Validation of local and non-local neoclassical predictions for the radial transport of plasmas of low ion collisionallity

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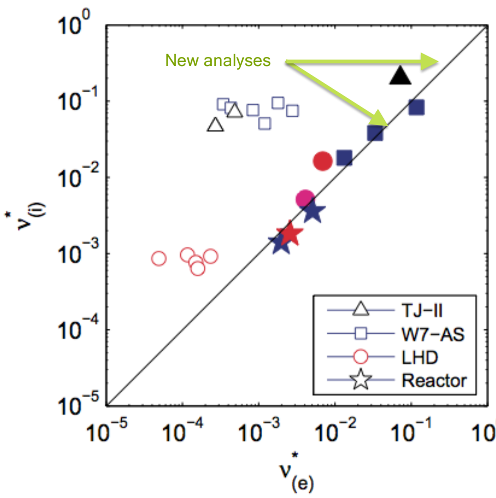

Figure 1:

Neoclassical (NC) transport is a fundamental aspect of stellarator plasma scenario development: predictive 1D transport simulations (see for example [1]) with NC transport at the core, complemented with simple models for anomalous transport at the edge, allow for estimates of confinement time, power load to the walls, fuelling and heating requirements... This way to proceed has been supported by a step-by-step systematic validation of the predictions of NC theory with experimental results in a number of medium-sized stellarators (LHD, W7AS, TJ-II...) in regimes as reactor-relevant as possible (see [2] and refs. therein). Generally speaking, these simulations tend to show, with some exceptions, reasonable agreement between the experimental and the NC particle and heat fluxes within the core region. A relevant feature of these studies is that all of their NC simulations rely on the local ansatz of NC transport and make use of the monoenergetic approach [3]. A recent contribution (see [4] and refs. therein) has extended them by investigating, for several discharges, differences between the results of local and monoenergetic NC codes (e.g. DKES) and non-local, non-monoenergetic NC codes (FORTEC-3D). These differences could in principle explain some of the discrepancies between NC simulations and the experimental results, or improve the results in those situations where the agreement is at best rough. In this work we expand the range of these studies. The CXRS system permits us to measure the full profile of ion temperature and identify TJ-II discharges [5] in which ion collisionality is relatively low (up to one fifth of that studied in previous cases) and the electron collisionality is low, but not too much (so that the radial electric field is negative). This situation is closer to reactor relevant conditions than in previous NC studies in TJ-II.

Equations

FORTEC-3D solves the global drift kinetic equation for $f_1(r,\psi,\theta,K,\mu)$:

$$(\mathbf{v}_\parallel+\mathbf{v_E}+\mathbf{v_M})\cdot\nabla f_1+\frac{\mathrm{d}K}{\mathrm{d}t}\frac{\partial f_1}{\partial K}-C(f_1)=-(\mathbf{v_M}\cdot\nabla+\frac{\partial}{\partial K})f_M+\mathscr{P}f_M\,, \tag{1}$$

where K is the kinetic energy, $\mathbf{v_M}=\frac{K+v_\parallel^2}{q}\frac{\mathbf{B}\times\nabla B}{B^3}$ is the magnetic drift, $\mathbf{v_E}=\frac{\mathbf{E}\times\mathbf{B}}{B^2}$ the E × B flow, and the collision operator $C(f_1)+\mathscr{P}f_M$ includes energy-scattering and conserves momentum. The other symbols have their usual meaning. The radial particle and energy fluxes are moments of the distribution function:

$$\Gamma_b=\langle\int \mathrm{d}v^2 f_1 v_M\cdot\nabla r\rangle\,,\qquad Q_b=\langle\int \mathrm{d}v^2 K v_M f_1\cdot\nabla r\rangle\,,$$

and the radial electric field is estimated from ambipolarity of NC fluxes, $\Gamma_e(E_r)=\Gamma_i(E_r)$.

In the so-called *local and monoenergetic limit*, the magnetic drift at the LHS of Eq. (1) is neglected, together with the temporal variation of the kinetic energy and the energy-scattering of the collision operator, and v_E is simplified. This makes it possible to write the particle and energy fluxes as linear combinations of the thermodynamical forces:

$$\begin{aligned}\frac{\Gamma_b}{n} &= -L_{11}^b\left(\frac{1}{n}\frac{dn}{dr}-Z_b e\frac{E_r}{T_b}-\frac{3}{2}\frac{1}{T_b}\frac{dT_b}{dr}\right)-L_{12}^b\frac{1}{T_b}\frac{dT_b}{dr}\,,\\ \frac{Q_b}{nT_b} &= -L_{21}^b\left(\frac{1}{n}\frac{dn}{dr}-Z_b e\frac{E_r}{T_b}-\frac{3}{2}\frac{1}{T_b}\frac{dT_b}{dr}\right)-L_{22}^b\frac{1}{T_b}\frac{dT_b}{dr}\,,\end{aligned}$$

where L_{ij}^b are called thermal transport coefficients and are calculated by convolution of monoenergetic transport coefficients:

$$L_{ij}^b(r,n,T_i,T_e,E_r)=\frac{2}{\sqrt{\pi}}\int_0^\infty K^2\,e^{-K^2}K^{1+2(\delta_{i,2}+\delta_{j,2})}D_{ij}\,,$$

solution of the local monoenergetic DKE.

The so-calculated fluxes are then to be compared with the experimental ones, from transport-balance simulations with ASTRA:

$$\begin{aligned}\frac{\partial n_e}{\partial t} &+ \frac{1}{V'}\frac{\partial}{\partial r}V'\Gamma_e=S_e\,,\\ \frac{3}{2}\frac{\partial n_b T_b}{\partial t} &+ \frac{1}{V'}\frac{\partial}{\partial r}V'Q_b=P_b+Z_b\Gamma_b E_r\,.\end{aligned} \tag{2}$$

The particle sources S_e include recycling from the wall (calculated with the neutral transport code EIRENE) and injection of NBI (calculated with the code FAFNER). Since the plasma-wall interaction is strong at TJ-II, the particle source depends strongly on the particle confinement $S_e=S_e(\tau_p\sim n_e/\Gamma_E)$, which adds one extra equation to Eqs. (2). The absorbed power P_b includes, for both species, power deposition from NBI, collisional energy-exchange, Joule effect (which is negligible except at the edge) and, in the case of electrons, radiation. The evolution of the profiles is slow enough so that the first term in the LHS of Eqs. (2) can be ignored.

Results

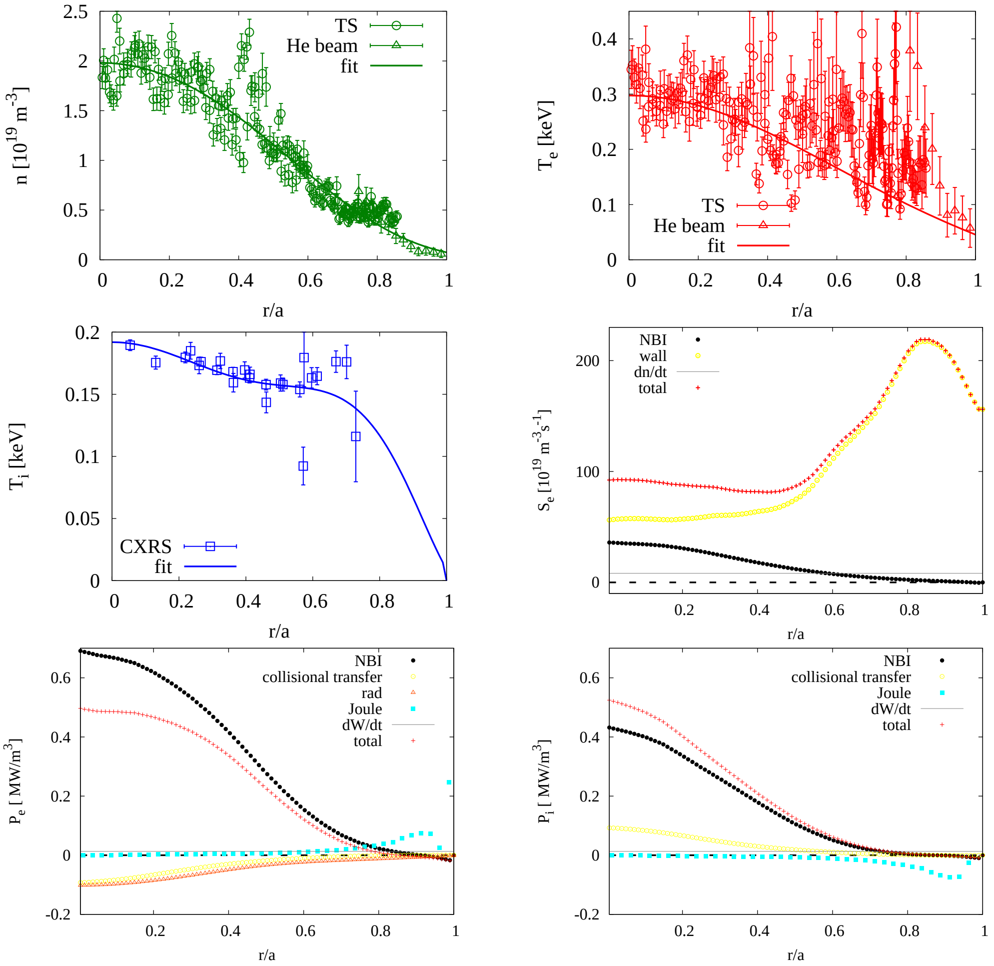

Figure 2: *Experimental profiles of discharge #28263, representative of low-collisionality NBI-heated TJ-II plasmas: density (top left), electron (top right) and ion temperature (center left), particle source (center right), power to the electrons (bottom left) and to the ions (bottom right).*

Comparison between theory and experiment yields good agreement for the radial electric field and the particle flux at the core region. Nevertheless, the ion and electron energy fluxes seem to be understimated by a factor of 2 in this radial region. This is unexpected, since due to lack of NC optimization, the energy flux should be “more NC” than the particle flux TJ-II. A hypothetical overestimation of the NBI-deposited power would get the experimental results closer to the prediction, but if it exists it is unlikely to be that large. At outer positions, the disagreement grows, as seen in previous works. Doppler reflectometer measurements indicate a more negative electric field than the one predicted by NC theory; this could be caused by orbit losses from NBI, which are large due to lack of NC optimization.

Non-local NC effects do not improve in a relevant manner the agreement between theory and experiment for these plasmas, probably because of their low ion temperature. In the core region, where the radial electric field is small, the magnetic drift is comparable to the $\mathbf{E}\times\mathbf{B}$ drift and tends to make the radial electric field less negative and to reduce the ion energy flux.

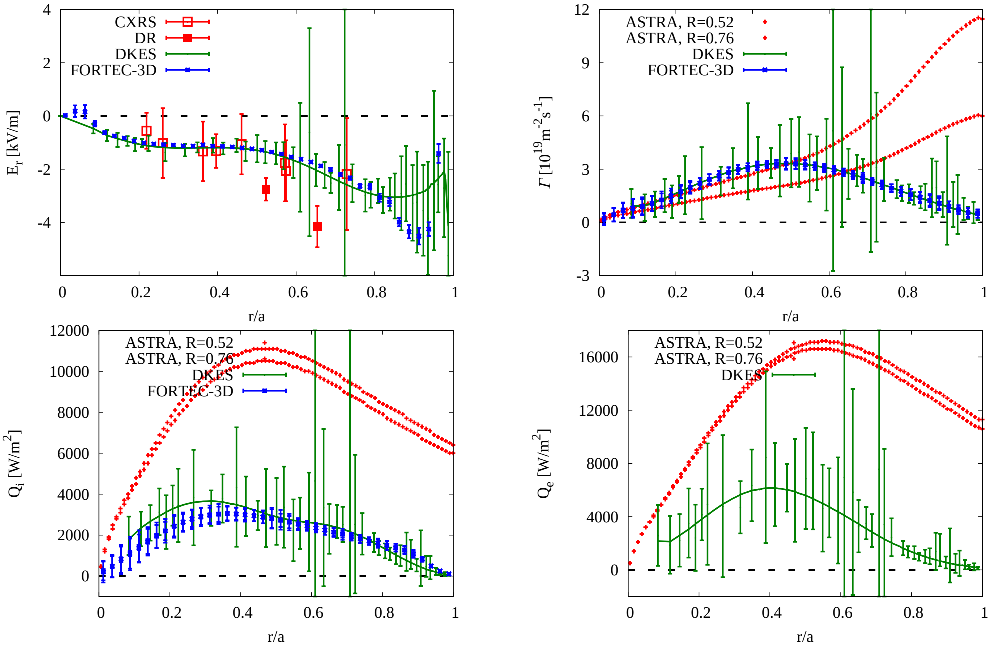

Figure 3: *Result of the analysis for #28263: radial electric field (top left), particle flux (top right), ion energy flux (bottom left) and electron energy flux (bottom right).*

At outer radial positions, the radial component of the magnetic drift makes the fluxes larger and the radial electric field more negative. The particle flux does not change since in the ion root it is set by electrons, and it does not depend strongly on the radial electric field.

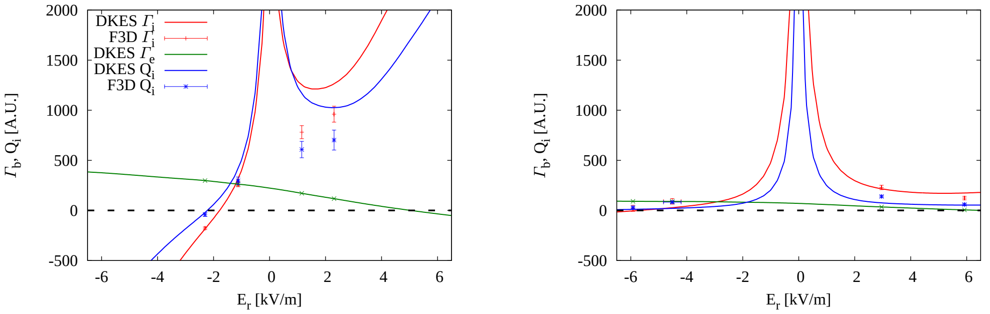

Figure 4: *Radial fluxes as a function of the radial electric field at* $r/a = 0.3$ *(left) and* $r/a = 0.9$ *(bottom).*

References

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