SPECTROSCOPIC MEASUREMENT OF THE NON-THERMAL ELECTRON-ROOT FEATURE IN W7-AS

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1. Introduction

In the advanced stellarator W7-AS [1], the radial electric field E_r [2] is measured by active charge exchange recombination spectroscopy (CXRS) [3] on He III: radial profiles of the poloidal and toroidal rotation velocity, the ion temperature and the helium density are determined after CX in a modulated diagnostic beam [4]. Then the radial force balance equation is solved with these measured data, providing radial profiles of E_r. In parallel, neoclassical DKES (Drift kinetic equation solver) transport calculations [5] are performed, taking into account the W7-AS magnetic field geometry [6]. DKES provides, among other things, the neoclassical transport matrix as a function of the minor plasma radius, the collisionality and E_r. The ambipolarity condition of the thermal particle fluxes is then solved to determine the neoclassical radial electric field. The measured and calculated E_r are compared [7]. In general, consistency is found. The total number of possible solutions for the ambipolarity condition, the so-called roots, is always odd. At W7-AS, for most discharges the ion-root is predicted by DKES and measured by CXRS, showing strongly negative E_r in the gradient region and small negative or slightly positive values near the plasma center. The strongly positive electron-root, which is expected to show some favourable plasma properties [13], is predicted by DKES for the close vicinity to the magnetic axis. However, only in a few cases with particular discharge conditions those positive E_r could be observed experimentally. Outward drifts of trapped suprathermal electrons are assumed to be decisive for the ambipolarity condition, rather than thermal electron fluxes [8]. To attain the desired electron-root in W7-AS, two heating scenarios (70 and 140 GHz electron cyclotron resonance ECRH) are available.

2. The ECRH driven electron-root at 140 GHz

Strongly positive E_r, as described above, are observed in W7-AS for 140 GHz ECRH second harmonic X-mode discharges at 2.5 T with perfectly located on-axis deposition. Up to + 600 V/cm are measured by CXRS close to the magnetic axis at minor radii $r < 5$ cm. An example for such a discharge with an ECRH power of 760 kW at low density is shown in Figure 1 below. The high central electron temperatures T_e (upper left) result from the strongly positive E_r (lower left) reducing the central electron heat diffusivity χ_e (lower right). This is confirmed by the steepened $\nabla T_e(r \approx 3$ cm). The experimental heat balance analysis (dot-dashed) comes much closer to the neoclassical calculation for the ambipolar E_r (crosses) than to the calculation for $E_r = 0$ (points), supporting the existence of the strongly positive E_r. However, the χ_e agreement near the plasma center is not perfect, possibly indicating that the neoclassical DKES results are not valid for such strong E_r and high rotation velocities. For higher ECRH power (up to 1.25 MW), the electron-root is maintained even for higher electron densities $n_e(0)$ up to $\approx 7 \cdot 10^{19}$ m^{-3}. For low $n_e(0) \approx 2 \cdot 10^{19}$ m^{-3}, $T_e(0)$ up to ≈ 6 keV are achieved.

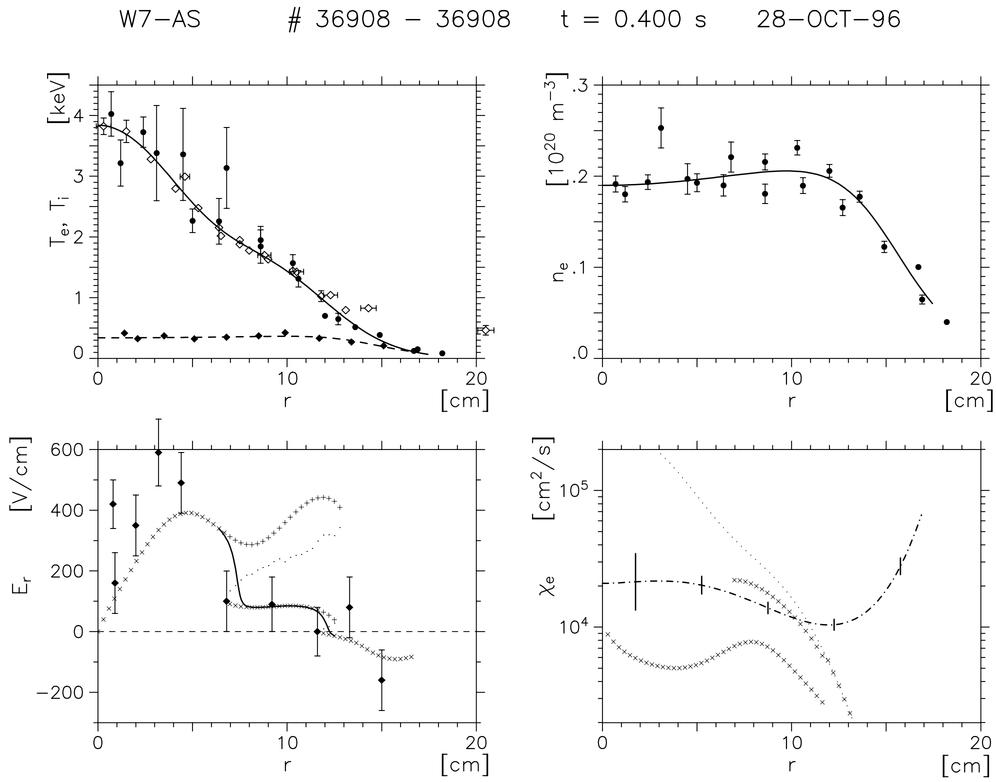

Figure 1: Upper left: electron temperature (solid line), ion temperature (broken line). Upper right: electron density. Lower left: radial electric field (dots: CXRS, crosses and points: neoclassical calculation). Lower right: electron heat balance (dot-dashed: experimental, crosses and points: neoclassical calculation).

For r > 6 cm, the neoclassical ion-root with small E_r is predicted by DKES (lower left, crosses) and measured by CXRS (lower left, dots). For r < 5 cm, CXRS measures positive E_r consistent to the neoclassical electron-root solution calculated by DKES. From Monte-Carlo simulations [9], however, it is found that the radial electron fluxes being decisive for the ambipolarity condition in this case result from outward drifting suprathermal trapped electrons, created by the highly localized ECRH in the local magnetic field minimum in the ECRH launching plane. Hence the strongly positive E_r can be driven by that 'convective' contribution, rather than by thermal fluxes alone (as assumed by DKES). This is supported by the fact that the strongly positive E_r can be removed experimentally by removing this local magnetic field minimum, thus reducing the fluxes stemming from the population of trapped suprathermal electrons [11] (an effect which is not predicted by DKES). The electron cycclotron emission ECE measurements reveal two different time scales for the T_e decay directly after switching the ECRH power off [8]: in central radial regions with the strongly positive E_r a rapid decay (during less than 1 ms due to the instantaneously missing suprathermal fluxes, hence collapsing positive E_r followed by an instantaneously increasing χ_e) is followed by a slower decrease on a time scale comparable to the radial region outside the electron-root (a behavior which is also not predicted by assuming thermal electron fluxes alone).

3. The electron-root with 70 GHz

Up to now, the purely thermal electron-root could not be realized free from any doubt experimentally in W7-AS. This is in contradiction to DKES calculations, which predict the appearance of the electron-root for low density ECRH discharges from the thermal fluxes only. To come closer to a situation where the thermal electron fluxes are more decisive for the ambipolarity condition, low density discharges with 70 GHz O-mode at 2.5 T with 370 kW are performed. They have reduced suprathermal electron fluxes roughly by a factor of 2-3 in comparison to 140 GHz [9] and, hence, higher significance of thermal fluxes. High helium concentrations (about 30%) are maintained to provide a good signal-to-noise ratio for CXRS. During magnetic field B scans the ECRH power deposition zone is shifted across the magnetic axis. The T_e profiles are monitored by ECE during these scans to control for the power deposition. For perfect on-axis deposition the central driven electron fluxes are maximum, providing the best chances for the formation of the electron-root. During these scans, T_i , E_r and the density of He III (in arb. units) are measured by CXRS. For the electron-root, increased $T_i(0)$ is expected because of the reduced χ_i as a consequence of the strong central E_r. It is still subject to investigations why this effect cannot be observed for the 140 GHz electron-root. In parallel, the impurity density profiles are expected to become hollow as result of the outward convection due to their high Z . That effect has already been demonstrated on He^{++} experimentally with the positive ion-root in W7-AS [10] and for the 140 GHz electron-root as shown above. Following neoclassical calculations alone, the impurity density should be reduced almost to zero in vicinity of the axis. The experimentally observed density reduction, however, is less pronounced. As we perform CXRS on He III, we use that ion species to monitor the radial He III density profile. VUV measurements, radially resolved soft-X after ablation of Al and C, as well as bolometry are used additionally to measure the expected outward convection. Figure 2 shows some results of the B scans. Perfect on-axis deposition is sustained for B ≈ 2.55 T, as supported by ECE. Maximum $T_e(0)$ ≈ 3.5 keV are obtained, slightly less than for the 140 GHz electron-root. A strongly positive E_r (r = 1.6 cm) is observed by CXRS up to +550 V/cm at 2.55 T (plot in the middle), E_r(r = 1.6 cm) ≈ 0 V/cm is found for off-axis deposition. As expected, T_i(r = 1.6 cm) increases considerably (left plot) for on-axis, measured by CXRS as well as by CX neutral particle energy analysis. The He III density profile (right plot, inv. density peaking factor) becomes hollow for on-axis deposition. Unfortunately, these findings are restricted to an extremely narrow zone very close the magnetic axis (r ≈ 1-3 cm), thus making conclusions difficult; especially for the line integrated soft-X and VUV data. The spatial resolution for CXRS is restricted to about ± 1 cm. The expected outward convection of impurities might, to a considerable amount, be compensated by enhanced anomalous central impurity particle diffusivities observed at low n_e [12], resulting in less hollow impurity density profiles than expected from neoclassical considerations alone. This is confirmed by impurity transport calculations, taking into account this high central diffusivity (D up to ≈ 2-3 m^2/s being a factor ≈ 10 larger than the neoclassical prediction). Together with the outward convection resulting from the observed ≈ +550 V/cm the measured He^{++} density profiles are well reproduced by this calculation. A heat balance analysis, as performed for the 140 GHz electron-root, is impossible for this case because only two ECE measurement points are within the interval with positive E_r. Increasing the heating power to expand the radial zone is impossible because the 370 kW used for the scans are the maximum for the 70 GHZ gyrotrons available at W7-AS. Reducing the electron density to enhance the observed effects is not possible because of the wall recycling fluxes, and because a minimum He density has to be maintained to allow for the CXRS measurements with a reasonable signal-to-noise ratio. The fast central T_e decay after switching the ECRH off, as described for the 140 GHz electron-root, are found for the 70 GHz discharges, too.

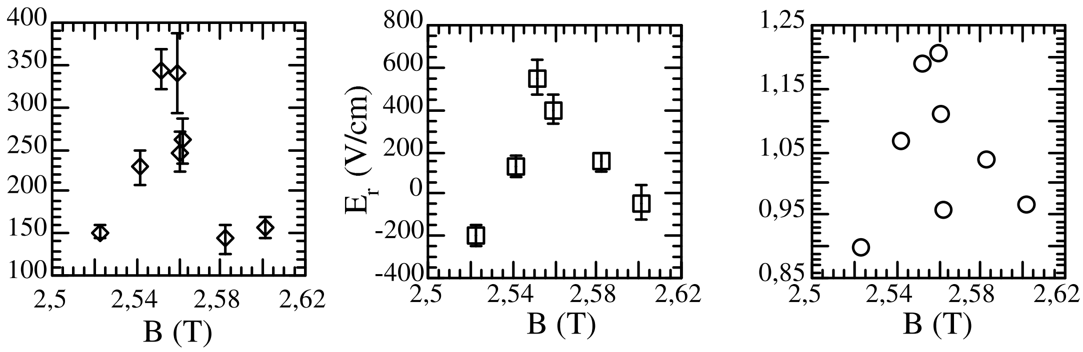

Fig. 2: Left: central ion temperature, middle: central radial electric field, right: inverse density profile peaking factor for He III. All versus the magnetic field strength measured at r = 1.6 cm.

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