Core Density Peaking Experiments in JET, DIII-D and C-Mod in Various Operational Scenarios – Driven by Fueling or Transport?

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*See the author list of X. Litaudon et al (2017), Nucl. Fusion 57 102001.
Do We Understand Where Core Density Peaking is Coming from?

- High density in the core is desirable for fusion $P_{fus} \sim n_e^2$

- Previous works [1-5] have identified strong dependency between density peaking and collisionality $\nu^*$ or $\nu_{eff}$
  - Multi-machine steady state databases
  - Theory + GK modelling have identified mechanisms

- In this talk, we will clarify what is still missing:
  - Origin of the peaking (transport versus fueling)
    - Linear regression limited to database averages
  - Test of models against dedicated $\nu^*$ scans

- This is the first time when electron particle transport coefficients in H-mode have been measured in tokamaks with high resolution diagnostics yielding a unique dataset

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Gas Puff Modulation Experiment to Obtain Electron Particle Diffusivity $D$ and Convection $\nu$

- Gas puff modulation at 2-4Hz frequency at the top of the vessel
- Both high resolution Thomson Scattering and density profile reflectometry diagnostics to follow the propagating density wave
- Modulation amplitudes of the order of 1% in the core measured
- Using perturbative approach, $\tilde{n} = A \sin(\omega t + \phi)$, and linearization and some algebra, we will obtain the electron particle transport coefficients $D$ and $\nu$
The Experimental Set-up for the 3-point $\nu^*$ Scans – the DIII-D Scan Here as an Example

- Collisionality scan is obtained by changing $B_T, I_P, \text{NBI power, torque and fueling}$
- Dimensionless parameters matched typically to within 10% both in DIII-D and JET
- Change in $\nu^*$ in each scan a factor of 5-6
- Excellent dataset for code validation
Five Separate Dimensionless $\nu^*$ Scans Performed in Total on JET and DIII-D – Density Peaking Increases with Decreasing $\nu^*$ in All H-mode Scenarios

Baseline ELMy H-mode

Hybrid-like scenario

DIII-D

ELMy H-mode in Hydrogen

L-mode plasma

How does I-mode on C-Mod compare?
Inward Pinch Increases with Decreasing $\nu^*$

- Particle transport coefficients are higher on DIII-D than on JET
- Higher transport coefficients on DIII-D due to larger plasma volume and higher NBI power density and ECH consequences on the origin of the density peaking
- Lowest $\nu^*$ discharge on DIII-D jumps off the scan

Averaged over $\rho=\{0.5,0.8\}$

\[
\frac{NBI}{DIII-D} \frac{S_{NBI}}{n_e} = \frac{DIII-D}{JET} \frac{S_{NBI}}{n_e}
\]
Beam Emission Spectroscopy (BES) Data Suggests an Increase in ITG at low $\nu^*$ – Indicative of Increase in the Inward Thermo-Diffusion Pinch

**Beam Emission Spectroscopy (BES), ITG range**

- Low-k fluctuations ($k_\theta \rho_s < 1$) increase moderately with lower collisionality

- Higher k fluctuations ($k_\theta \rho_s \sim 1 - 5$) decrease moderately with lower $\nu^*$

**Doppler Back Scattering (DBS)**

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NBI Fueling Contributes around 50-70% to the Density Peaking in JET H-mode Plasmas

- The experimental D and V show that the contribution of NBI fueling to $n_e$ peaking is 50-70% in the ELMy H-mode scan in JET.

- This fraction is independent of $\nu^*$.

- In this parameter regime (3-point $\nu^*$ scan) at $q_{95}=5$, $T_i/T_e=1$, $\beta_N=1.4$, $\rho*=0.003$ and $\nu^*=[0.1,0.5]$, the NBI fueling is dominant.
On DIII-D, Density Peaking from NBI is 15-30%

- The experimental D and V show that the fraction of NBI fueling is 15-30% on DIII-D

- This fraction decreases with decreasing $\nu^*$

- Clearly JET and DIII-D are different wrt density peaking. Why?
  - NBI particle source – no, DIII-D source stronger
  - Transport – yes, Trapped Electron modes (TEM) stronger than in JET, JET is deeply ITG dominated
  - Diffusion larger on DIII-D than on JET, JET has larger confinement time, thus the source stays in the plasma way longer in JET
Model and Code Validation ....
GENE [1] predicts flat or even hollow (at high $\nu^*$) density profiles, implying that the NBI particle source dominates in contributing to density peaking.

GENE in agreement with “transport versus fueling” contributions to the density peaking.

Non-linear GENE predicts also flat density profile in JET, suggesting that the NBI particle source dominates in contributing to density peaking.

JET

DIII-D

Stand-alone TGLF predicts the peaking factor in agreement with experimental density peaking.
TGLF Modelling of the JET $\nu^*$ Scan in H-mode –
NBI Source Contributes to Density Peaking at 50-90% Fraction

- TGLF [1] peaking factor from NBI source using the JINTRAC transport code [2]:
  - Low $\nu^*$: 47%
  - High $\nu^*$: 90%

- TGLF predicts similar results for Hybrid and ELMy H-mode in Hydrogen 3-point $\nu^*$ scans

- In L-mode, NBI source less important ~10%

- TGLF performs well against JET discharges for each $\nu^*$

Predictive Capability of TGLF Is Good in DIII-D Provided That $T_i$ Is Predicted Well

- TGLF predictions for the high $\nu^*$ case in agreement with experiment
- TGLF does not predict the flat $T_i$ profile at $\rho=0.5$-$0.8$ for the low $\nu^*$ case
  - Leads to an overestimation of NBI contribution
- Predictive capability of TGLF is fairly good in JET and DIII-D $\nu^*$ scans except for the low $\nu^*$ case on DIII-D
TGLF simulations are in agreement with experimental peaking factors only when the predicted $T_i$ and $T_e$ profiles are in agreement with experimental ones.

This is also seen in stand-alone TGLF simulations.

What happens at lower $\nu^*$ in JET?
- Does NBI fueling lose its dominance to inward pinch?
Predictive Transport Modelling Can Reproduce the Lowest $\nu^*$ JET Discharges

- TGLF captures density peaking with ICRH only $T_e > T_i$
  - Very low density + 8MW of ICRH

- GENE also predicts density peaking correctly

- TGLF reproduces density peaking in low density JET hybrid plasma

- Simulation without fueling suggests ~50% NBI contribution as in the H-mode $\nu^*$ scan

Revisit database corners (no modulation)
The C-Mod discharges do not have NBI fueling – relevant information on the role of NBI fueling and I-mode particle transport is a special case with no density pedestal.

L-mode plasmas have different q-profile and $T_e/T_i$ ratio and thus, density peaking originating from different reasons.

In line with the JET and DIII-D L-mode results, i.e. the I-mode core density peaking does not have any $\nu^*$ dependence.

Gas puff modulation was also performed on C-Mod, but the modulated density data is too noisy to able to extract the particle transport coefficients.
Conclusions: Core Density Peaking – Driven by Fueling or Transport?

- JET is NBI source dominant 50-70% and DIII-D transport dominant (only 15-30% from NBI)
  - Trapped Electron modes (TEM) play a stronger role than in JET (JET is deeply ITG dominated)
  - Lower $\nu^*$, higher magnetic shear, larger $R/L_T e$ and higher $\beta$ in DIII-D than in JET
  - JET has larger confinement time than DIII-D, thus the source stays in the plasma way longer in JET

- Validation of TGLF and GENE against the unique experimental particle transport dataset:
  - TGLF quite convincing against various experimental results provided that $T_i$ predicted accurately enough
  - GENE qualitatively agreeing well with various experimental trends, underestimates the pinch at $T_e/T_i \sim 1$

- Density peaking (also in future devices) depends critically on the parameter regime, such as $\nu^*$, $T_e/T_i$, $L_{Te}/L_{Ti}$, $\beta$ and q-profile

- I-mode particle transport characteristics (core density peaking) are similar to those of L-mode in JET and DIII-D
Particle balance transport coefficients from the experiment in 2 steps

Inside rho<0.8
\[ \frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma \approx S_{NBI} \]

Steady state (1 eq 2 unknowns):
\[ -D \nabla n_e + V n_e = \frac{1}{V} \int V_{S_{NBI}} dv \]

Step 1: Use perturbative approach is to obtain absolute values for the transport (takes the code validation to the next level)
  - Standard approach is to linearize using the ansatz:
    \[ \tilde{n}(\rho, t) = A \sin(\omega t + \phi) \]
    \[ D_{inc} = -\omega \frac{\sin \phi \cdot \int_V A \sin \phi \, dv - \cos \phi \cdot \int_V A \cos \phi \, dv}{A \phi' \cdot \langle |\nabla \rho|^2 \rangle \cdot V'} \]

Step 2: Collisionality scan is also a density gradient scan thus providing \( D_{inc} = f(\nabla n) \). Integration yields [1]:
\[ D \approx \frac{1}{Vn} \int_0^{Vn} D_{inc} d(Vn) \]
Various Analysis Techniques Employed to Obtain the Particle Transport Coefficients

- Density evolution:

- In steady state:

- To disentangle transport from the source perturbative approach is needed
  - Use ansatz: \( \tilde{n} = A(\rho) \sin(\omega t + \phi(\rho)) \)
  - After some algebra [1]:

\[
D \approx -\omega \frac{\sin \phi \cdot \int_v A \sin \phi \, dv - \cos \phi \cdot \int_v A \cos \phi \, dv}{A \phi' \cdot (|\nabla \rho|^2) \cdot \nabla'}
\]

in JET

\[
v \approx -\omega \frac{(A'Y - \phi'AX) \sin \phi + (\phi'AY + A'X) \cos \phi}{A^2 \phi' \cdot (|\nabla \rho|^2) \cdot \nabla'}
\]

in DIII-D

\[
v \approx \frac{D\nabla n}{n} + \frac{1}{n} \int_v S_{NBI} \, dv
\]

Similar 3-Point $\nu^*$ Scan Performed on DIII-D – And Density Peaking Increases with Decreasing $\nu^*$ as in JET
We find good agreement between the reflectometer and Thomson Scattering up to $\rho \sim 0.6$

\[ v = -\omega \frac{(A'Y - \varphi'AX) \sin \varphi + (\varphi'AY + A'X) \cos \varphi}{A^2 \varphi'V'\langle(\nabla \rho)\rangle} \]

\[ D = -\omega \frac{Y \sin \varphi + X \cos \varphi}{A \varphi'V'\langle(\nabla \rho)^2\rangle} \]

\[ v = \frac{\langle(\nabla \rho)^2\rangle}{\langle(\nabla \rho)\rangle} \frac{\partial n_e}{\partial \rho} D + \frac{\int V'Sd\rho}{n_e V'\langle(\nabla \rho)\rangle} \]

Source

\[ X = \int V'(A \cos \varphi)d\rho \]

\[ Y = \int V'(A \sin \varphi)d\rho \]
There is a clear difference in amplitude and phase behavior for the 3-point scan

- Reflectometer data came recently available for all 3 discharges – analysis is ongoing
C-Mod: Gas Puff Modulates Density in I-mode at 5.6T

ICRF (MW), Te0 (keV), D2 demand (a.u.)

NL04 (10^20 m^-2),

n_e @ R=86cm,84cm,78cm,69cm (10^20 m^-3)
No Evidence on Time-Dependent Plasma Background from Fluctuations at 3Hz

- No effect of gas puff modulation on fluctuation level from the correlation reflectometry

- The assumption of the time independent background seems justified

![Graphs showing time-dependent plasma background fluctuations](image-url)
TGLF Simulation around the Operational Parameters of the JET $\nu^*$ Scan