Gyrokinetic Modelling
of Electron and Boron Density Profiles
of H-mode plasmas in ASDEX Upgrade

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J. Candy and R.E. Waltz are warmly acknowledged for providing
GYRO, M. Kotschenreuther and W. Dorland for providing GS2
Motivations

- Electron particle transport largely understood at qualitative level, requires further quantitative validation.

- At the same time, achieved understanding on electron particle transport can be used as a handle to shed light on the not yet fully unraveled physics of impurity transport.

- Simultaneous comparison between theoretical predictions and observations of electron particle and impurity transport expected to shed mutual light on the physical mechanisms responsible for both.

- In case theoretical modelling is found in qualitative / quantitative agreement, then it can lead to the identification of the control parameters which govern the response of electron and impurity densities.

- During the last AUG campaign, experiments on core plasma response to central ECH in NBI heated H-mode plasmas (toroidal rotation, electron and ion temperature, electron and boron densities) [McDermott EPS 2010 & this mtg 04.01]
Outline

- Survey of experimental observations, central ECH in NBI heated H-mode plasmas in AUG  [ R. McDermott EPS 2010 P1.1062 & this mtg 04.01  ]

- Local parameters, modelling approach and numerical tools

- Modelling of normalized logarithmic gradient of the electron density profile

\[ \frac{R}{L_{ne}} = - \frac{Rdn_e}{dr}/n_e \]

- Modelling of the normalized logarithmic gradient of the Boron density profile, role of rotation

\[ \frac{R}{L_{n_B}} = - \frac{Rdn_B}{dr}/n_B \]

- Conclusions
Central ECH increases the density peaking in AUG NBI heated H-modes at low plasma current

- ... and flattens ion temperature and rotation  [McDermott EPS 2010 & this mtg 04.01]

- Confirms and extends previous observations  [Manini PPCF 04 & NF 06, Angioni NF 04 & PoP 05]
Boron density profiles are flat or hollow in NBI heated only phases

- Likewise electron density, boron density peaking increases in response to central ECH, but remains significantly less peaked than electrons around mid-radius

- Flat to hollow carbon profiles in H-modes also observed in JET [Weisen NF 05, Giroud IAEA 06]
Local parameters at $r/a = 0.5$ where $R/L_{\text{ne}}$ is maximum, input of gyrokinetic modelling

- Average values over stationary phases with various NBI / ECH heating powers
- $R/L_{\text{ne}}$ increases with increasing $T_e / T_i$, $L_{Ti} / L_{Te}$ and decreasing collisionality

![Graphs showing $R/L_{\text{ne}}$ as a function of various parameters](image-url)
Boron mostly hollow or flat with NBI only, moderately peaked with high ECH power

- R/LnB at r/a = 0.5 remains always smaller than the corresponding R/Lne

![Graph 1](image1)

![Graph 2](image2)
Compare density peaking with previous multi-device database

- Dependence on collisionality stronger with respect to previous database, suggests a combined effect of reduced collisionality and increased $Te/Ti$ & $LTi/LTe$ in enhancing the density peaking.

[Angioni PPCF 09]
GK modelling looks for $R/Ln$ at which particle flux over heat flux matches the exp value

- Intepretative transport analysis (particle, power balance) with TRANSP & ASTRA
- Particle source provided by beam neutrals only (wall neutrals neglected)
- Largest uncertainty from profile of radiated power density
- For given set of input parameters, taken from experimental measurements,
- Identify value of $R/Ln$ at which

$$\frac{\Gamma_{trb}}{Q_{tot trb}} = \frac{\Gamma_{NBI} - \Gamma_{W}}{Q_{H exp} - Q_{inc}}$$

- Good agreement between GK linear (GS2) and nonlinear (GYRO) calculations of $R/Ln$ scans
- QL rule from QuaLiKiz [ Bourdelle PoP 07 ]

Nonlinear : GYRO & Linear : GS2
Experimental behaviour reproduced by QL & NL gyrokinetic modelling

- Microinstabilities and turbulence are ITG
- Mode real frequency moves from large (NBI only) to close to zero (high ECH)
- Real frequency almost perfect proxy of both measured and predicted value of \( R/L_{ne} \)  
  [Fable PPCF 2010]
- Results are sensitive to input parameters (e.g. \( \frac{T_e}{T_i} \), \( R/L_{Te} \), \( \nu_{ei} \))

![Graphs showing experimental data and predictions for QL GS2, NL GYRO](image)
All parameters important to reproduce experimental behaviour

- Any single parameter varied alone \([T_e/T_i, \nu_{ei}, (R/L_{Te}, R/L_{Ti})]\)
predicts an increase of R/L_ne much weaker than when all parameters are varied together, like in the experiment.
Better understanding on the physical mechanisms from an analytic expression

- **Gyrokinetic equation**

\[
(\omega - \omega_{Gk} + iv_{ei} ) \hat{g}_k = \left\{ \omega_{Dk} \left[ \frac{R}{L_n} + \left( \frac{E}{T_e} - \frac{3}{2} \right) \frac{R}{L_{Te}} \right] - \omega \right\} F_M J_0(k_{\perp} \rho_s) \hat{\phi}_k,
\]

- **Particle flux**

\[
\Gamma_{QL} = \sum_k \left( \frac{k_y c_s^2}{\Omega_{ci}} \int d^3v F_M \frac{(\hat{\gamma}_k + \hat{v}_k)[R/L_n + (E/T_e - 3/2)R/L_{Te}] - (\hat{\gamma}_k \hat{\omega}_{Gk} - \hat{\omega}_{rk} \hat{v}_k)}{(\hat{\omega}_{rk} + \hat{\omega}_{Gk})^2 + (\hat{\gamma}_k + \hat{v}_k)^2} J_0(k_{\perp} \rho_s)^2 |\hat{\phi}_k|^2 \right).
\]

- With decreasing ITG real frequency, and increasing R/LTe,
  - outward contribution produced by collisions decreases, and
  - inward contribution at low energy from thermodiffusion is enhanced

[ Angioni PPCF 09, Angioni PoP 09, Fable PPCF 10 ]
With ECH, outward pure convection drops and inward thermodiffusion increases

- Pure convection is outward, and decreases with decreasing real frequency (term $\hat{\omega}_r k \hat{D}_k$).

- Thermodiffusion contribution increases (increase of $R/L_{Te}$).

- The two effects together lead to the strong increase of density peaking with increasing ECH power.

![Graph showing the relationship between $D_{Th}/D_N$ and $R_{V_{tot}}/D_N$ with $T_e/T_i$.
Modelling of Boron, include both turbulent and neoclassical transport

- Sum turbulent and neoclassical convection and diffusion

\[
\frac{R}{L_{nZ}} = - \frac{RV_{Z \text{ trb}} + RV_{Z \text{ NC}}}{D_{N Z \text{ trb}} + D_{N Z \text{ NC}}}
\]

\[
\downarrow
\]

\[
\frac{R_i}{L_{nZ}} = - \frac{RV_{Z \text{ trb}}/\chi_{i \text{ trb}} + RV_{Z \text{ NC}}/\chi_{i \text{ PBan}}}{D_{Z \text{ trb}}/\chi_{i \text{ trb}} + D_{Z \text{ NC}}/\chi_{i \text{ PBan}}}
\]

- Normalization to effective heat conductivity ensures appropriate size of turbulent transport component, as compared with actual experimental heat flux
GK modelling of Boron, turbulent transport contributions

- Turbulent impurity flux can be decomposed in [Y. Camenen et al PoP 2009]
diagonal diffusion, thermo-diffusion, roto-diffusion and pure convection

\[
\frac{R \Gamma_{nZ}}{nZ} = D_{NZ} \frac{R}{L_{nZ}} + D_{ThZ} \frac{R}{L_{TZ}} + D_{UZ} u'_Z + RV_{pZ}
\]

- Turbulent impurity flux computed by gyrokinetic calculations in the plasma rotating frame
- Gyrokinetic formulation described in [A.G. Peeters et al. PoP 2009] has been implemented in GS2 [N. Kluy et al PoP 2009]

- In this frame, toroidal rotation produces the Coriolis drift, and its radial gradient becomes

\[
u'_Z = R^2 d\Omega_Z / dr / v_{thZ}
\]

- Centrifugal effects have been neglected (but might be non-negligible …)
Neoclassical transport almost negligible at $r/a = 0.5$, turbulent roto-diffusion small but significant

- Turbulent diffusion increases with increasing $T_e/T_i$ (increasing ECH power)
- Turbulent thermodiffusion outward, turbulent pure convection inward (both can be large)
- Roto-diffusion smaller, but non-negligible
Comparison over the entire dataset delivers a promising (may I say satisfactory?) agreement

- Agreement for the NBI heated only phase, roto-diffusion is the critical ingredient to predict negative values of R/LnB (local hollowness)
- Experimental trend from R/LnB \(\leq 0\) with NBI only to R/LnB > 0 with high ECH power is reproduced by the modelling
- However particularly the phase with low ECH power is not predicted accurately

With roto-diffusion

Without roto-diffusion
Outward thermodiffusion and roto-diffusion become small with high ECH power, leading to positive $R/LnB$

- With negligible neoclassical transport, $R/LnB$ results from the sum of turbulent contributions only

\[
\frac{R}{LnB} \approx -\frac{D_{ThZ}}{D_{NZ}} \frac{R}{L_{TB}} - \frac{D_{UZ}}{D_{NZ}} u_{Br}' - \frac{RV_{PZ}}{D_{NZ}}
\]
Small variations of parameters can have large impact on the R/LnB predictions

- Predictions of R/LnB result from unbalance among big & opposite contributions, can be largely modified by relatively small variations of each one
- Reduction or increase of R/L_{TB} and/or u’ can largely impact predicted R/LnB, particularly for the low ECH phase
- Role of roto-diffusion to provide almost continuous transition from slightly hollow to moderately peaked boron profiles with increasing ECH power is confirmed

![Graph showing the impact of roto-diffusion on R/LnB predictions](image)
Conclusions

- Electron and boron density peaking increases in response to central ECH in NBI heated AUG H-mode plasmas. Boron significantly less peaked than electrons, can be locally hollow with NBI only.

- Gyrokinetic predictions of R/Lne and R/LnB are in agreement with the observations (quantitative for electrons, promising/satisfactory for boron).

- Thereby, theoretical modelling allows the identification of control parameters which govern the electron and boron density responses.

- Combination of effects (increase of Te/Ti & LTi/LTe in ITG turbulence) explain electron density peaking, where the real frequency of the mode is shown to be an almost perfect proxy of R/Lne.

- “... density profile behaviour can be interpreted as a macroscopic fingerprint of the type of turbulence present in the core of the plasma“ [Angioni PPCF 09]

- Neoclassical transport negligible, turbulent roto-diffusion appears to be the necessary ingredient to predict the observed variation from slightly hollow to moderately peaked boron profiles with increasing ECH power.

- Roto-diffusion likely to be the missing ingredient which can explain hollow carbon profiles in typical H-mode plasma conditions.
THE END