Advances in the Measurement and Control of Tokamak Edge Turbulence

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Abstract: Independent, absolutely calibrated measurements of the Mach number of the poloidal ion flow, the ion sound speed, and the radial electric field have been obtained in the CASTOR tokamak during electrode biasing experiments. Good agreement between the poloidal ion flow speed and the radial electric field everywhere in the scrape-off layer proves the existence of the EXB drift. Furthermore, the poloidal phase velocity of ion saturation current fluctuations is well correlated with these measurements, indicating that the turbulent structures evolve in a reference frame moving in the poloidal direction with a speed equal to the EXB drift. The fluctuations of electron temperature and density are reduced a factor of two during biasing.

1. Introduction

Dedicated experiments were performed in the CASTOR tokamak (R=0.4 m, a=0.085 m, B_T=1T, I_p=5-10 kA) in order to prove the existence of the EXB drift [1]. New probe diagnostics had to be developed specifically for this task. The Gundestrup probe (GP) [2] provides measurements of the Mach number of the poloidal ion flow M_θ, which needs to be multiplied by the ion sound speed c_s in order to be compared with the radial electric field E_r measured by a 16-pin rake probe (RP). The ion sound speed was estimated using electron temperature measurements (T_e) from a standard swept Langmuir probe (LP). The resulting poloidal velocity V_θ was systematically higher than the calculated EXB drift speed $V_{EXB}=E_r/B$. Further measurements of the poloidal phase velocity of ion saturation current fluctuations $V_{\theta,PHASE}$ turned out to agree nearly perfectly with V_{EXB}, which indicates that turbulent structures are "frozen" into a reference frame moving poloidally with the speed V_{EXB}. It was concluded that the most probable source of error had to be a gross overestimate of T_e by the LP which leads to unreasonably high values of c_S. A new diagnostic, baptized the "tunnel probe" (TP), [3] was developed in order to provide fast, simultaneous, dc measurements of T_e and density n_e. The TP is governed by completely different physics than the LP, and therefore consitutes an independent measurement of T_e. It turns out to measure electron temperatures that are 2-3 times lower, thereby resolving the question about the validity of the c_s estimate and bringing into agreement all three measurements of V_θ. The measurements will be described in Section 2. Electrode biasing in CASTOR provides a means to modify the E_r profile and thereby study the effect of EXB shear on plasma fluctuations. In Section 3 it is shown that fluctuations of T_e and n_e are strongly suppressed by biasing.

2. Measurements

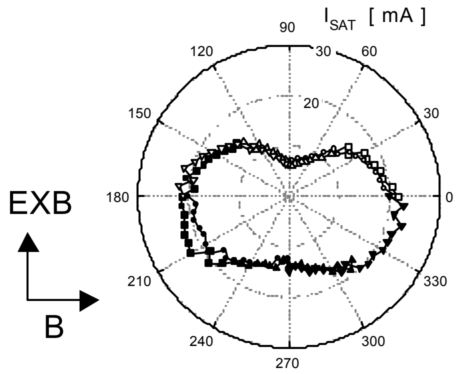
This section describes the probe diagnostics that were developed for the experiments in CASTOR, and the different physical measurements that were obtained.

2.1 Poloidal Mach Number Measurements by Gundestrup probe

Gundestrup probes [2] are used to measure ion flows in magnetized plasmas. The standard design consists of six to twelve conducting pins mounted around an insulating housing in order to obtain a significant variation of the angle between the magnetic field and the probe surface. According to fluid and kinetic modeling, the current density collected by each pin is largely determined by the Bohm-Chodura boundary condition [4]. Despite the rigour of the physics formulation, the precision of flow measurements by GPs has so far been limited to large parallel and perpendicular Mach numbers ($|M_{||}|$, $|M_\perp| > 0.1$). This is because slight angular misalignments and finite gap width between the pins and the housing cause non-negligible uncertainty of the individual effective collecting areas.

The GP design has been improved and tested in order to render it attractive for flow measurements even in unbiased edge plasmas where small poloidal flows are expected. The ion collecting surface is a nearly continuous cylindrical conductor (a copper tube of diameter 11.7 mm and length 2.2 mm) divided into eight segments separated by 0.2 mm gaps. The segments are fastened to an insulating boron nitride tube. The eight collectors are biased negatively into ion saturation in order to measure the angular distribution of ion current with good temporal resolution. A single LP tip is installed at the front end of the GP; its voltage is swept to obtain current-voltage (*I*-*V*) characteristics and calculate the plasma parameters in the proximity of the probe.

That the GP is a nearly perfect cylinder is demonstrated by rotating the probe through ±45° about its axis and comparing the polar diagrams of ion saturation current; they should be indistinguishable. This was verified on a series of reproducible discharges in CASTOR (Fig. 1). The GP was placed at r=78 mm and rotated 5° between discharges. The eight curves of ion current overlap nicely. Minima of ion current occur at 90° and 270° where the magnetic field is nearly tangent to the surface. The magnetic field pitch angle is about 2° due to the high safety factor (q~10), so we simply equate the toroidal and parallel directions because that angle happens to be about the same as the accuracy of our angular positioning system.We conclude that the goal of building a probe with a simple, ideal geometry has been achieved, thereby eliminating a major source of uncertainty and permitting the direct application of modeling of magnetized ion mass flow onto a conducting cylinder. From these data, the Mach number of the poloidal (perpendicular) ion flow is derived by fitting to the models [4].



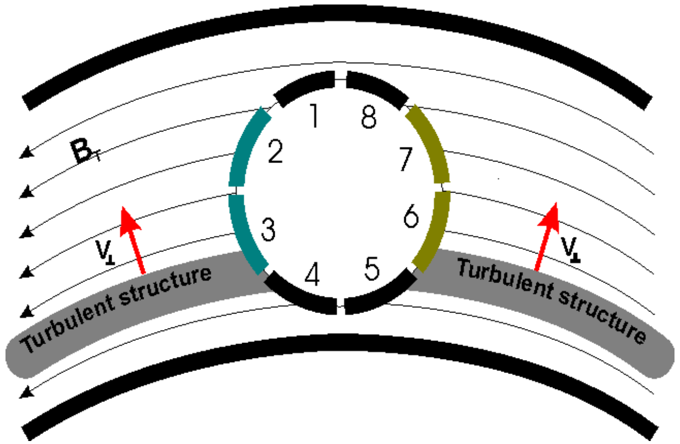


FIG. 1. Ion current collected by the 8 segments of the GP as a function of angle. Each symbol corresponds to one of the segments.

FIG. 2. Schematic of GP collector orientation in CASTOR. Cross correlation measurements between segment pairs 2-3 and 7-6 give the poloidal phase velocity of ion current fluctuations.

2.2 Poloidal Phase Velocity Measurements by Gundestrup Probe

The GP is also used as a poloidal array in order to compare the measured ion mass flow V_θ with the phase velocity of fluctuations $V_{\theta,\mathrm{PHASE}}$ moving poloidally across the collectors (Fig. 2). The signals from the most upstream and downstream pairs of the segments are recorded with a sampling rate of 5MHz. Then, the cross-correlation function is calculated and the transit time of a poloidally localized structure across the corresponding segments is deduced from the shift of its maximum. The phase velocity of fluctuations is calculated as the ratio of the distance between the adjacent segments (4.5 mm in our particular case) and the transit time.

2.3 Radial Electric Field Measurements with Rake Probe

The radial electric field is deduced from the radial profile of the floating potential V_f measured by the means of a 16-pin RP (Fig. 3). It is seen from the figure, the gradient of V_f is enhanced with biasing (U_b= +100 V) at both sides of the electrode, i.e. in the SOL as well as inside the separatrix. The radial electric field is calculated following the expression $E_r=-(\nabla U_{fl}+\alpha\nabla T_e)$ where the factor α is rather uncertain in magnetized plasmas [5] and ranging from 1.3 to 3. As seen from the left panel of Fig. 3, the actual radial profile of T_e must be taken into account because of rather large local gradients observed within the separatrix (∇T_e ~ -2 V/mm), but also in the SOL (-1V/mm). However, these numbers might need to be revised in light of the new electron temperature measurements that are presented in Section 2.5.

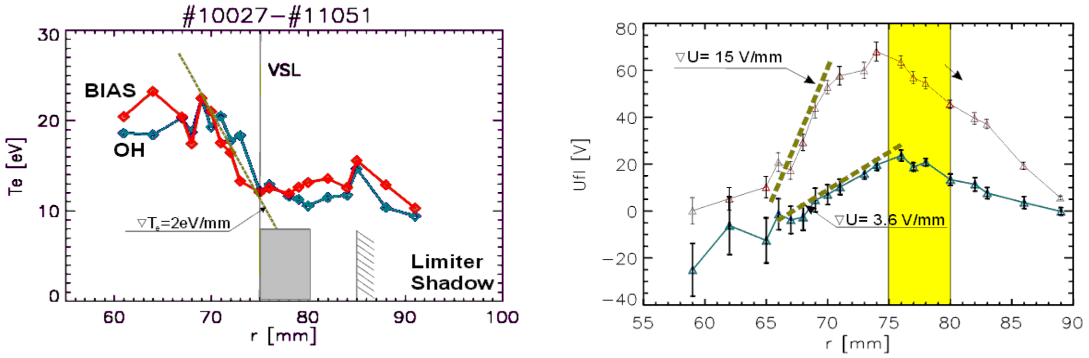


FIG. 3. Radial profile of T_e (left) and V_f (right) in ohmic and biased phase of discharges measured by the LP located at the tip of the GP. Position of the separatrix is at r=75 mm, which corresponds to the location of the tip of the biasing electrode. The radial extent of the biasing electrode is marked by the yellow box.

2.4 Comparison of the Flow Measurements

The poloidal flow V_θ has been measured by three independent methods. The results are compared in Fig. 4. The $V_{\theta,\mathrm{PHASE}}$ measurements agree well with the V_{EXB} drift calculated using E_r as measured by the RP. This indicates that the turbulent structures are "frozen" into a reference frame moving poloidally at the EXB drift speed. However, the GP poloidal flow measurements appear to be systematically higher. Since the GP only measures a dimensionless Mach number, a measurement of c_s is needed in order to convert the M_θ measurements into absolute velocity. This was obtained in [1] from LP measurements of T_e. If, on the other hand, we take M_θ and E_r to be correct, we can calculate c_s. This is a little bit complicated because T_e appears in the expression for E_r, but it turns out that in order to explain the observed discrepancy, the correct T_e would have be 2-4 times lower than that given by the LP. In the next section we show that this may actually be the case.

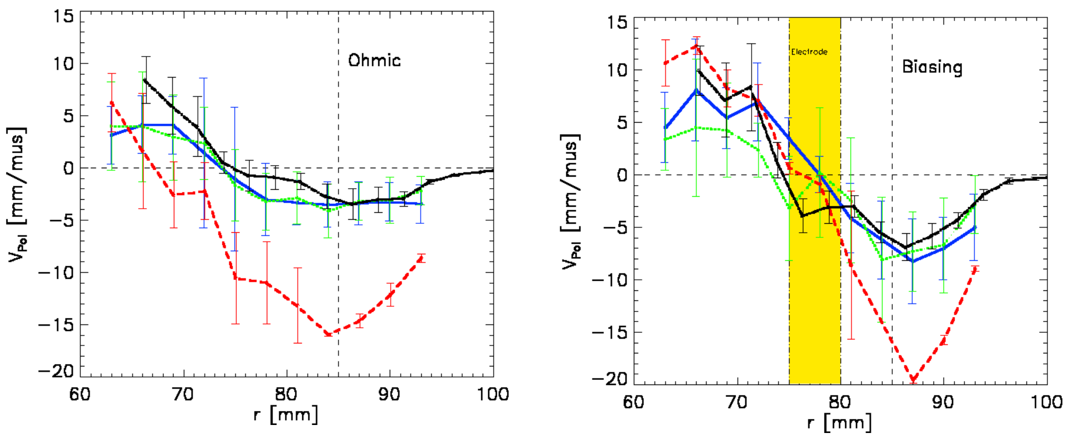


FIG. 4. Radial profile of fluctuation velocities (blue and green lines), and flow velocity (red line) measured by the GP. The black line is the ExB velocity deduced from the RP data. Left: ohmic phase of the discharge. Right: Biased phase of the discharge.

2.5 Electron Temperature and Density Measurements withTunnel Probe

The tunnel probe [3] is a new kind of LP for use in the tokamak scrape-off layer (SOL). It provides simultaneous dc measurements of electron temperature T_e and parallel ion current density $J_{//}$ at the same point in space. It consists of a hollow conducting tunnel a few millimetres in diameter and typically 5 mm deep that is closed at one end by an electrically isolated conducting back plate. Both conductors are biased negatively to collect ions and repel electrons. The tunnel axis is parallel to the magnetic field. Plasma flows into the open orifice and the ion flux is distributed between the tunnel and the back plate. The ratio of the two ion currents is determined by the magnetic sheath thickness at the concave surface of the tunnel, and is therefore a strong function of T_e. The self-consistent, two-dimensional kinetic code XOOPIC [6] is used to determine the theoretical relation between the current ratio and T_e. Combined with the measured sum of the two currents, n_e at the sheath entrance can also be estimated. The kinetic simulations and a convincing experimental validation in the Tore Supra tokamak have already been published [7]. A detailed description of the CASTOR TP and related design issues were reported in Ref. [3].

The physics governing the TP is fundamentally different than for a classical LP. The applied voltage on the LP is swept at 1 kHz in order to measure a restricted part of the electron distribution function. The TP, on the other hand, is biased to a fixed potential that is sufficiently negative to repel all electrons. The temperature of the electrons is measured even though none are collected. It is necessary to compare the two methods. This was done during a radial scan of the TP. The back plate was biased to -100 V, whereas the tunnel was swept as a LP. The I-V characteristics were analyzed to give standard LP T_e measurements, and the ion saturation branch was used for TP current ratio analysis. We thus obtain simultaneous, independent measurements of T_e at the same point in space. It is systematically observed that the TP evaluation of T_e is 2-3 times lower than the LP. One possible reason is that since the sweep frequency of the LP is comparable to the typical frequency of density, temperature, and potential fluctuations in the plasma, the fitted I-V characteristic rectifies these values and produces results that are higher than the time average. This problem is still under investigation. For now, it suffices to say that most mechanisms that we have considered predict that the LP should overestimate the real T_e, and that the TP is more reliable. The ion sound speed calculated with these new T_e measurements results in lower GP flow measurements, and brings them into good agreement with the RP.

3. Reduction of Turbulence by Electrode Biasing

The first analysis of electron temperature and density fluctuations measured by the TP indicates a strong reduction of the level of turbulence during electrode biasing. In this experiment, the biasing electrode was placed at the separatrix (r=75 mm) and biased to +100 V. The radial electric field was calculated using the V_f profile measured by the RP and the mean T_e profile from the TP. Both T_e and n_e fluctuations are strongly reduced in the SOL (Fig. 5).

4. Summary

Measurements in the CASTOR tokamak confirm that the poloidal ion flow speed is equal to the EXB drift. Turbulent structures appear to move at the EXB drift speed in the poloidal direction. Electrode biasing causes significant reduction of electron temperature and density fluctuations in the SOL.

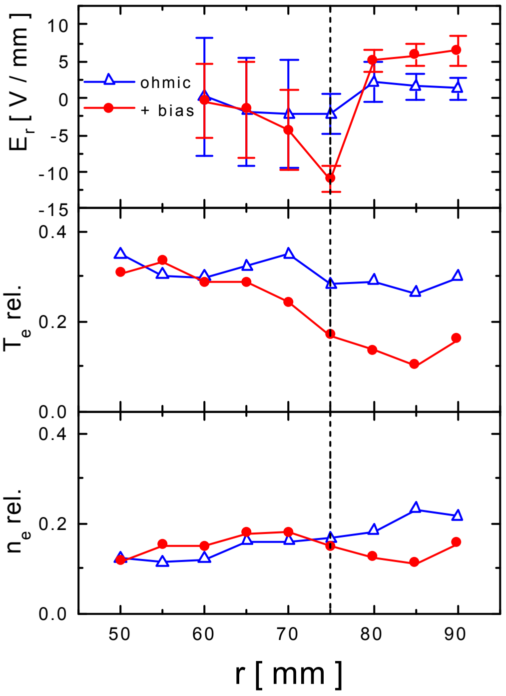


FIG. 5. Top panel: radial electric field before (open triangles) and during (close circles) biasing. Middle panel: relative fluctuation amplitude of electron temperature. Bottom panel: relative fluctuation amplitude of electron density.

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