Core Confinement in Wendelstein 7-X Limiter Plasmas

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Wendelstein 7-X (W7-X) was built to assess the concept of optimized stellarators at reactor-relevant values of both collisionality and plasma beta. It is a first-of-its-kind experiment in a possible line of optimized, helical-axis advanced stellarators (HELIAS [1]). The mission of W7-X is the assessment of the HELIAS line as an alternative route to fusion electricity.

The first operation phase of W7-X was performed from Dec. 10, 2015 until Mar.10, 2016. Top priorities for the first plasma operation were integrated commissioning, testing components, diagnostics and device control [2]. Any proof of stellarator optimization, however, was not expected in the first campaign since sufficient densities and plasma beta values could not be achieved in this phase. Nevertheless, the investigation of typical features of stellarator transport physics could be conducted at the attainable low densities once device conditions allowed sufficiently long, stable discharges. This paper addresses a prominent feature of long-mean-free-path physics in stellarators, the core electron-root confinement (CERC) [3] resulting from stellarator-specific non-intrinsically ambipolar particle fluxes. CERC has been observed in other stellarators and heliotrons [3, 4]. Its specific characteristics are peaked electron temperature profiles with high central values along with positive radial electric fields $E_r > 0$ - large enough in magnitude to strongly reduce both ion and electron neoclassical transport coefficients. In preparation of the experiments reported here, transport simulations with a neoclassical transport code [5] predicted CERC for the experimental settings reported here. Theory predicts gyrokinetic turbulence has no effect (in leading order) on E_r, even if most of the energy transport is turbulent [6].

In the first experimental campaign of W7-X [7], one specific magnetic field configuration was mainly used to avoid detrimental plasma interaction with the metallic walls. The rotational transform of this configuration at the edge was $\iota_a > 5/6$ with the 5/6 island chain lying within the last-closed flux surface [8]. Five inboard graphite limiters defined the last closed flux surface at an effective minor radius of $a = 0.49$ m. For this study, variations of the effective helical ripple ε_{eff} from 0.7% to 1.4% were made by small variations of currents in one coil type. One of the stellarator specific long-mean-free-path transport regimes depends on ε_{eff} ($D_{1/\nu} \sim \varepsilon_{eff}^{3/2} n^{-1} T^{7/2}$), however, when E_r affects the transport it does not depend on ε_{eff} (e.g. $D_{\sqrt{\nu}} \sim n^{1/2} T^{5/4} E_r^{-3/2}$). Therefore, the magnetic field variation allowed one to assess the effect of ε_{eff} on the plasma confinement and to check the occurrence of $1/\nu$-transport. The routinely available electron cyclotron heating power in X2 mode (B_0=2.5T) was 4.3 MW. Typical stationary line averaged densities for the studies reported here were around $\int n_e dl$ =1 - 2 x 10^{19} m^{-2} (with L = 1.3m). While steadily improving the wall conditioning [9] and monitoring both the released heat on the limiters and the concentration of impurities [10], it was possible to increase the energy in a pulse from $\int P dt$ = 2 to 4MJ. The pulse length limit was increased from 1s to 6s.

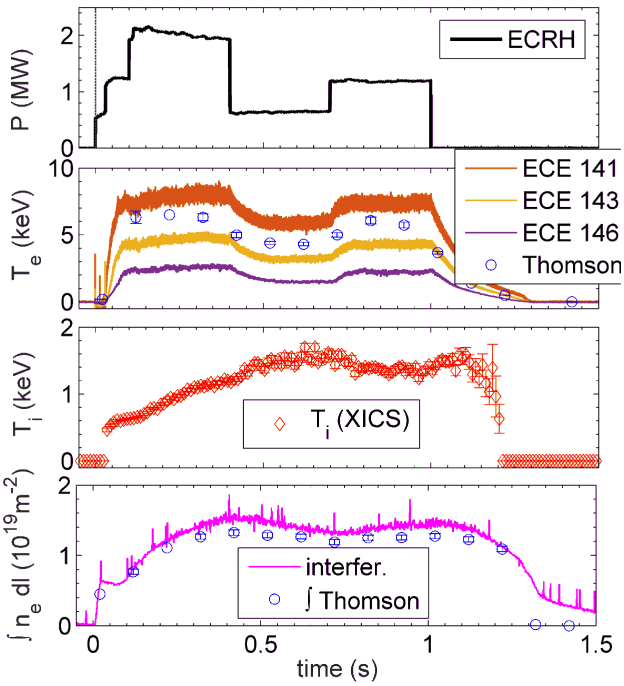

Fig. 1: Waveforms of power-step experiments for the assessment of core confinement in W7-X limiter discharges.

Fig. 1 shows waveforms reflecting the electron and ion temperature response to power steps (2MW, 0.6 MW and 1.3MW) at line densities of about $\int n_e dl = 1.5 \times 10^{19}$m^{-2}. Switching the heating power down and up reveals response time scales in the plasma decay and build-up. In the very center, electron temperatures of up to about $T_e \sim$ 8keV (at 2MW) were measured from the electron cyclotron emission. The central ion temperature was measured from the Doppler width of Argon XVI tracer lines [11] to be much lower than T_e ($T_i \sim$ 1.7 keV). It is noted that the central ion temperature is observed to increase even when the heating power is decreased, but falls when the heating power is increased again. Profile measurements indicate this apparent contradiction can be explained by taking into account local variations of the density and temperature profiles. At present, the density profile is thought to be largely determined by recycling fluxes from the limiters.

The diagnostics set [12] allowed to determine profiles of transport relevant quantities. The spatial distribution of temperatures and densities for a period of low heating power and corresponding fits are shown in Fig. 2. The electron temperature is higher than the ion temperature up to about 0.6 of the normalized minor radius. At the time this paper was written, systematic discrepancies of electron cyclotron emission and Thomson scattering in the center and deviations in the gradient region have not yet been resolved and are the subject of ongoing investigations [13, 14].

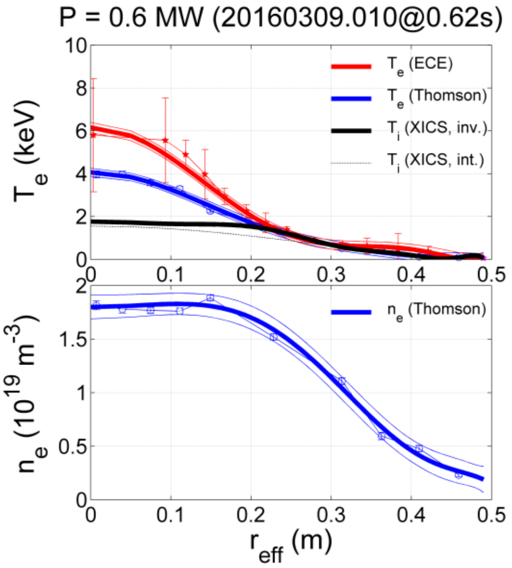

Fig. 2: Measured temperature profiles and density profiles with fits for the 600kW (cf. Fig. 1). Edge values come from limiter Langmuir probes [17].

Nonetheless, these measurements can be used to derive neoclassical particle and energy fluxes. For the specific case, DKES [15] based analyses and SFINCS [16] simulations have been performed. The latter goes beyond the incompressible $\vec{E} \times \vec{B}$-drift approximation of DKES. Employing fits to the temperature and density data, energy fluxes ($Q_{e,i}$) and particle fluxes ($\Gamma_{e,,i}$) have been determined. Electron energy fluxes at vanishing radial electric field (and thus reflecting the $1/\nu$-regime) result in maximum electron heat fluxes ($Q_e+\Gamma_e T_e$) which are at least a factor of 6 larger than the applied heating power. This contradiction is resolved by taking into account the E_r dependence of the transport coefficients and enforcing the ambipolarity condition for the electron and ion fluxes $\Gamma_e(E_r,\ldots) = Z\Gamma_i(E_r,\ldots)$.

A result of the spatial dependence of the self-consistent radial electric field of both calculations from DKES and SFINCS assuming $Z_{eff} = 1$ is shown in Fig. 3. The profile of the radial electric field shows a spatial bifurcation from the CERC regime in the core ($E_r>0$) to the ion-root transport regime ($E_r<0$) at about the region of maximum electron temperature gradient. Similar behavior is also found for higher heating power than shown in Fig. 3, whereby the electron-root plasma volume grows with the heating power. The effective helical ripple scan showed that a ε_{eff} dependence as strong as in the $1/\nu$-regime was not reflected in the transport.

Consistent with electron-root physics at low densities, the experimental finding shows the electron transport is reduced by strong radial electric fields ($\sqrt{\nu}$–regime). The outer, colder plasma region, however, is still the largest fraction of the plasma volume. Global figures for the energy confinement time for the power steps indicate τ_E to scale like $\tau_E \sim P^{-0.5\pm 0.1}$ which is compliant with ion-plateau scaling ($P^{-0.6}$) at higher collisionality but with the tendency of lower power degradation. Experimental evidence for positive radial electric fields in the plasma core is given by reflectometry [18] and X-ray imaging spectroscopy [19]. Both diagnostics measure a reversal of poloidal flow velocities. Reflectometry data with clearer indication of flow reversal are found in different discharges [7]. The comparison of neoclassical theory and measurements in Fig. 3 exhibit similar E_r values as well as having the same radial position of the E_r bifurcation.

From the measurements reported here and comparisons with neoclassical predictions it is concluded that low density, centrally electron-cyclotron-resonance heated W7-X limiter plasmas show core-electron-root confinement.

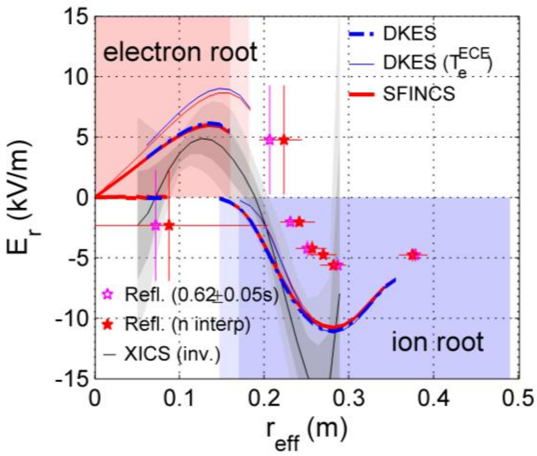

Fig. 3: Calculated radial electric field compared to measurements for the lowest heating power (t=0.62s) in Fig. 1. The shaded area reflects the error band of the XICS data.

These findings are the first clear evidence for neoclassical transport and long-mean-free-path physics in W 7-X. It is noted, however, that these result in W7-X limiter plasmas at low densities do not allow one to conclude on stellarator optimization. A more detailed validation of the experimental findings is underway to reveal more details and open issues resulting from this study, e.g. to determine effects due to particle sources, in particular recycling fluxes and resulting charge exchange losses.

The results from the limiter discharges make the reported findings a reference case for later investigations in divertor configurations. Impact of the core electron root on plasma currents [20], radiation [21] and impurity behavior [10,11] will be reported elsewhere. The findings contribute to the understanding of stellarator-specific transport in W7-X and will thereby impact future studies at higher densities expected in the forthcoming experimental campaign.

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