, Rev. Sci. Instrum. **68**, 373 (1997).
[6] M. A. Pedrosa *et al.*, Rev. Sci. Instrum. **70**, 415 (1998).
[7] G. Serianni, W. Baker, and S. Dal Bello, Rev. Sci. Instrum. **74**, 1558 (2003).
[8] J. G. Bak, S. G. Lee, and the KSTAR Project Team, Rev. Sci. Instrum. **74**, 1578 (2003).
[9] L. Yan, W. Hong, J. Qian, C. Luo, and L. Pan, Rev. Sci. Instrum. **76**, 093506 (2005).
[10] K. H. Finken, S. S. Abdullaev, T. Eich, D. W. Faulconer, M. Kobayashi, R. Koch, G. Mank, and A. Rogister, Nucl. Fusion **41**, 503 (2001).
[11] K. H. Finken, Fusion Sci. Technol. **37**, 421 (2002).
[12] H. Van Goubergen, R. R. Weynants, S. Jachmich, M. Van Schoor, G. Van Oost, and E. Desoppere, Plasma Phys. Controlled Fusion **41**, L17 (1999).
[13] P. Peleman, S. Jachmich, M. Van Schoor, G. Van Oost, Czech. J. Phys. **55**, 381 (2005).