§8. Inter-Machine Validation Study of Neoclassical Transport Modelling in Medium- to High-Density Stellarator-Heliotron Plasmas

Dinklage, A.[a], Yokoyama, M.[b], Wakasa, A.[c], Tanaka, K.[b], Murakami, S.[c], Seki, R.[b], Morisaki, T.[b], Ida, K.[b], Yoshinuma, M.[b], Suzuki, C.[b], Suzuki, Y.[b], Yamada, H.[b], Velasco, J.L.[d], López-Bruna, D.[d], López-Fraguas, A.[d], Ascasíbar, E.[d], Arévalo, J.[d], Baldzuhn, J.[a], Beidler, C.D.[a], Feng, Y.[a], Geiger, J.[a], Jakubowski, M.[a], Maassberg, H.[a], Turkin, Yu.[a], Wolf, R.[a], LHD Experiment Group[b], TJ-II Team[d], W7-X Team[a], W7-AS Team[a]

[a] *Max-Planck Institut für Plasmaphysik,*
[b] *National Institute for Fusion Science,*
[c] *Dep. Nuclear Engineering, Kyoto University,*
[d] *The National Fusion Laboratory, CIEMAT*

Stellarator-Heliotrons (S-H) offer an alternative route to steady-state fusion reactors and one mission of the largest S-H devices is to provide a physics basis for burning S-H plasmas. In contrast to tokamaks, 3D magnetic fields in S-H lead even in the plasma core to localized, trapped particles significantly enhancing the radial neoclassical transport for reactor-relevant conditions (long-mean-free-path (*lmfp*), T_e~T_i, high-$nT\tau$). In order to test a recently concluded benchmarking of calculations of neoclassical transport coefficients[1)], and extending previous studies of electron energy transport at low densities[2)], this study compares experimental findings with neoclassical transport predictions for medium- to high-density S-H plasmas.

The focus of this study is put on recent experiments conducted in LHD and TJ-II also involving findings from Wendelstein 7-AS (W7-AS)[3)]. Purpose of this experimental inter-machine study was to apply and to test neoclassical transport models in the transition from medium- to high-density, *lmfp* S-H plasmas. In 3D magnetic configurations, radial electric fields (E_r) must arise to satisfy the ambipolarity condition which is not intrinsically satisfied as in axisymmetric tokamaks. In the *lmfp* at sufficiently high densities above a few times 10^{19} m^{-3}, E_r is well predicted by the neoclassical ambipolarity condition and is found to be in the so-called ion-root. E_r has particular impact on the energy fluxes of the ions. In LHD *lmfp*, high-$nT\tau$ plasmas, large contributions of neoclassical ion transport to the overall energy fluxes are consistent with previous findings in high-density W7-AS plasmas[3)]. In conjunction with lower-density TJ-II discharges indicating the validity range of local neoclassical theory, the results are of vital importance to increase the predictive capability of confinement for reactor-relevant S-H plasmas.

Dedicated experiments performed in LHD and TJ-II can be summarized as follows. In LHD, discharges with high heating power (about the same power densities as the W7-AS data set) with n_e>3×10^{19} m^{-3}, $T_{e,i}$>1 keV have been obtained. The variation of the heating power (ion/electron heating ratio as well), density and magnetic configuration forms a systematic database. In TJ-II, obtained parameters have been n_e~4×10^{19} m^{-3}, T_e~300 eV and T_i~120 eV. The neoclassical particle and energy fluxes are evaluated by convoluting the monoenergetic transport coefficients calculated by DKES[4)] in W7-AS and TJ-II, and by DGN/LHD[5)] in LHD; both approaches were benchmarked[1)].

It is found that the measured negative E_r is consistent with neoclassical ambipolar ion-root conditions for all devices. Higher density and comparable temperatures towards reactor-relevant S-H plasmas tend to weaken the bifurcation capability of E_r as reported for electron-root conditions[2)]. Differently, in TJ-II the experimentally observed E_r is more negative than the predicted neoclassical ambipolar field. For reactor conditions, nonetheless, the findings conform to neoclassical theory for the determination of E_r, extending previous findings in lower-density regime[2)]. Steady-state energy balance analyses were performed using the integrated transport code, TASK3D[6)] for LHD discharges, and by ASTRA[7)] in TJ-II. For W7-AS, the experimentally determined particle and energy fluxes were compared to neoclassical fluxes with transport coefficients from DKES and found to be consistent with neoclassical theory up to 2/3 of the minor radius in *lmfp*, high-$nT\tau$ conditions. It is found in an LHD discharge that the ion energy flux is well described by the neoclassical energy flux up to 2/3 of the plasma radius reproducing the general tendency found in W7-AS for the aforementioned discharges with high-$nT\tau$[3)]. Moreover, the LHD experiments indicate an increase of both ion and electron neoclassical energy fluxes when the plasma beta value and consequently, the Shafranov shift is increased. In TJ-II, the ion energy flux has been found to be beyond the prediction of local neoclassical theory. These findings are relevant in the assessment of the validity range of local neoclassical theory[8)].

Summarizing, an inter-machine dataset obtained in devices of different size and a variety of magnetic configurations will be comprehensively analyzed to assess the ranges of validity of neoclassical transport predictions. This study is providing quantitative tests for the assessment of neoclassical transport in the reactor-relevant regime of S-H devices.

1) C.D.Beidler *et al.*, Nucl. Fusion 51 (2011) 076001.
2) M.Yokoyama *et al.*, Nucl. Fusion 47 (2007) 1213.
3) J.Baldzuhn *et al.*, Plasma Phys. Control. Fusion 40 (1998) 967.
4) S.P.Hirshman *et al.*, Phys. Fluids 29 (1986) 2951.
5) A.Wakasa *et al.*, Contrib. Plasma Phys. 50 (2010) 582.
6) M.Yokoyama *et al.*, Plasma and Fusion Res. 7 (2011) 2403011.
7) G.V.Pereverzev, IPP 5/98, Max-Planck Institut für Plasmaphysik (2002).
8) V.Tribaldos *et al.*, Plasma Phys. Control. Fusion 47 (2005) 545.