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Experimental study on neoclassical properties of the ions in the edge plasma of the tokamak TEXTOR

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Abstract

The ions in the edge plasma in front of the limiter ALT II in Ohmic discharges of TEXTOR are in the banana/plateau regime. The qualitative dependencies of the ion speed parallel to the magnetic field are the same as those expected from neoclassical theory. Significance of charge exchange collisions for the loss of toroidal angular momentum is presented. With reasonable assumptions for the density of the deuterium atoms also quantitative agreement between the experimental and theoretical ion drift speeds can be achieved.

Keywords: TEXTOR; Boundary plasma; Momentum balance; Neoclassical transport; Neutral confinement and transport

1. Introduction

The transport in the edge plasma of tokamaks determines plasma fueling, particle exhaust, wall loading and can influence significantly the properties of the core plasma as e.g. in L–H mode transitions. Ion flows parallel to the magnetic field play an important role in this transport and have been observed also in several other tokamaks, e.g. Alferov et al. [1]. The Mach number of the ion flow can reach values near $M = 1$, i.e., the energy density of the flows can attain values of the order of the thermal energy, [2]. Flows can lead to significant asymmetries of the energy load on the wall and of particle exhaust of pump limiters.

The signatures of the flows on the two sides of the separatrix determined by the leading edge of the limiter ALT II in TEXTOR have been found to be quite different [2]. The ions in the edge plasma in front of ALT II are in the banana/plateau regime and the electrons are in the Pfirsch–Schlüter regime as concluded from the experimental values of the collisionalities. In this region the observed ion drift speeds parallel to the magnetic field have qualitatively the same properties as expected from neoclassical theory: The direction of the speed is the same as that of the induced plasma current and is independent of the direction of the toroidal magnetic field. Quantitatively the agreement between the experimental and theoretical drift speeds, Hinton and Hazeltine [3], is satisfactory for lower densities but the respective ratio tends to zero for higher densities. In the present paper evidence is presented that the discrepancy at the higher densities is to a large extent due to charge exchange collisions between the deuterons and atomic deuterium.

2. Experimental set-up and diagnostic methods

The measurements have been performed in the tokamak TEXTOR. The major radius is 1.75 m and the ALT II radius is 0.467 m. For this study the toroidal magnetic field was 2.25 T, the induced plasma current 0.34 MA and the pulse length of a discharge was about 6 s. The results

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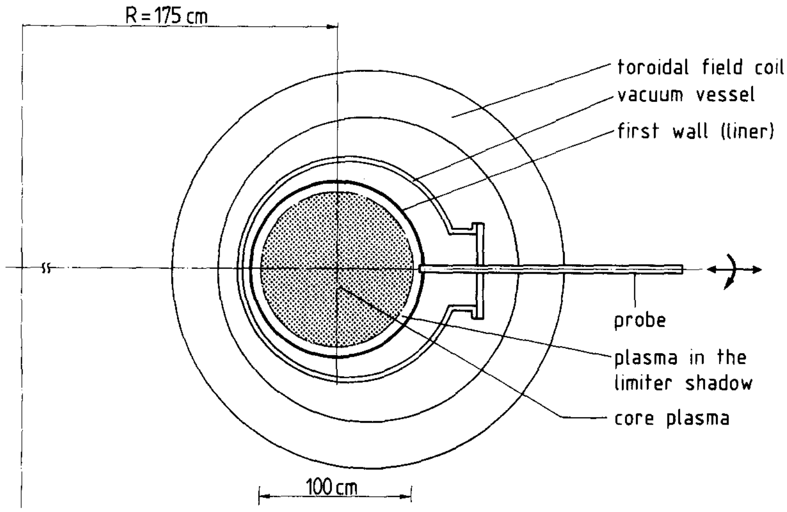

Fig. 1. Position of the rotating electrical double probe on TEXTOR.

were obtained in Ohmic discharges with a power of 0.4 MW. The averaged core density $\langle n_e \rangle$ varied between $(1 \ldots 4)\ 10^{19}\ \mathrm{m}^{-3}$, the electron temperature on axis between $T_e(0) = 1.3$ and 0.7 keV, and Z_{eff} between about 3 and 1.

Most of the results rely on measurements by means of the rotating electric double probe, operated in the equatorial plane, Fig. 1. It was rotated during the discharge around its axis with a frequency of 2 Hz and allows to determine in a magnetized plasma the calibrated density, the electron and ion temperatures, the floating potential and the Mach number of the ion flow parallel to the magnetic field (cf. references in [2]). The ion temperature was also measured by means of Lithium-beam-activated-charge-exchange spectroscopy [4]. The recycling deuterium flux density is inferred from emission spectroscopy on D_α. The measurements were performed during the stationary phase of the discharges.

3. Experimental results

The ion speed parallel to the magnetic field measured in the edge plasma, 1.7 cm in front of the ALT II limiter, [2], is compared in Fig. 2 with the neoclassical prediction of [3],

$$\langle v_{i,\parallel} \rangle = \frac{kT_i}{ZeB_\theta}\left[\alpha \frac{\partial \ln T_i}{\partial r} - \frac{\partial \ln p_i}{\partial r} + \frac{Ze}{kT_i} E_r\right] \qquad (1)$$

taking the local value. The main contribution to the theoretical value of the ion speed is due to the grad n term, the next largest, the $E \times B$ term, is about one order of magnitude smaller. The term $\alpha(\partial \ln T_i / \partial r)$ was always negligible. There is good agreement between experimental and theoretical results for low density. The divergence with increasing density is presumably caused by the increasing loss of toroidal angular momentum due to the increasing frequency of charge exchange collisions which are not included in theory [3]. This statement is supported by the observation that the recycling of deuterium at the limiters increases with increasing mean core density, Fig. 3.

Valanju et al. [5] have extended neoclassical theory for the toroidal ion flow by including losses of toroidal angular momentum due to charge exchange collisions and obtained a velocity which is by a factor D,

$$D = \left[1 + \left(\frac{2}{\sqrt{\pi}}\right)\left(\frac{\nu_x}{\omega}\right)\left(\frac{R}{r}\right)^2\right]^{-1} \qquad (2)$$

smaller than that given by Eq. (1). ν_x being the charge exchange frequency, ω = mean transit frequency of the ions from the outboard to the inboard of the torus, q = safety factor, and R = major radius.

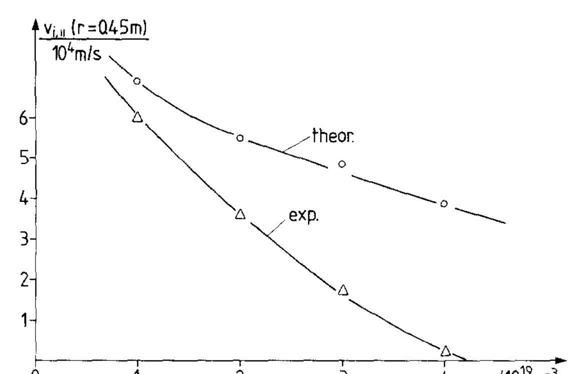

Fig. 2. Experimental and theoretical ion drift speeds parallel to the magnetic field as functions of the mean core density.

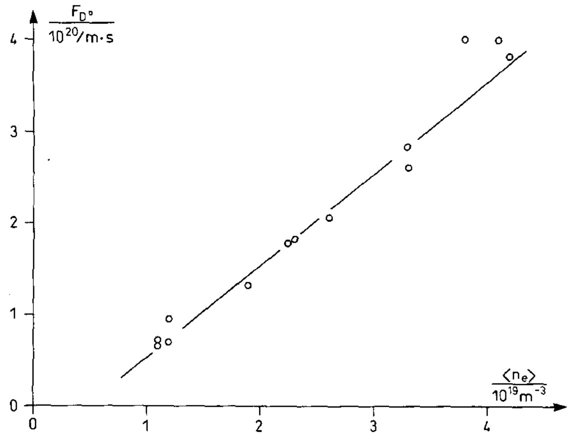

Fig. 3. D^0 flux at the limiter ALT II (integrated over its poloidal width) as function of the mean core density.

Assuming that the charge exchange collisions are the dominant effect we have determined the density of atomic deuterium n_{D^0} to get agreement between the experimental and theoretical ion drift values, Fig. 4. The order of magnitude of the obtained neutral density $O(10^{16}\ m^{-3})$ seems to be reasonable.

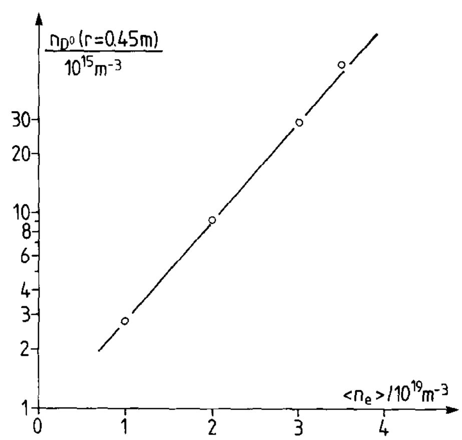

Fig. 4. Flux surface averaged density of D^0 as function of the mean core density.

It is important to note that the mean free path for D^+–D^0 collisions is larger than the circumference of the torus which implies that the determined values of the atomic deuterium n_{D^0} are values averaged over the flux surfaces of the ions. Since the mean free path for ionization is only a few cm the density n_{D^0} within a flux surface is very inhomogeneous. However, the flux averaged values seem to be of particular interest for further studies of transport in tokamaks.

The relative increase $d(\ln n_{D^0})/d\langle n_e \rangle$ over the mean core density range is larger than the relative increase of the recycling D^0 flux at ALT II $d(\ln F_{D^0})/d\langle n_e \rangle$ by $\leq 20\%$. (This trend is considered to be significant although the error of a single value is estimated to be of the same order.) The penetration depth of the D_α light emitting atoms decreases with increasing density so that the change of the ionization length does not explain the different rates of increase; therefore besides charge exchange collisions other effects should contribute more and more with increasing density, e.g. orthogonal viscosity or magnetic pumping due to the magnetic ripples, Boozer [6]. Therefore the n_{D^0} values of Fig. 4 are expected to be upper limit values. Concluding, it seems to be worthwhile to study the possibility of steering the transport of toroidal angular momentum of the ions in the edge plasma by steering the D^0 density in further detail but also to follow the indication that other processes than charge exchange become increasingly important with increasing plasma density.

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