Ambipolar Electric Fields and Transport

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I. Introduction

In the W VII-A Stellarator with large aspect ratio ($A = 20$), very small helical field ripple and nearly perpendicular neutral beam injection (NI) heating, radial electric fields have strong influence on the confinement properties. From Doppler shift measurements of impurity lines, a large poloidal plasma rotation ($v_{EXB} \sim 10 - 30$ km/s) was derived which is associated with the NI heating power and with strong pressure gradients. The large ambipolar electric fields, which reduce significantly the deviations of particle orbits from the magnetic surfaces, lead to an increased heating efficiency of the NI /1/ and to an improved particle confinement ($\tau_p \sim 100$ ms). Also in ECR heated discharges ($f_{ECRH} = 70$ GHz) poloidal plasma rotation ($v_{EXB} \sim 10$ km/s) was found at higher plasma densities ($n_e \sim 5 \times 10^{13}$ cm^{-3}).

The influence of the ambipolar electric fields on transport in the plateau regime is described within neoclassical theory by a simple model. Based on this model, the ambipolar electric fields are calculated for an ECR heated discharge. The influence of these fields for reducing the heat conduction of the thermal ion component in NI discharges as well as the impurity transport is briefly discussed.

II. Model of transport in the plateau regime

For simplicity, we assume an axisymmetric magnetic field model and use the Krook collision term. The stationary drift kinetic equation

$$(\underline{v}_{\parallel} + \underline{v}_D)\cdot\underline{\nabla} f = - \nu \, (f - f^{Max}) \qquad (1)$$

is linearized with the ansatz $f = f^{Max} + f_1$, and only the ambipolar potential $\Phi(r)$ is taken into account for calculating the drift velocity $\underline{v}_D = \underline{v}_{EXB} + \underline{v}_{\nabla B}$. The solution of eq. (1) is well known /2/:

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*) see paper W VII-A Team, NI Team, ECRH Team "Influence of the Magnetic Configuration on Plasma Behaviour in the WENDELSTEIN VII-A Stellarator", this conference

$$f_1 = \frac{v_{th}}{\iota\,\omega_c} \cdot \frac{\nu^* \sin\theta - (c_\parallel + \gamma)\cos\theta}{(c_\parallel + \gamma)^2 + \nu^{*2}} \cdot (c_\parallel^2 + \tfrac{1}{2} c_\perp^2) \cdot \left[\frac{n'}{n} + \frac{q\Phi'}{T} + (c^2 - \tfrac{3}{2}) \frac{T'}{T} \right] f^{Max} \tag{2}$$

with $c = v/v_{th}$, rotational transform ι, collisionality $\nu^* = R\nu/\iota v_{th}$ and the poloidal drift parameter $\gamma = R\Phi'/\iota r B_o v_{th}$, all other quantities have the usual meaning. The radial fluxes are averaged over the magnetic surfaces and the particle flux Γ and the heat flux Q are given by:

$$\begin{aligned} \Gamma &= -\,n \left\{ D_n \left(\frac{n'}{n} + \frac{q\Phi'}{T}\right) + D_T \frac{T'}{T} \right\} \\ Q &= -\,nT \left\{ \chi_n \left(\frac{n'}{n} + \frac{q\Phi'}{T}\right) + \chi_T \frac{T'}{T} \right\} \end{aligned} \tag{3}$$

with the transport coefficients: $\left(\alpha = \dfrac{V_{th}^3}{2\iota R \omega_c^2} \right)$

$$\begin{aligned} D_n &= \alpha(1/2\ G_o + G_2 + G_4) \\ D_T &= \alpha(3/4\ G_o + G_2 + 1/2\ G_4 + G_6) \end{aligned} \tag{4a}$$

$$\begin{aligned} \chi_n &= \alpha(3/2\ G_o + 5/2\ G_2 + 2\ G_4 + G_6) \\ \chi_T &= \alpha(15/4\ G_o + 21/4\ G_2 + 7/2\ G_4 + 3/2\ G_6 + G_8). \end{aligned} \tag{4b}$$

The function $G_m\ (\gamma + i\nu^*)$ is the Hilbert integral transform of the moments of the Gaussian:

$$G_m\ (\gamma + i\nu^*) = \frac{1}{\sqrt{\pi}} \operatorname{Im} \left\{ \int_{-\infty}^{\infty} \frac{x^m\ e^{-x^2}}{x - (\gamma + i\nu^*)}\, dx \right\}.$$

For small values $\gamma \ll 1$ and $\nu^* \ll 1$, the transport coefficients in eq. (4) become constant, whereas for large values $\gamma \gg 1$ or $\nu^* \gg 1$, the transport coefficients are proportional to $\nu^*/(\gamma^2 + \nu^{*2})$. Due to the large aspect ratio of W VII-A, the poloidal drift parameter $\gamma \propto A/\iota$ is much greater than in usual tokamaks.

The model outlined above is restricted to the Plateau regime. For most of the W VII-A discharges, the electrons as well as the thermal ions are within the Plateau regime, whereas impurities are close to or within the Pfirsch-Schlüter regime. Thus, for investigating the impurity transport, the model had been generalized. A 1st order density correction $n_1(r,\theta)$ in the collision term and small nonambipolar potentials $\Phi_1(r,\theta)$ had been included in the linearisation of the drift kinetic equation (1). The densities $n_{1\alpha}$ for all particles species α (= e,i,z) are calculated by means of the parallel force balance equation with the Braginskii friction term with parallel velocities $V_{\parallel\alpha}(r,\theta)$ estimated from the continuity equation. The 1st order potential Φ_1 is determined by the quasi-neutrality condition $\sum q_\alpha \cdot n_{1\alpha} = 0$. For doing this, the full linear equation system (for all species α) is solved yielding the fluxes Γ_α and Q_α depending on the ambipolar field Φ'. Neglecting impurities, the parallel force balance equation can be replaced by the generalized Ohm's law yielding an analytical expression for Φ_1 which drive the Pfirsch-Schlüter diffusion.

The high energetic ions of the NI (up to 27 keV) with small parallel velocities have large deviations from magnetic surfaces and can be lossed directly (~ 10 cm plasma radius in W VII-A). Neoclassical theory is based on the assumption of distribution functions close to Maxwellians, this includes that the step size of the transport process is very small compared with the radial plasma size. The beneficial effect of strong ambipolar electric field on the confinement of these ions had been demonstrated by Monte Carlo simulations /1/, however, this effect cannot be described by neoclassical theory. Thus, we are restricted to the estimation of the thermal loss fluxes.

The ambipolar electric fields are calculated from the condition of ambipolarity of the particle fluxes $\sum q_\alpha \Gamma_\alpha = 0$. Fits to experimental data are used for the density and temperature profiles.

III. ECR heated discharges

Strong poloidal plasma rotation was observed in ECR heated discharges (2.5 T; 70 GHz; $P_{RF} \sim 160$ kW) with higher plasma densities ($n_e \sim 5 \times 10^{13}$ cm^{-3}). The profiles in Fig. 1 are fits to n_e and T_e data measured by Thomson scattering and to T_i measured by CX analysis and by Doppler broadening of the C^{4+} impurity line. For these profiles, the ambipolar electric field has been calculated (Fig. 2), experimental data for E_r at 2 radii are derived from the Doppler shift measurements. These values are calculated from the poloidal rotation velocity where the diamagnetic drift velocity of the C^{4+} ions is included, v_{dia} was estimated assuming a corona model. This procedure yields a lower limit for the radial electric fields.

In Fig. 3, the ion heat conduction coefficient χ_T (comp. eq. 4) is shown. In these ECRH discharges, however, the ion heat conduction has only small influence, since the ion energy balance is dominated by collisional ion heating and CX losses.

IV. NI heated discharges

In discharges heated by neutral beam injection the measured poloidal plasma rotation was significantly larger than the calculated one for thermal plasmas. Monte Carlo simulations indicate that the ambipolar electric fields are driven by the fast ions of the NI slowing down distribution. The electric fields derived from the measurements lead to a very strong reduction of the ion heat conduction. For the high ion temperatures ($T_i \sim 1$ keV), the ion energy balance is mainly determined by collisional heating of the NI slowing down, the collisional cooling by the electrons ($T_e < T_i$) and the reduced ion heat conduction /3/.

V. Conclusions

In the plateau regime the transport coefficients can be strongly reduced by poloidal plasma rotation which is driven by ambipolar electric fields. This effect becomes important with large aspect ratio and low rotational transform and is confirmed in the W VII-A Stellarator. For Maxwellian plasma distributions, the measured rotation is in agreement with theoretical predictions based on neoclassical theory. Furthermore, calculations indicate a reduced impurity transport due to the poloidal plasma rotation.

References

/1/ F.P. Penningsfeld et al., Computation of Fast Ion Confinement by Electric Fields in W VII-A Stellarator, paper No. 210, this conference

/2/ T.E. Stringer, International School of Plasma Physics (1971); Course on Instabilities and Confinement in Toroidal Plasmas, p. 109

/3/ W VII-A Team et al., Plasma Confinement and the Effect of Rotational Transform in the WENDELSTEIN VII-A Stellarator, IAEA-CN-44/DI1, London 1984

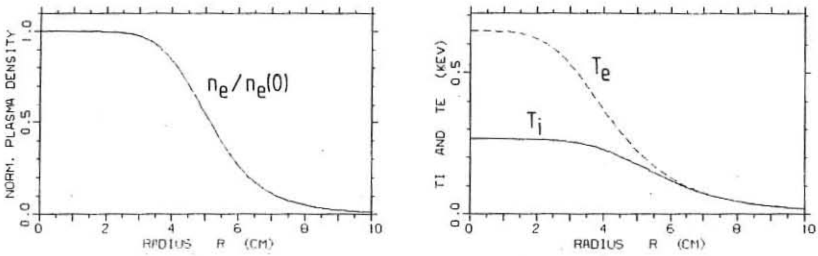

Fig. 1: Density and temperature profiles of an ECRH discharge (2.5 T, 70 GHz) used for the calculations.

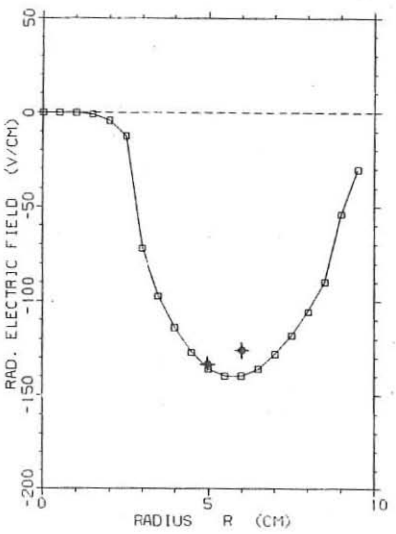

Fig. 2: Ambipolar electric fields calculated by means of $T_e = T_i$.

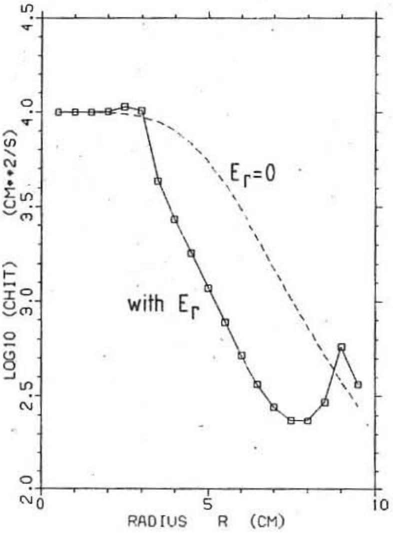

Fig. 3: Ion heat conduction coefficient χ_T with the ambipolar electric fields of Fig. 2.