Neoclassical transport in the High density H-mode in Wendelstein 7-AS – revisited with new tools

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Introduction

In view of the aim for long-pulse operation of Wendelstein 7-X, it is important to understand under which circumstances one can expect to avoid impurity accumulation. Unless the impurity sources at the edge were kept small in Wendelstein 7-AS (W7-AS) normal confinement (NC) plasmas, impurities often accumulated in the centre which resulted in a radiation collapse that terminated the discharge [1]. However, this was avoided in so-called high-density H-mode (HDH) plasmas, which were NBI heated and characterised by a density exceeding a certain heating-power-dependent threshold ($1.5 - 2.1 \cdot 10^{20}\mathrm{m}^{-3}$). The transport in the HDH regime was analysed in Ref. [2], but the experimentally observed efficient flush-out of impurities could not be explained by neoclassical transport, and there was no definite experimental evidence for turbulent mode activity at the plasma edge. Recently, analytical work [3, 4] has shown that when the impurities are in the highly collisional Pfirsch-Schlüter regime and the main ions in the long-mean-free-path regime, neoclassical "temperature screening" (outward flux of impurities driven by the temperature gradient) can prevent accumulation in stellarators, even when the radial electric field points inwards. To include this effect in a numerical analysis of the neoclassical impurity transport in the W7-AS HDH mode, one needs a more detailed physics model than was used in previous investigations. In this work, we therefore use the SFINCS code [5, 6], which enables us to include the full linearised Fokker-Planck collision operator as well as the variation of the electrostatic potential, ϕ_1, on the flux surface. The SFINCS results are compared with results from the DKES code [7], which employs a pitch-angle scattering collision operator.

Results

First, we illustrate when temperature screening is possible for the present stellarator, W7-X, by chosing one radius and studying how the transport coefficients vary when the density is varied (so as to vary the collisionality). The transport coefficients for temperature gradient and radial electric field E_r are $D_T \equiv D_{11}^{zz} + D_{11}^{zi} + D_{12}^{z}$ and $D_{Er} \equiv ZD_{11}^{zz} + D_{11}^{zi}$, respectively, where $\Gamma_z/n_z = D_{11}^{zi}A_{1i} + D_{11}^{zz}A_{1z} + D_{12}^{z}A_{2i}$, $A_{1a} = d\ln p_a/dr - Z_a eE_r/T_a$, and $A_{2a} = d\ln T_a/dr$. For high-Z impurities in W7-X there is a density range where the collisionalities fulfill $\nu_\star^{zz} \gg 1$,

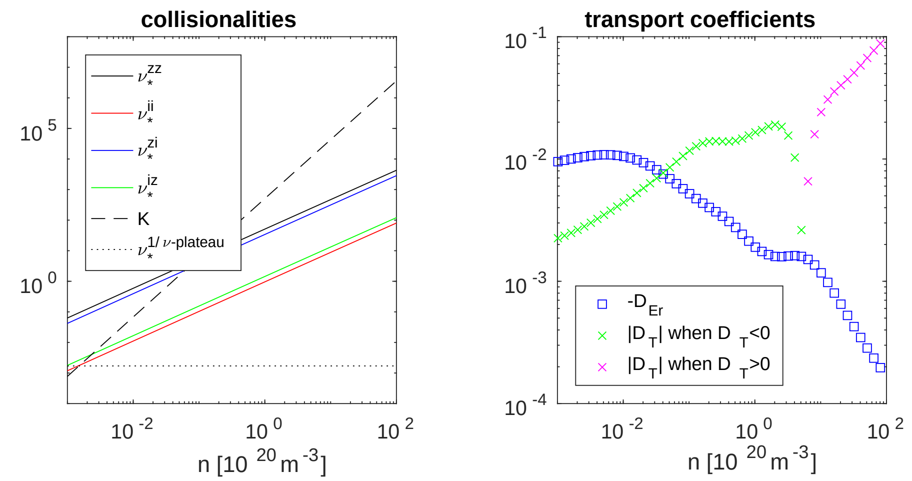

Figure 1: Density scan in W7-X standard configuration at $r/a = 0.88$ with C^{6+}, $Z_{\text{eff}} = 2$, $T_i = T_C = 1$ keV, $E_r = -5$ kV/m. Collisionality definitions: $\nu_\star^{ab} = Rn_b Z_a^2 Z_b^2 e^4 \ln\Lambda/(12\pi^{3/2}\varepsilon_0^2 T_a^2)$, $\nu_\star^{1/\nu-\text{plateau}} = (4/(3\pi))^2(2\varepsilon_{\text{eff}})^{3/2}/(b_{10}R/r)^2$

$\nu_\star^{iz} \ll 1$ and the condition $K \equiv \nu_\star^{iz}\nu_\star^{zz}(n_i/n_z)\sqrt{m_i/m_z} \gg 1$. It was seen in ref. [3] that a collisionality range exists where $-D_T > -D_{Er}$ also for C^{6+}, see fig. 1. Because $D_T = -(3/2)D_{11}^{zi}$, one can under these circumstances expect outward impurity flux for large enough values of $(d\ln T_i/dr)/(d\ln n_i/dr)$.

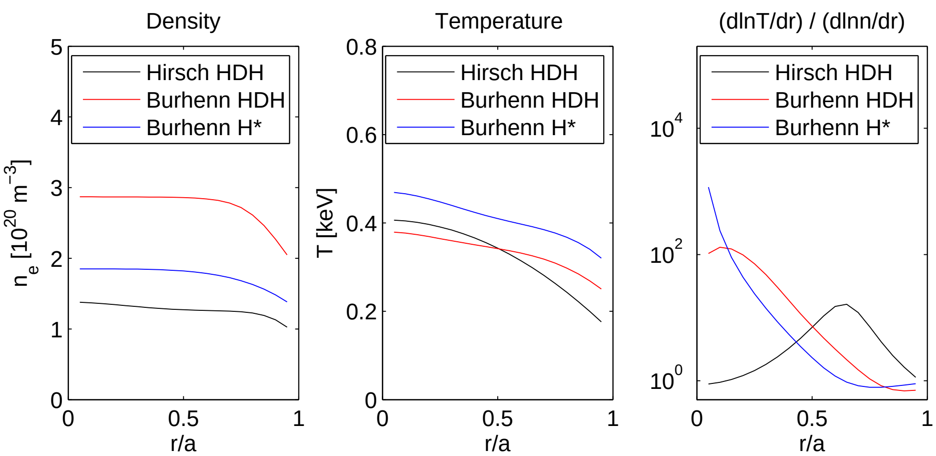

Figure 2: Profiles from Burhenn *et al.* [2] and Hirsch *et al.*[8]. $T_e = T_i = T_z$ is assumed.

We now continue with W7-AS, where we study the H* and HDH profiles from Burhenn *et al.* [2], see fig. 2, and we include carbon with $Z_{\text{eff}} = 1.5$. The equilibrium is taken from discharge 55595, see fig. 70 of ref. [8]. The transport analysis in figs. 3 and 4 shows that the difference between the DKES results and the SFINCS results without ϕ_1 is rather small, both in terms of radial electric field and particle fluxes. The carbon flux is inward, so we do not have an explanation for the impurity losses in HDH mode. When ϕ_1 (which is of the order $Ze\Phi_1/T \sim 10^{-2}$) is included the carbon flux becomes even more inward. The green curves in the right plot in figs. 3 and 4 show that when E_r is artificially divided by 3 the flux can become outward at some radii, as expected.

To compare with the W7-X case in fig. 1, a density scan is performed at $r/a = 0.4$ (where $(dT/dr)/(dn/dr) \gg 1$, see fig. 2). The density scan results in fig. 5 exhibit no region with $-D_T > -D_{E_r}$. In fact, the density at which D_T switches sign to make the temperature gradient contribute to inward transport (which in the W7-X case was a very high density) is here lower than the density from the experimental profile, n_{exp}. The right plot in fig. 5 shows that even if the temperature gradient is doubled, the carbon flux is still inward. We also see from the collisionalities in the left plot that the main ions are in the plateau regime, rather than in the $1/\nu$ regime as in the analytical theory of ref. [3]. Figure 6 again demonstrates that when artificially lowering the electric field one can find collisionalities where $D_T \sim D_{E_r}$ and where the carbon flux is outward. In conclusion, we can presently not explain the flush-out of impurities in W7-AS HDH mode with the new neoclassical numerical tools. The next steps are to test the sensitivity to the profiles and to include different impurity species.

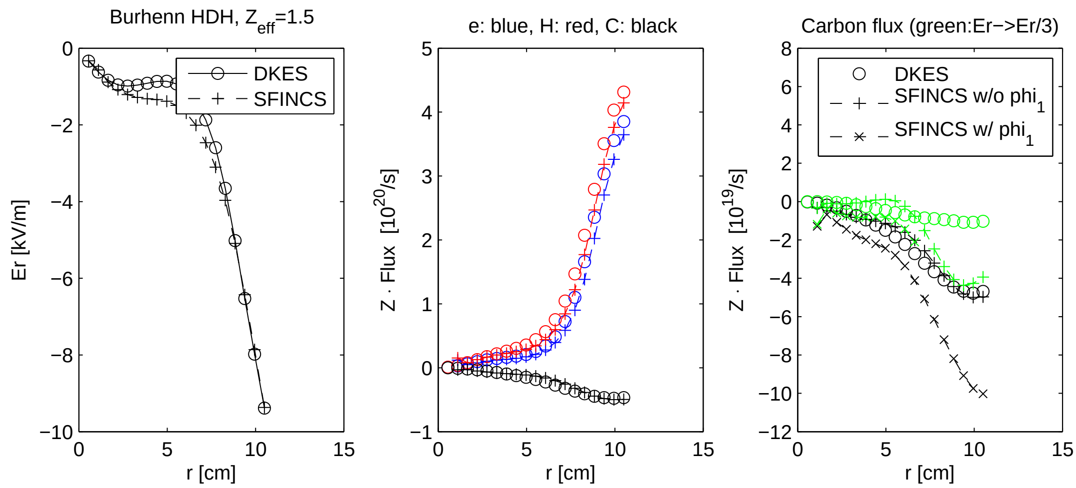

Figure 3: Neoclassical analysis for W7-AS HDH mode with DKES and SFINCS.

References

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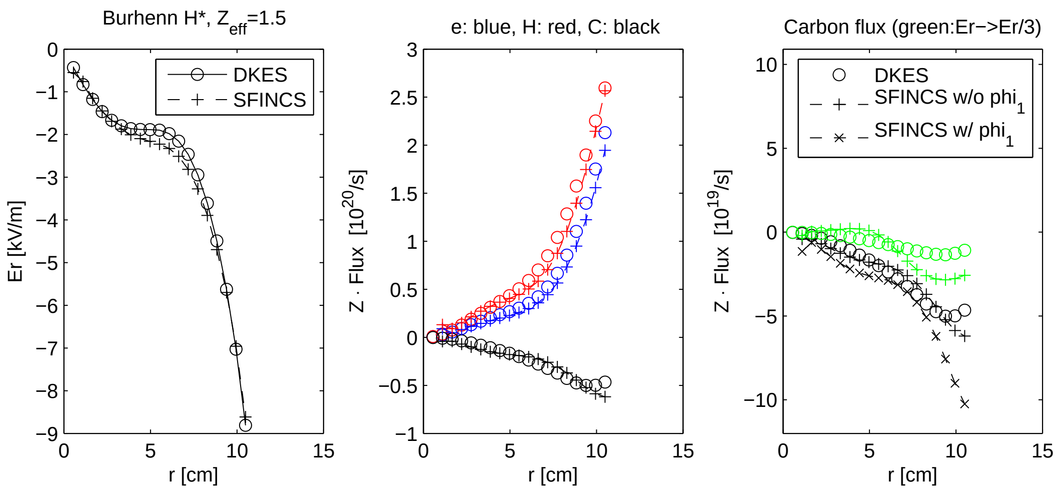

Figure 4: Neoclassical analysis for W7-AS H* mode with DKES and SFINCS.

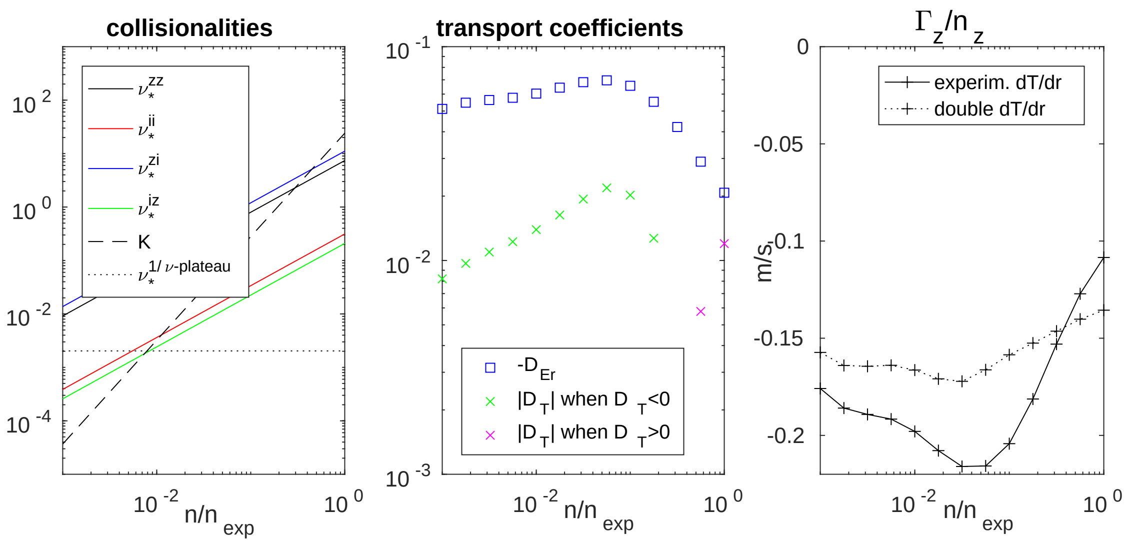

Figure 5: Density scan in W7-AS HDH with C^{6+}, $Z_{\mathrm{eff}} = 1.5$, $r/a = 0.4$.

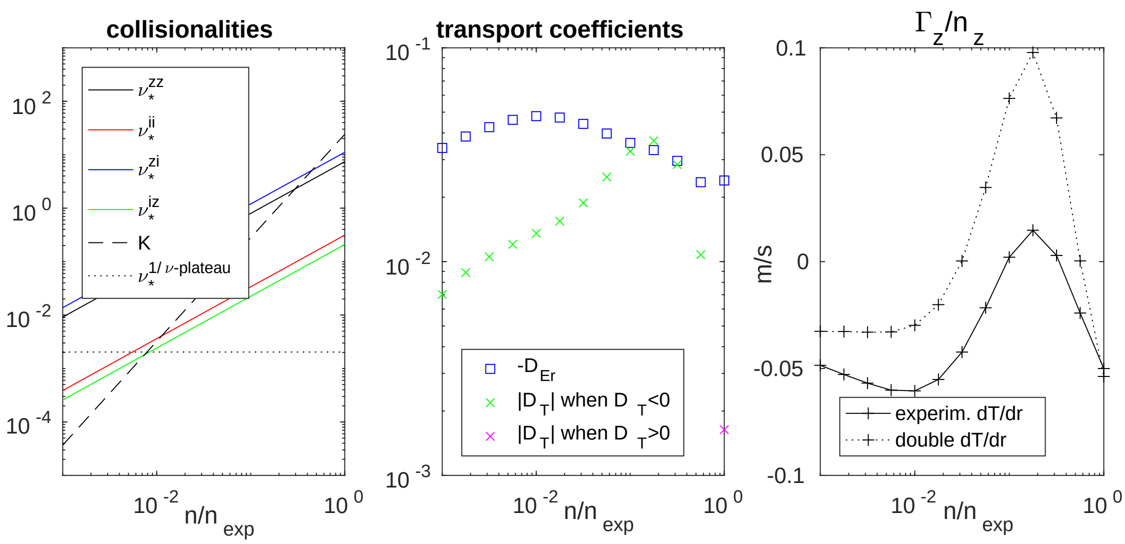

Figure 6: Density scan in W7-AS HDH with C^{6+}, $Z_{\mathrm{eff}} = 1.5$, $r/a = 0.4$, E_r divided by 2.