Peaked Density Profiles in Low Collisionality H-mode in JET, ASDEX Upgrade and TCV

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- Motivation
- AUG-JET combined density profile database
- Most relevant and significant variables governing density profile peaking
- Regressions and ITER extrapolations
- Density profiles under intense electron heating
- Impact on fusion performance
- Conclusions
Peaked density profile ⇒ more fusion power

\[ P_{\text{fus}} \propto n_D n_T <\sigma v> \propto n^2 T^2 \propto p^2 \text{ for } 7 \leq T \leq 20 \text{ keV} \]

Peaked density profiles ⇒ more bootstrap current.

Peaked density profiles ⇒ higher core density for given edge density.

Peaked density profiles may compensate for lower than expected density limit in ITER (Borrass, NF 2004)

Peaked density profiles prone to neoclassical impurity accumulation at high Z and/or at low anomalous transport (e.g. C. Giroud, EX / 8-3)
Separate studies in AUG & JET

- Density profiles in ELMy H-mode more peaked at low collisionality $\nu_{\text{eff}} = 10^{-14} Z_{\text{eff}} R_0 n_e T_e^{-2} \text{ (SI,eV)}$

C. Angioni et al, PRL 90 (2003) 205003

H. Weisen et al, NF 45 (2005) L1-L4

**COMBINED DATABASE (2006)**
277 JET H-modes, 343 AUG H-modes

Reduced colinearities between physics variables
Dimensionless physics variables

- Fundamental parameters from drift wave theory
  \[ \rho^* = 4.37 \times 10^{-3} \left( \frac{m_{\text{eff}} \langle T_e \rangle^{1/2}}{aB_T} \right) \]
  \[ \nu_{\text{eff}} = 2 \times 10^{-14} \langle n_e \rangle R_0 / \langle T_e \rangle^2 \]
  \[ \beta = 4 \times 10^{-3} \langle p \rangle / B_T^2 \] (as used by ITPA)

- Dimensionless NBI source term from diffusion-convection equation in steady state
  \[ \frac{R_0 \nabla n}{n} = - \frac{R_0}{D} \left( \frac{\Gamma}{n} + V \right) \]

\[ \Gamma^* = \frac{R_0 \Gamma}{nD} \approx 2T \frac{\chi}{D} \frac{\Gamma}{Q_{\text{NBI}}} \frac{Q_{\text{NBI}}}{Q_{\text{TOT}}} \frac{R_0}{T} \frac{dT}{dr} \]

- Additional variables: \(N_{\text{GR}}, q_{95}, T_e(\rho=0.2)/\langle T_e \rangle, \delta, (R_0)\)

- Flux due to edge neutrals in core region poorly known, but typically one order of magnitude below NBI flux (Zabolotsky NF 2006, Valovic NF lett. submitted). Not included here.
• Peaking factor: $n_e(\rho=0.2)/<n_e>$
• But different diagnostics & different analysis on JET and AUG ⇒ systematic errors ⇒ large errors on regressions
• Method: JET density profiles from interferometry remapped onto (virtual) AUG interferometer geometry, JET & AUG inverted using same geometry and same set of basis functions
• JET original and remapped/inverted agree within 2%, validates virtual interferometer method.
• Systematic errors may exist for other variables.
  – Introduced $R_0$ as a device label.
  – If regressed variable scales with $R_0$ that may indicate possible systematic errors in variables or inadequate choice thereof
Bivariate correlations

- Wide variety of discharges conditions, with and without beam fuelling
- Correlation of $\ln \nu_{\text{eff}}$ with $N_{\text{GR}}=\langle n_e \rangle/\langle n_{\text{GR}} \rangle$ is strong
- Correlations of $\ln \nu_{\text{eff}}$ with $\Gamma^*$ and $\rho^*$ in combined database are weak
- Density peaking increases as $\nu_{\text{eff}}$ drops, even in absence of NBI fuelling
- Greenwald fraction nearly as correlated with density peaking as $\ln(\nu_{\text{eff}})$
- Peaking in NBI-only discharges correlates with source parameter
- Correlations with $\rho^*$, $q_{95}$, $T_e(0.2)/\langle T_e \rangle$, $\delta$ and $\omega_c \tau_E$ are insignificant
Multivariate regressions

- \[ n_{e2}/<n_e> = a_0 + \sum_i a_i X_i \text{ and } n_{e2}/<n_e> = a_0 \prod_i X_i^{a_i} \]
- \[ 1 \leq n_{e2}/<n_e> \leq 2 \Rightarrow \text{both forms equivalent} \]
- Tested many combinations of variables

Criteria*:

1. **Statistical relevance** of variable \( i \)
   \[ \text{StR}_i = a_i \times \text{STD}(X_i)/\text{STD}(n_{e2}/<n_e>) \]
   (How much does the variation of variable \( i \) contribute to the variation of \( n_{e2}/<n_e> \)?)

2. **Statistical significance**
   \[ \text{StS}_i = a_i / \text{STD}(a_i) \]
   (How well is the coefficient of variable \( i \) determined?)

3. **RMSE of fit**
   (How good is the fit?)

* O. Kardaun, Classical Methods of Statistics, Springer Verlag, 2005
Multivariate regressions

- Strong correlation between $v_{\text{eff}}$ and $N_{\text{GR}}$

  $\Rightarrow$ regress with only one and both, with and without device label $R_0$
  
  (details: see poster/paper EX/8-4 or C.Angioni NF lett. submitted)

- Summary of multivariate study:

  - $v_{\text{eff}}$ is the most relevant whenever included in a fit (mostly also most significant)
  - $\Gamma^*$ is relevant and significant whenever included
  - $N_{\text{GR}}$, $R_0$ and/or $\rho^*$ become significant and relevant only if $v_{\text{eff}}$ is excluded
  - $\beta$ may be significant or not depending on other variables. Small contribution.
  - $q_{95,T_e}(\rho=0.2)/\langle T_e \rangle$, $\delta$ always insignificant and irrelevant
Multivariate regressions

\[ \frac{n_{e2}}{\langle n_e \rangle} = 1.35 \pm 0.015 - (0.12 \pm 0.01) \ln \nu_{\text{eff}} + (1.17 \pm 0.01) \Gamma^* - (4.3 \pm 0.8) \beta \]  

**ITER: 1.45**

- All fits including \( \nu_{\text{eff}} \) predict peaked profile for ITER \( \frac{n_{e2}}{\langle n_e \rangle} > 1.4 \)
- All fits excluding \( \nu_{\text{eff}} \) predict flat profile for ITER \( \frac{n_{e2}}{\langle n_e \rangle} \sim 1.2 \)
- However theory (dimensionless scaling) and appearance of strong \( R_0 \) dependence when \( \nu_{\text{eff}} \) omitted, suggest that it is wrong to exclude \( \nu_{\text{eff}} \).
- JET/AUG study therefore suggests that ITER will have \( \frac{n_{e2}}{\langle n_e \rangle} > 1.4 \)

**EXAMPLE**

![Graph showing data points for AUG, JET, AUG ICRH, and JET ICRH with fitting lines and labels](image)
Other parameters

- Combined database does not (yet) have Ti and local shear, n_C, but subset of JET data does.

- Impurities generally not more peaked than electrons, carbon even significantly less (Giroud EX/8-3).

- No correlation of n_e2/\langle n_e \rangle and l_i or local magnetic shear from polarimetry (at odds with theory and with L-mode results elsewhere)

- No correlation between n_e2/\langle n_e \rangle and T_e2/\langle T_e \rangle (at odds with theory)

- Evidence for thermodiffusion: weak dependence on T_i/T_e in JET subset

- T_i/T_e influence qualitatively consistent with theory: low T_i/T_e \Rightarrow flatter profiles

- Coefficient for source in fit for R/L_n at mid-radius provides experimental value for \chi/D \sim 1.5 consistent with anomalous transport theory (Garbet, 2004)

\[
R \nabla n_e/n_e = 0.97 \pm 0.34 - (0.65 \pm 0.1) \ln \nu_{\text{eff}} + (1.46 \pm 0.63) \nabla T_e/T_e + (0.65 \pm 0.4) T_i/T_e
\]

\textbf{ITER: } R \nabla n_e/n_e \approx 2.6, n_e2/\langle n_e \rangle \sim 1.46
Peaked, purely electron heated H-modes with $\beta_N=2$ in TCV

- Theory suggests that strong TEM may reduce or completely remove density peaking by outward thermodiffusion (Garbet, PPCF 2004)
- Flattening with core ECRH observed in several devices, i.e. TCV L-modes (Zabolotsky EX/P3-7) and often attributed to TEMs.
- Suggest $\alpha$-heated ITER may have flat density profile
- Flattening not seen in JET ICRH H-modes, possibly due to low power

- Recent 1.5 MW ECRH-heated TCV H-modes at $\nu_{\text{eff}} \sim 0.4$ are peaked despite $T_e/T_i \sim 2$ at $\beta_N \sim 2$
  
  (L. Porte, EX/P6-20)

- Weak $T_e/T_i$ influence on JET and these TCV results suggest thermodiffusive density flattening not significant in ITER, which will be closer to equipartition.
• $P_{\text{fus}}$ increases by >30% for $n_{e2}/\langle n_e \rangle = 1.46$ (ITER) at constant $\beta$ and $n_{D,T}$

• For inductive reference $Q=10$ scenario (Polevoi 2003), auxiliary heating can be reduced from 40MW with flat profile to 15MW.

• $\Rightarrow Q \sim 30$ if $\tau_E$ unchanged!

• No correlation between $n_{e2}/\langle n_e \rangle$ and dimensionless global energy confinement time $\omega_{ce}\tau_E$:

• $\Rightarrow$ we expect current confinement predictions for ITER to hold, even if density peaking has is not explicitly accounted for in scaling laws for $\tau_E$

![Graph showing relative DT fusion power vs. $n_{e2}/\langle n_e \rangle$](image)
Pressure profile merit factor

- Fusion power for fixed $\beta$ maximized for $d\ln<\sigma v>/d\ln T_i=2$ (around 10keV)
- $\Rightarrow p_{\text{fus}} \propto \rho^2$, $P_{\text{fus}} \propto \int \rho^2 dV = <\rho^2>V$
- $\Rightarrow$ Pressure profile merit factor $<\rho^2>/\langle \rho \rangle^2$
- Density profile contribution to merit factor is $<\rho^2>/\langle \rho \rangle^2$

$\langle \rho^2 \rangle/\langle \rho \rangle^2 \propto \int \rho^2 dV = <\rho^2>V$
- $\Rightarrow$ Pressure profile merit factor $<\rho^2>/\langle \rho \rangle^2$
- Density profile contribution to merit factor is $<\rho^2>/\langle \rho \rangle^2$

$<\rho^2>/\langle \rho \rangle^2$ and density contribution increase towards lower collisionalities
- Effect of density peaking not cancelled by temperature flattening
- Regression for ITER : $<\rho^2>/\langle \rho \rangle^2 \sim 1.55$ and $\langle \rho^2 \rangle\langle T \rangle^2/\langle \rho \rangle^2\langle T^2 \rangle \approx 1.25$
Conclusions

- Dominant contribution to density peaking in H-mode is anomalous
- Collisionality is most significant variable
- NBI fuelling in JET and AUG also significant
- Scaling with $\nu_{\text{eff}}$, $T_e/T_i$ and beam source consistent with $D/\chi_{\text{eff}} \sim 2/3$
- Scaling does not follow simple theoretical expectations with $q_{95,i,T_e(0.2)}/\langle T_e \rangle$
- NBI-free, ECH heated H-modes in TCV with $\beta_N=2$ and $T_e/T_i=2$ show that peaking is not suppressed by electron heating
- Extrapolations to ITER predict $n_{e2}/\langle n_e \rangle > 1.4$
- Pressure profile merit factors $\langle p^2 \rangle/\langle p \rangle^2$ and $\langle p^2 \rangle/\langle p \rangle \langle T^2 \rangle$ increase towards low $\nu_{\text{eff}}$ similarly to $n_{e2}/\langle n_e \rangle$
- ~30% extra fusion power due to density peaking in ITER inductive reference scenario (fixed $\beta$ and $n_{D,T}$)