Non-local NC simulations in stellarators/heliotrons using the FORTEC-3D code

Presented by J.L. Velasco[1],
including work and discussion by S. Satake[2], A. Dinklage[3], M. Yokoyama[2], D. López-Bruna[1] and many people from TJ-II team[1], LHD Exp. Group[2] and W7-AS Team[3] and others[4,5,6]

[1] *Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain.*
[2] *National Institute for Fusion Science, Toki, Japan.*
[3] *Max-Planck Institute fuer Plasmaphysik, Greifswald, Germany.*
[4] *Research Oganization for Information Science and Technology, Japan.*
[5] *Department of Nuclear Engineering, Kyoto University, Kyoto, Japan.*
[6] *Princeton Plasma Physics Laboratory, Princeton, NJ, USA*

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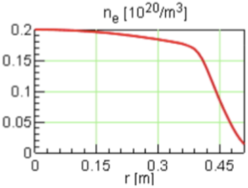
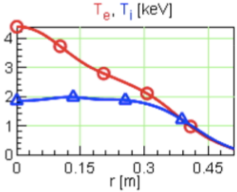
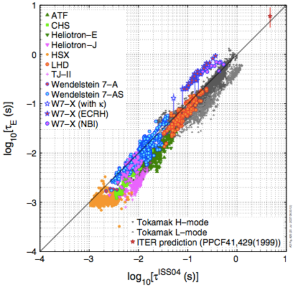
Long term goal: support predictive simulations of W7-X scenarios and stellarator reactors (based on NC transport in the core + simplified turbulent transport in the edge + sources).

$$\frac{3}{2}\frac{\partial n_b T_b}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial r}V' Q_b = P_b \,.$$

[Pedersen EPS 2014, Dinklage NF 2007]







- How accurately does NC theory describe radial heat and particle transport in a stellarator? / Where do we need GK simulations?
- Does including higher order NC terms improve the description?
- Is the situation different for particle and heat transport?

What to expect

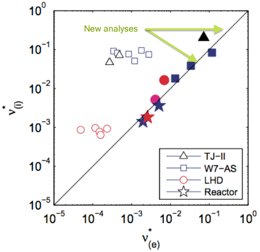
- The long-wave-length radial electric field is expected to be set by Neoclassics in stellarators far enough from quasisymmetry e.g. [Calvo PPCF 2013] because:

$$\langle \mathbf{J} \cdot \nabla r \rangle = \langle \mathbf{J}_{NC} \cdot \nabla r \rangle + O({\rho*}^3)\,, \quad \rho^* \equiv \frac{\rho_L}{L_0}\,,$$

  but no such result exists for the radial particle and energy fluxes.
- Empirical (and tautological) rule: neoclassical transport dominates when it is large enough:
  - Low collisionalities (core region, where T_i and T_e are large).
  - Configuration far from omnigeneity ($1/\nu$) [Parra submitted 2014].
- ρ^* is small (e.g., $\rho^* \sim 10^{-2}$ for TJ-II) so higher-order NC terms should be negligible.
  - High T_i and small $|E_r|$ is a standard situation in the core region of stellarators. $\Rightarrow \mathbf{v_M} \cdot \nabla \delta f$ may be non-negligible for ion transport.

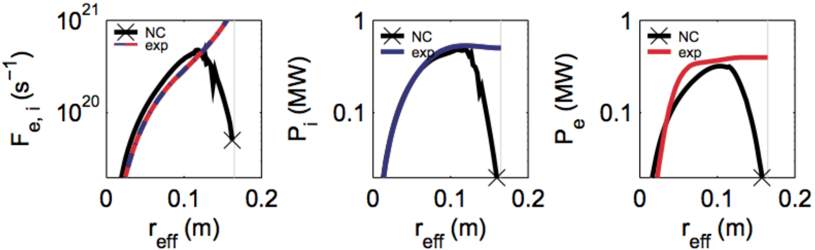
[Dinklage NF 2013]

- Medium-size stellarator/heliotrons at medium-to-high densities, $n_e > 4 \times 10^{19}\, m^{-3}$, $T_b \sim keV$.
- Ion root (E_r small and negative), ion energy transport is dominant.



- Predicted NC energy fluxes roughly comply with experimental fluxes (from transport balance) 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. [Satake EPS 2014]

[Dinklage NF 2013] W7-AS #34609



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Global NC: FORTEC-3D [Satake EPS 2014]

Solve the time-independent drift kinetic equation for $\delta f(r,\zeta,\theta,v,\xi)$:

$$\left[(\mathbf{v}_{\|}+\mathbf{v_E}+\mathbf{v_M})\cdot\nabla+\dot{v}\frac{\partial}{\partial v}+\dot{\xi}\frac{\partial}{\partial\xi}\right]\delta f - C(\delta f) = -(\mathbf{v_M}\cdot\nabla+\frac{\partial}{\partial K})f_M+\mathcal{P}f_M\,.$$

Differences w.r.t. local and monoenergetic approximation (DKES, [Beidler NF 2011]:

- $\mathbf{v_E}=\frac{\mathbf{E}\times\mathbf{B}}{B^2}$ is *compressible*.
- $C(\delta f)+\mathcal{P}f_M$ includes pitch-angle and energy scattering + momentum conservation.
- $\mathbf{v_M}=\frac{v^2(1+\xi^2)}{q}\frac{\mathbf{B}\times\nabla B}{B^3}$ is the magnetic drift $\Rightarrow$ need to keep $\frac{\partial\delta f}{\partial v}$.

Take moments:

$$\Gamma_b=\langle\int \mathrm{d}^3v\delta f v_M\cdot\nabla r\rangle\,,\quad Q_b=\langle\int \mathrm{d}^3v v^2 v_M\delta f\cdot\nabla r\rangle.$$

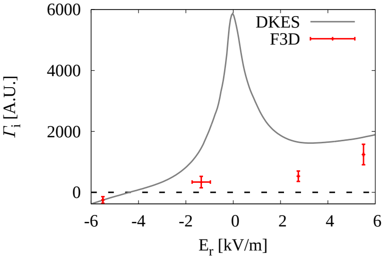
E_r from ambipolarity of NC fluxes: $\Gamma_e(E_r)=\Gamma_i(E_r)$.

The $\mathbf{v_M} \cdot \nabla \delta f$ term

Solve the time-independent drift kinetic equation for $\delta f(r,\zeta,\theta,v,\xi)$:

$$\left[(\mathbf{v}_{\|} + \mathbf{v_E} + \mathbf{v_M}) \cdot \nabla + \dot{v}\frac{\partial}{\partial v} + \dot{\xi}\frac{\partial}{\partial \xi}\right]\delta f - C(\delta f) = -(\mathbf{v_M}\cdot\nabla + \frac{\partial}{\partial K})f_M + \mathcal{P}f_M\,.$$

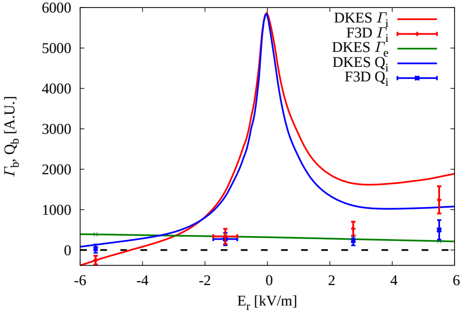
- $\mathbf{v_E} \cdot \nabla \delta f$ is formally higher order, but need to keep it for low collisionalities.
- $\mathbf{v_M} \cdot \nabla \delta f$ of same order than $\mathbf{v_E} \cdot \nabla \delta f$.
  - Usually neglected.
  - For $|E_r|$ small enough may be a bad idea.



Overestimate of NC radial fluxes in the core of stellarators? ⇒
⇒ Underestimate of turbulent fluxes?

Effect on theoretical predictions

- $\mathbf{v_M} \cdot \nabla \delta f$ reduces Γ_i and Q_i for a given E_r.
- E_r from ambipolarity of NC fluxes: $\Gamma_e(E_r) = \Gamma_i(E_r)$
- Γ_e depends (more) weakly on E_r.

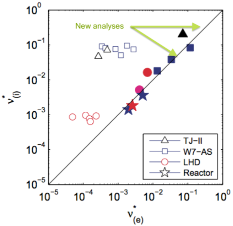


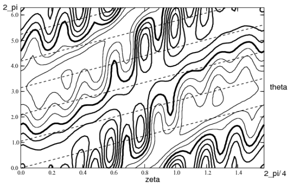
- E_r slightly less negative.
- Γ very slightly reduced.
- Larger reduction in Q_i.

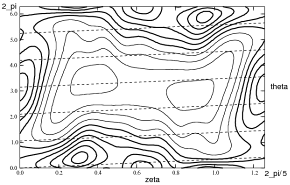
The size of the peak is larger:

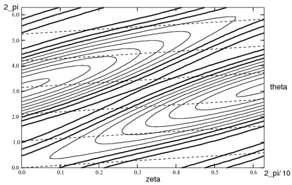
- The smaller the collisionality.
- The larger the deviation from omnigeneity.

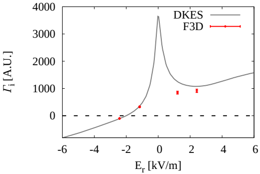
(competing effects).

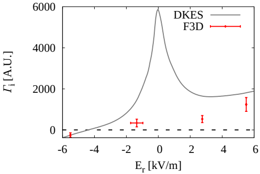


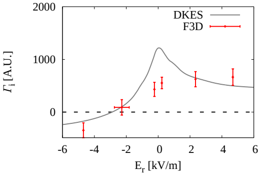












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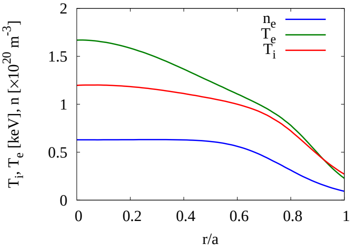
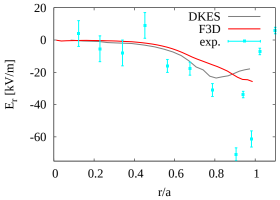
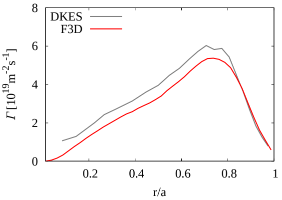
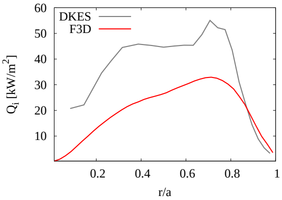
W7-AS #34313



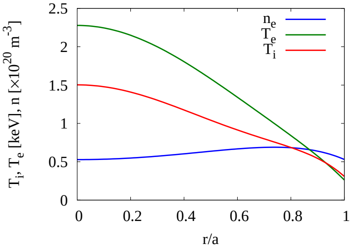
- Low-collisionality W7-AS case.
- Reasonable agreement in E_r.
- Q_i reduced by a factor 2.



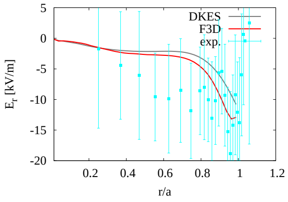


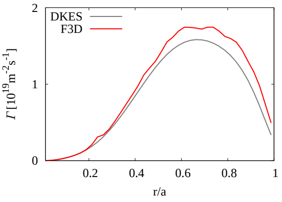


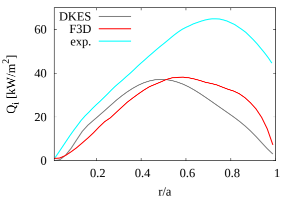
LHD #28263



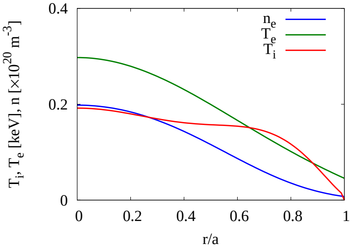
- Lowest collisionality and ripple.
- Q_i from 25% below exp. to 50% below.



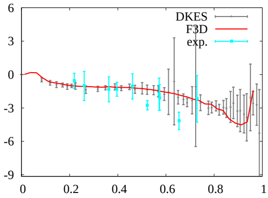


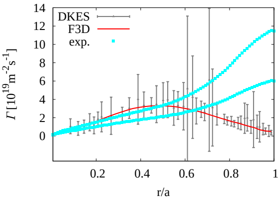


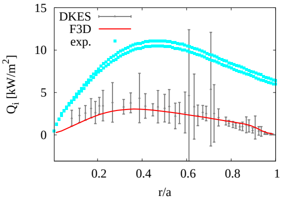
TJ-II #19065



- Agreement in E_r and Γ.
- Predicted Q_i always below experiment (high collisionality).







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Summary

- Neglecting higher order NC terms can lead to underestimate of radial energy flux in the core of stellarators, specially:
  - if the stellarator is not optimized.
  - if the collisionality is small.
- Need to calculate turbulent contribution.
- Bootstrap current? (time-consuming!).
- When W7-X starts operation, check NC predictions.