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

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H-modes in JET, ASDEX Upgrade and TCV

- 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 $\Rightarrow$ more fusion power

$$P_{\text{fus}} \propto n_D n_T \langle \sigma v \rangle \propto n^2 T^2 \propto p^2 \text{ for } 7 \leq T \leq 20 \text{ keV}$$

Peaked density profiles $\Rightarrow$ more bootstrap current.

Peaked density profiles $\Rightarrow$ 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 $\nu_{\text{eff}} = 10^{-14} Z_{\text{eff}} R_0 n_e T_e^{-2}$ (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
  \[ \rho^* = 4.37 \times 10^{-3} \left( m_{\text{eff}} \langle T_e \rangle \right)^{1/2} / (a B_T) \]
  \[ \nu_{\text{eff}} = 2 \times 10^{-14} \langle n_e \rangle R_0 / \langle T_e \rangle^2 \]
  \[ \beta = 4 \times 10^{-3} \langle p \rangle / B_T^2 \]  (as used by ITPA)

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

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

- 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: \( n_e(\rho=0.2)/\langle n_e \rangle \)
• 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 $\omega_{ce}\tau_E$ are insignificant
Multivariate regressions

- \( \frac{n_{e2}}{\langle n_e \rangle} = a_0 + \sum a_i X_i \) and \( \frac{n_{e2}}{\langle n_e \rangle} = a_0 \prod X_i^{a_i} \)
- \( 1 \leq \frac{n_{e2}}{\langle n_e \rangle} \leq 2 \Rightarrow \) both forms equivalent
- Tested many combinations of variables
- Criteria*
  1. **Statistical relevance** of variable \( i \) \( \text{StR}_i = \frac{a_i \times \text{STD}(X_i)}{\text{STD}(n_{e2}/\langle n_e \rangle)} \)
     (How much does the variation of variable \( i \) contribute to the variation of \( n_{e2}/\langle n_e \rangle \)?)
  2. **Statistical significance** \( \text{StS}_i = \frac{a_i}{\text{STD}(a_i)} \)
     (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 $\nu_{\text{eff}}$ and $N_{\text{GR}}$

$\Rightarrow$ regress with only one and both, with and without device label $R_0$

**significance/relevance**

<table>
<thead>
<tr>
<th>Variables excluded</th>
<th>$\Gamma^*$</th>
<th>$\ln \nu_{\text{eff}}$</th>
<th>$N_{\text{GR}}$</th>
<th>$\rho^*$</th>
<th>$\beta$</th>
<th>$R_0$</th>
<th>rmse</th>
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<tbody>
<tr>
<td>$N_{\text{GR}}$</td>
<td>5.2/0.39</td>
<td>5.2/0.49</td>
<td>1.0/0.13</td>
<td>2.5/-0.24</td>
<td>2/0.25</td>
<td>0.113</td>
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<tr>
<td>$N_{\text{GR}}$ &amp; $R_0$</td>
<td>4.8/0.34</td>
<td>10.2/-0.04</td>
<td>0.2/-0.02</td>
<td>1.7/-0.16</td>
<td>0.114</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ln \nu_{\text{eff}}$</td>
<td>7.3/0.49</td>
<td>3.0/-0.53</td>
<td>0.9/0.14</td>
<td>1.5/0.17</td>
<td>4.1/0.47</td>
<td>0.121</td>
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<tr>
<td>$\ln \nu_{\text{eff}}$ &amp; $R_0$</td>
<td>6.2/0.42</td>
<td>8.5/-0.61</td>
<td>2.5/-0.27</td>
<td>0.9/0.09</td>
<td>0.126</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>5.2/0.39</td>
<td>4.3/-0.57</td>
<td>0.9/0.13</td>
<td>1.4/0.2</td>
<td>2.6/0.31</td>
<td>2.2/0.29</td>
<td>0.112</td>
</tr>
<tr>
<td>$R_0$</td>
<td>4.7/0.34</td>
<td>5.2/0.68</td>
<td>0.4/0.05</td>
<td>0.04/-0.05</td>
<td>1.7/0.18</td>
<td>0.114</td>
<td></td>
</tr>
</tbody>
</table>

- $\nu_{\text{eff}}$ 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 $\nu_{\text{eff}}$ 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

\[
n_{e2}/\langle n_e \rangle = 1.35 \pm 0.015 - (0.12 \pm 0.01) \ln \nu_{\text{eff}} + (1.17 \pm 0.01) \Gamma^* - (4.3 \pm 0.8) \beta \quad \text{ITER: 1.45}
\]

- All fits including \( \nu_{\text{eff}} \) predict peaked profile for ITER \( n_{e2}/\langle n_e \rangle > 1.4 \)
- All fits excluding \( \nu_{\text{eff}} \) predict flat profile for ITER \( n_{e2}/\langle n_e \rangle \approx 1.2 \)
- 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 \( n_{e2}/\langle n_e \rangle > 1.4 \)
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/⟨n_e⟩ and I_i or local magnetic shear from polarimetry (at odds with theory and with L-mode results elsewhere)

- No correlation between n_e2/⟨n_e⟩ and T_e2/⟨T_e⟩ (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 ⇒ flatter profiles

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

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

ITER: \( R \nabla n_e/n_e \sim 2.6, \ n_e2/⟨n_e⟩ \sim 1.46 \)
Lack of shear dependence confirmed with polarimeter-EFIT

- Subset of 51 samples has polarimeters constrained EFIT
- Similar density profile for flat & positive shear
- Finite density gradients at zero shear
- No correlation of peaking with $R \nabla q/q$ when most important dependencies subtracted out (below)
- Theoretically puzzling
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.
Implications for fusion power

- \( P_{\text{fus}} = 17.6 \times 10^6 \int n_D n_T <\sigma v> dV \)
  increases by >30% for \( n_{e2}/<n_e> = 1.46 \) (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.

  \( \Rightarrow Q \approx 30 \) if \( \tau_E \) unchanged!

- No correlation between \( n_{e2}/<n_e> \) 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 \( \tau_E \)

- Ti profile as in inductive reference scenario assumed

- Improvement less strong if Ti profile is broader
Performance increase depends on Ti profile

- Each sample in JET database treated as model for ITER: scaled to $\beta_N=1.8$, $N_{GR}=0.86$, $V=831\text{m}^3$,
- Dilution adjusted to get 400MW for Ti profile like ITER inductive reference \((\text{Polevoi 2003})\) and for flat $n_{D,T}$.
- Peaked Ti profiles (small pedestals) lead to strongest increase with peaked density profiles.
- Most temperature profiles in JET are broader than in ITER inductive scenario.
- This means less fusion power for given $\beta_N$, $N_{GR}$. 
• Fusion power for fixed pressure maximized for $d\ln \langle \sigma v \rangle / d\ln T_i = 2$ because $p_{\text{fus}} = n_D n_T \langle \sigma v \rangle \propto \langle \sigma v \rangle p^2/T^2$ (around 10keV)

• $\Rightarrow p_{\text{fus}} \propto p^2$, $P_{\text{fus}} \propto \int p^2 dV = \langle p^2 \rangle V$

• $\Rightarrow$ Pressure profile merit factor $\langle p^2 \rangle / \langle p \rangle^2$

• $\langle p^2 \rangle / \langle p \rangle^2$ increases towards lower collisionalities

• Effect of density peaking not cancelled by temperature flattening as already expected from lack of correlation between temperature and density peaking

• Pressure profile consistency theory (Kadomtsev) falsified
Density profile merit factor

- Density profile contribution to merit factor is

\[
\frac{\langle p^2 \rangle}{\langle p \rangle^2} / \frac{\langle T^2 \rangle}{\langle T \rangle^2}
\]

- Density profile merit factor increases towards lower collisionalities

- Merit factors can be regressed just like density peaking factor
  Regression for ITER: \( \langle p^2 \rangle / \langle p \rangle^2 \sim 1.55 \) and \( \langle p^2 \rangle \langle T \rangle^2 / (\langle p \rangle \langle T^2 \rangle) \approx 1.25 \)

- Density contribution to power increase somewhat less (25%) than expected from Ti profile like inductive scenario (30%) because most temperature profiles are broader than in inductive scenario.
Discussion (I)

- Dominant contribution to density peaking in H-mode is anomalous
- Collisionality is most significant and relevant variable
- NBI fuelling in JET and AUG also significant and relevant
- Consistent with theory:
  Scaling with $\nu_{\text{eff}}, T_i/T_e$ and beam source consistent with $D/\chi_{\text{eff}} \sim 2/3$
- Inconsistent with theory:
  Scaling does not follow simple theoretical expectations with respect to magnetic shear and thermodiffusion ($q_{95}, l_i, T_e(0.2)/\langle T_e \rangle$)
- H-modes contrast with L-modes in TCV (dependence on current profile and no collisionality dependence, Zabolotsky EX/P3-7)
- 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. Flattening by alphas even less likely in ITER because of good equipartition.
• Extrapolations to ITER predict \( n_{e2}/\langle n_e \rangle > 1.4 \)

• Pressure profile merit factors
\[
\langle p^2 \rangle / \langle p \rangle^2 \text{ and } \langle p^2 \rangle \langle T \rangle^2 / \langle \langle p \rangle^2 \langle T^2 \rangle \rangle \text{ increase towards low } \nu_{\text{eff}} \text{ similarly to } n_{e2}/\langle n_e \rangle
\]

• \(~30\%\) extra fusion power due to density peaking in ITER inductive reference scenario (fixed \( \beta \) and \( n_{D,T} \))

• However if ITER \( T_i \) profiles are broader (higher \( T_{\text{ped}} \)) than in inductive scenario, density peaking may just make up for this…(at fixed \( \beta \))

• Peaked density \( \Rightarrow \) lower pedestal density for given \( N_{GR} \). Makes detachment harder.

• If density limit linked to pedestal, overall density may be increased with lower \( T_i \) (to conserve \( \beta \) for given scenario). Erodes some, but not all of the performance benefit of peaked density profiles (Weisen et al, PPCF, 2006)
Download this poster from crppwww.epfl.ch/~weisen/publications

Acknowledgement:

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References in 8-page paper:

• Double TCV and Kn1D neutral penetration calculations for TCV and JET show that peaking cannot be explained by edge neutral penetration, unless $\chi/D$ is assumed to vary by 2 orders of magnitude within confinement zone… (Zabolotsky NF 2006)

• Similarly for Ware pinch, $\chi/D$ needs to be $>50$ to produce peaking of right magnitude (but scaling with $V_{\text{loop}}$ not ok)
In D plasmas edge neutrals can penetrate by charge exchange chains (~ 4 steps before ionization)

In He plasmas charge exchange chains quenched because of low cross section for double CX (ionization more likely)

Nonetheless He plasmas as peaked as otherwise identical D plasmas (Zabolotsky NF 2006)
• See Giroud EX/8-3!

• Except when core accumulation, impurity density profiles are not more peaked than electron density.

• Carbon even considerably less peaked, irrespective of collisionality (Weisen NF 2005 L1-L4)