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

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Goal and background

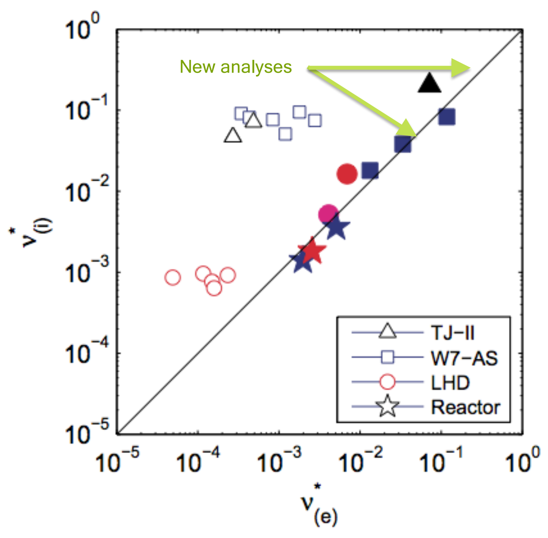
Questions we want to answer (already partially answered):

- How accurately does NC theory describe radial heat and particle transport?
- Do non-local NC simulations improve the description (and where)?
- Is the situation different for particle and heat transport?

Long term goal: support to W7-X and stellarator reactors.

Background A. Dinklage *et al.*, Nucl. Fusion *53*, 063022 (2013)

- Medium-size stellarator/heliotrons at medium-to-high densities, $n_e > 4\times10^{19}\,m^{-3}$, $T_b \sim keV$.
- Ion root (E_r small and positive) $\Rightarrow$ ion energy transport is dominant.
- Predicted NC energy fluxes roughly comply with experimental findings in the core region (but there is room for improvement).



- Bad agreement in outer positions.
- Preliminary results of simulations with FORTEC-3D predict that non-local effects have more impact in Q_b than in Γ. S. Satake *et al.*, Thursday O4.130

Workplan

- Extend database of well-diagnosed discharges:
  - Those of J. Arévalo, *et al.*, Nucl. Fusion *54*, 013008 (2014)
  - low ν_i^*, standard TJ-II and low-volume (low-ripple) configurations.
  - high n, standard TJ-II configuration.
  - Other devices (LHD and W7AS). S. Satake *et al.*, Thursday O4.130
- Calculate experimental, NC local and NC non-local fluxes and compare.

Equations

Global NC: FORTEC-3D S. Satake *et al.*, Thursday O4.130

- Solve the global drift kinetic equation for $f_1(r,\psi,\theta,K,\mu)$:

$$(\mathrm{v}_\parallel+\mathrm{v}_\mathrm{E}+\mathrm{v}_\mathrm{M})\cdot\nabla f_1+\frac{\mathrm{d}K}{\mathrm{d}t}\frac{\partial f_1}{\partial K}-C(f_1)=-(\mathrm{v}_\mathrm{M}\cdot\nabla+\frac{\partial}{\partial K})f_M+\mathcal{P}f_M\,,$$

with $\mathrm{v}_\mathrm{M}=\frac{K(1+\lambda^2)}{q}\frac{\mathrm{B}\times\nabla B}{B^3}$ and $\mathrm{v}_\mathrm{E}=\frac{\mathrm{E}\times\mathrm{B}}{B^2}$.

- Take moments, $\Gamma_b=\langle\int \mathrm{d}v^2 f_1 v_M\cdot\nabla r\rangle$, $Q_b=\langle\int \mathrm{d}v^2 K v_M f_1\cdot\nabla r\rangle$.
- E_r from ambipolarity of NC fluxes: $\Gamma_e(E_r)=\Gamma_i(E_r)$.

Local and monoen. NC: DKES + momentum-conservation routines

C.D. Beidler *et al.*, Nucl. Fusion *51*, 076001 (2011)

- We can write:

$$\frac{\Gamma_b}{n}=-L_{11}^b\left(\frac{1}{n}\frac{dn}{dr}-Z_be\frac{E_r}{T_b}-\frac{3}{2}\frac{1}{T_b}\frac{dT_b}{dr}\right)-L_{12}^b\frac{1}{T_b}\frac{dT_b}{dr}\,,$$

$$\frac{Q_b}{nT_b}=-L_{21}^b\left(\frac{1}{n}\frac{dn}{dr}-Z_be\frac{E_r}{T_b}-\frac{3}{2}\frac{1}{T_b}\frac{dT_b}{dr}\right)-L_{22}^b\frac{1}{T_b}\frac{dT_b}{dr}\,.$$

- Thermal transport coefficients from convolution of monoenergetic coeff.:

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

solution of the local monoenergetic DKE (without non-local terms).

Experimental balance: ASTRA

- Solve the system of equations:

$$\frac{\partial n_e}{\partial t}+\frac{1}{V'}\frac{\partial}{\partial r}V'\Gamma_e=S_e\,,$$

$$\frac{3}{2}\frac{\partial n_bT_b}{\partial t}+\frac{1}{V'}\frac{\partial}{\partial r}V'Q_b=P_b+Z_b\Gamma_bE_r\,.$$

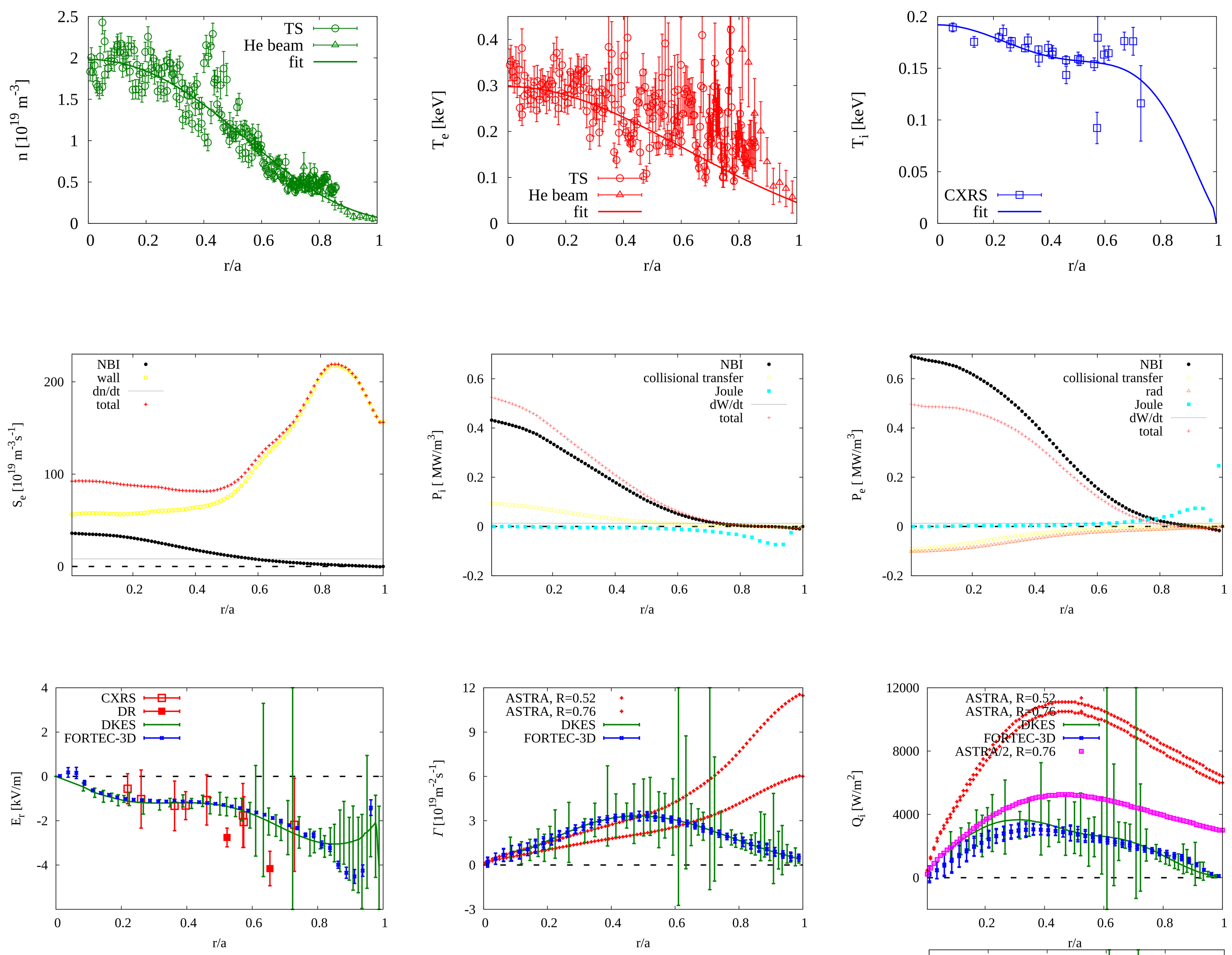
Input from the experiment

- B_{mn} from 3D equilibrium calculation (VMEC).
- T_e from Thomson Scattering, Helium Beam probe.
- n_e from Thomson Scattering, He Beam, interferometry and reflectometry.
- T_i and E_r from CXRS and Doppler reflectometry.
- Ion energy sources P_i: NBI (FAFNER), i-e energy exchange.
- Electron energy sources P_e: NBI, i-e energy exch. and radiation (from bolometry and soft X-rays). Γ_bE_r is negligible except close to the edge).
- Particle source S_e: NBI (FAFNER), recycling (EIRENE).
  $S_e=S_e(\tau_p)\Rightarrow$ extra equation $\tau_p\sim n_e/\Gamma_e$ (embedded in ASTRA).

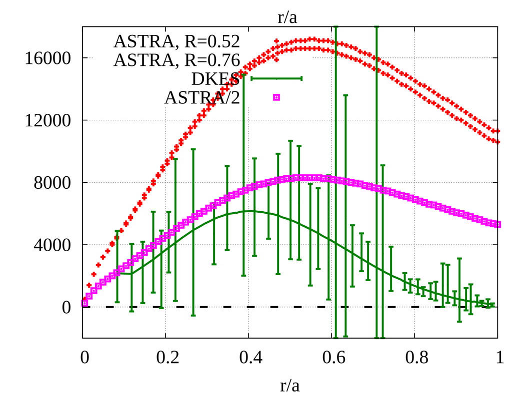
Results and discussion

Representative discharge of TJ-II #28263 from [Arevalo NF 2014]

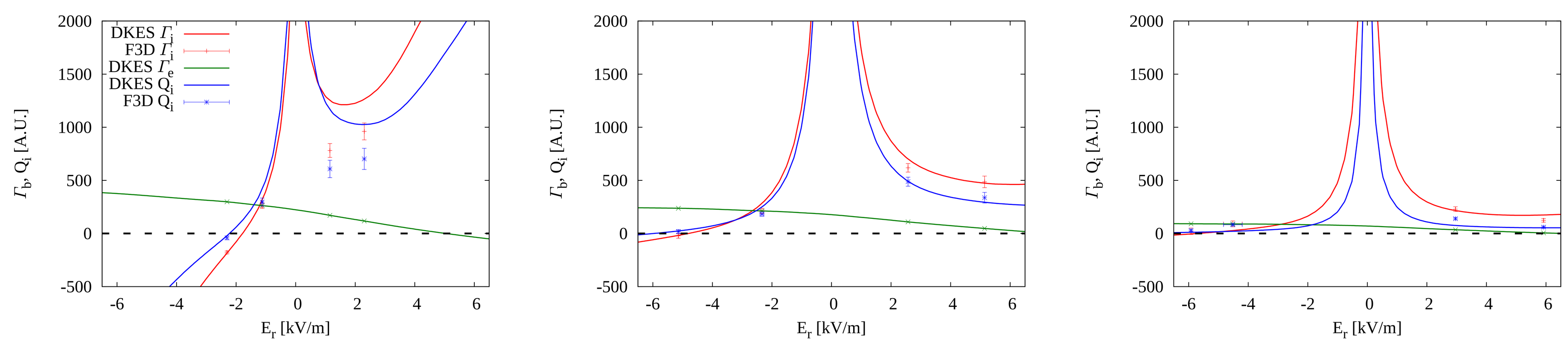
- Low n NBI plasma:
  - Not too low $T_i\Rightarrow$ low ν_i^* ; not too high $T_e\Rightarrow$ low ν_e^* but ion root.



- Good agreement for E_r and Γ up to $r/a=2/3$.
- Underestimation of Q_i and Q_e.
  - Due to lack of NC optimization Q_b should be "more NC" than Γ at TJ-II. And "more NC" than Q_b at other devices for similar collisionalities.



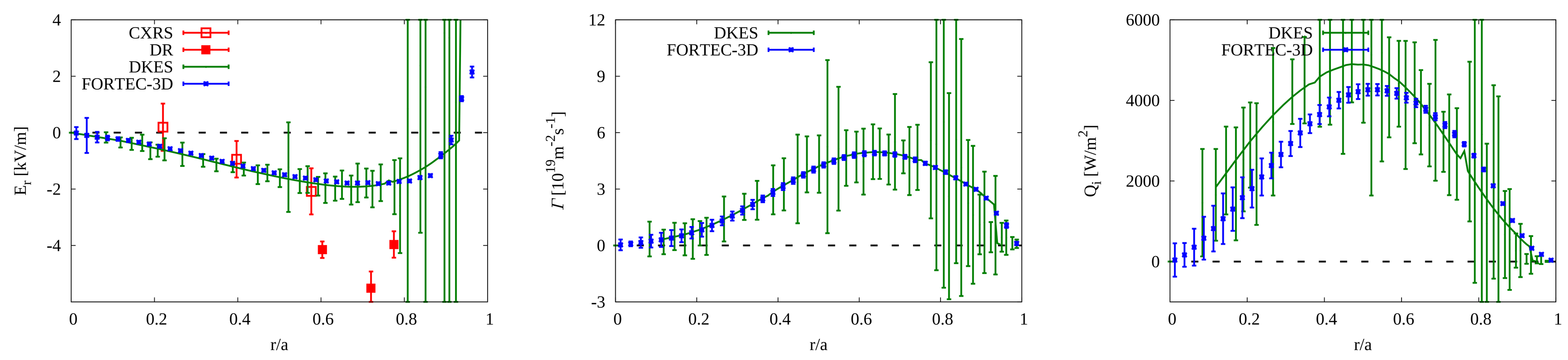
- **Small non-local effects** only in $E_r(r/a>0.5)$ and $Q_i(r/a>0.5)$ Γ is unafected in ion root plasmas.



$r/a=0.3$ $r/a=0.6$ $r/a=0.8$

- $\mathrm{v_E}$ is known to reduce the $1/\nu$ contribution to Γ and Q_i.
- When $|E_r|$ is small, the poloidal component of $\mathrm{v_M}$ plays this role.
  - At $r/a=0.3$, it reduces Q_i w.r.t. DKES.
  - At $r/a=0.6$, it reduces $|E_r|$ and Q_i.
    Γ does not change since it is set by electrons, and $\Gamma_e(E_r)\approx$ **const.**.
- At $r/a=0.8$ the radial comp. of $\mathrm{v_M}$ makes Q_i larger and E_r more neg.

These features are observed in similar plasmas of TJ-II (and others): #32577.



Non local effects do not improve comparison NC vs. experiment. Alternatives:

- Dividing the NBI-deposited power to both species by 2 provides good agreement in Q_b (but such overestimate of P_b is very unlikely).
- $\iota=8/5$ at $\rho\approx0.7$ could affect E_r. But no profile flattening.
- Orbit losses from NBI are large due to lack of NC optimization. Accounted for in particle and energy balance, but not in ambipolar equation.

Future work

- FORTEC-3D simulations for electrons.
- Analyze high-n discharges and other configurations.
- Extract general conclusions that may be relevant for W7-X operation.