Studies of Turbulence and Transport in the Alcator C-Mod and DIII-D Tokamaks with Phase Contrast Imaging and Gyrokinetic Modeling*


Poster EX-P3-1

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Summary of C-Mod results

• In C-Mod ohmic plasmas the impact of dilution of deuterium ions on transport was studied by injecting medium Z_i ions (Nitrogen, Neon) to verify TGLF (G. Staebler) predictions

• Importantly, in JET seeding plasmas with nitrogen reduces the injection of metallic impurities; similar methods may have to be used in ITER to control metallic impurity (tungsten) injection;

• In C-Mod dilution reduced the turbulent ion transport in the plasma core by increasing the critical ion temperature gradient scale lengths, thus stabilizing ITG modes, in agreement with TGLF predictions

• The density fluctuation amplitudes measured in the plasma core by Phase Contrast Imaging (PCI) showed substantial decrease with nitrogen seeding, in agreement with TGLF and GYRO simulations

• GYRO simulations also reproduced the observed reduction of ion heat transport

• In spite of increased radiation losses the neutron rates increased due to higher Ti
Recent dilution experiments in C-Mod were motivated by earlier experiments (2010-2012), confirmed by TGLF modeling (Staebler and Candy) that reducing $n_D/n_e$ by up to 20% by assuming a few% $Z_i = 8$ impurity species reduced core ion energy transport (Porkolab et al, PPCF 54, 124029 (2012))

Controlled Nitrogen seeding experiments in Alcator C-Mod in 2014 (Ennever, Porkolab, et al, Phys. Plasmas 22, 072507 (2015), ibid 23, 082509 (2016)) and more recently by Neon (Porkolab et al, IAEA FEC 2016) further diluted the plasma, resulting in a reduction of ion energy transport beyond the residual values and also reduced density fluctuations (electron energy transport was changed to a lesser extent)

Reduced ion transport was correlated with reduced turbulence as measured by Phase Contrast Imaging (PCI) in the region $r/a \approx 0.6-0.8$; turbulence is absent for $r/a < 0.5$ due to weak gradients (but sawtooothing at $r/a < 0.3$)

Nonlinear GYRO simulations in regions where turbulence dominates transport agreed with experimental energy fluxes and density fluctuation measurements – turbulence reduction was due either to changes in critical ion temp gradient (LOC regime) or changes in stiffness (SOC regime)

Global energy confinement did not change since improved ion energy confinement was countered by increased core radiation
Ohmic plasmas display two characteristic energy confinement regimes: Linear Ohmic Confinement (LOC) and Saturated Ohmic Confinement (SOC)

- The determining parameter is \( n_e q_{95} \)
  - Safety factor \( q_{95} \approx (B_T / B_p)(a/R) \)
- At low densities, the energy confinement time is linearly related to density: linear ohmic confinement (LOC)
- At high densities, the energy confinement time saturates and is independent of density: saturated ohmic confinement (SOC)
- LOC and SOC plasmas also have different intrinsic rotation directions

Figure from P. Ennever, M. Porkolab, J. Candy, et al, Phys. Plasmas 22, 072507 (2015).
Assuming that plasmas were diluted by a medium Zi impurity species (Zi = 8), TGLF predicted reduced ion energy transport in agreement with experiment.

<table>
<thead>
<tr>
<th>Ion Fraction (nD/n_e)</th>
<th>Z_{eff}</th>
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<tbody>
<tr>
<td>0.93</td>
<td>1.5</td>
</tr>
<tr>
<td>0.84</td>
<td>2.1</td>
</tr>
<tr>
<td>*0.76</td>
<td>*2.7</td>
</tr>
<tr>
<td>0.64</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*Experimental Value

A similar scan assuming Z_{imp} = 40 showed no effect of Z_{eff} on energy transport.

To determine the physics of dilution, ohmic C-Mod plasmas were seeded with nitrogen at a range of $I_p$ and $n_e$ values while $n_e$ was held fixed in time by using a cryopump.

- $q_{95}$ was changed by changing $I_p$, $B_T = 5.4$ T for all plasmas
- Changing $I_p$ changed $P_{OH}$, $T_e$, $T_i$
- Seeding increased $Z_{eff}$ by about 1
- Seeding decreased $n_D/n_e$ by 10-20%
Nitrogen seeding reduced the ion energy flux and increased the ion temperature gradient at $r/a = 0.8$, modifying the turbulent energy transport.

$q_{95} = 3.9$, SOC, $n_D/n_e = 0.95$ (unseeded), $0.84$ (seeded)
The turbulence was measured with phase contrast imaging (PCI), an absolutely calibrated diagnostic measuring line-integrated density fluctuations.

- The PCI system on C-Mod images density fluctuations along 32 chords onto a LN\textsubscript{2} cooled photoconductive HgCdTe detector.
- PCI signal $V \propto \int \tilde{n}_e \, dl$; only sensitive to waves moving perpendicular to chords.
- Line-integration means that fluctuations from the core and edge, top and bottom, are added together.
- Measures $k_R$ of turbulence, which is approximately $k_\theta$ in the core.
- Sensitive to waves with $f < 1.5$ MHz and $0.5$ cm\textsuperscript{-1} < $k_R$ < 30 cm\textsuperscript{-1}.
Nitrogen seeding significantly reduced high frequency (f > 150 kHz) PCI spectral feature in both LOC and SOC $q_{95} = 3.4$ cases.
Radially localized reflectometer channels measuring density fluctuations in the region of $0.8 \leq r/a \leq 0.9$ showed a decrease in high-$f$ fluctuations similar to PCI.
GYRO simulated turbulent density fluctuation amplitudes were compared to the PCI measurements using a synthetic diagnostic.

- The line-integrated measurements from PCI cannot be inverted to get localized density fluctuations.
- Instead the GYRO simulated local density fluctuations are line-integrated by the synthetic diagnostic.
- The synthetic diagnostic includes the experimental system response.
- It was developed by J. Chris Rost, and was detailed in J. C. Rost, et. al. Phys. Plasma 17 (2010) 062506.
In the high-current ($q_{95} = 3.4$) plasmas, a high-frequency feature of the experimentally measured PCI spectrum was reduced by nitrogen seeding.
The synthetic PCI amplitude from local GYRO simulations of the q_{95} = 3.4 plasmas at r/a = 0.85 agrees with the experimental PCI within uncertainties.
At $r/a > 0.75$ the ion turbulence level is well above marginal stability, and $Q_i \gg Q_{GB}$; however, seeding with nitrogen reduced both the turbulence and the heat flux.
Both nitrogen and neon seeding substantially increased the neutron rate ($T_i$ increased by about 10%).
Change in ohmic power with seeding is negligible and cannot explain the increase in neutron rate.
Neither nitrogen nor neon seeding improved global energy confinement.
Summary

- Nitrogen and neon seeding both showed net reduction in ion transport (and reduced turbulence) and improved fusion performance (increased neutron rate)

- Overall, neon and nitrogen show similar effects on transport and turbulence:
  - Ion transport was reduced
  - Similar reduction in turbulence
  - Ion temperature gradients with nitrogen seeding shown to increase
  - Although not discussed here, similar intrinsic rotation behavior

- The overall global energy confinement did not change due to increased radiation losses

- Implication for ITER is that increased radiative losses due to seeding by N or Ne may be mitigated by reduced core ion transport; however, negative impact of seeding on the edge pedestal needs to be resolved - different physics
Dedicated experiments were performed on DIII-D mimicking ITER Baseline Scenario. Plasmas were heated in DIII-D with Neutral Beams (NBI) and/or ECH to produce the following comparisons:

- (a) Low rotation, $T_e \sim T_i$, dominant torque-free electron heating
- (b) High rotation, $T_e < \sim T_i$, finite torque multi species heating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;n_e&gt;$</td>
<td>$\sim 4-6e19$ m$^{-3}$</td>
</tr>
<tr>
<td>$B_T$</td>
<td>$\sim 1.8$ T</td>
</tr>
<tr>
<td>$P_{NBI}$</td>
<td>$\sim 3$ MW</td>
</tr>
<tr>
<td>$P_{ECH}$</td>
<td>$\sim 3$ MW</td>
</tr>
<tr>
<td>$q_0$</td>
<td>$\sim 1.1$</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>$\sim 2$</td>
</tr>
<tr>
<td>$\delta_{\text{top}}$</td>
<td>$\sim 0.4$</td>
</tr>
</tbody>
</table>

Elming

$\rho \sim 1.3$ MA

$I_{\text{NBI}} \sim 1-2$ Nm

$\kappa \sim 1.9$

$q_{95} \sim 3.5$

$H_{98,y2} \sim 1$

$\delta_{\text{bot}} \sim 0.8$
Summary of DIII-D Results

• In DIII-D ITER Baseline Scenario (IBS) plasmas turbulent transport was studied by measuring density fluctuations with state of the art diagnostics and interpreted with the aid of TGLF, and with nonlinear gyrokinetic codes GYRO and GS2

• Torque-free direct electron heating with ECH replacing part of NBI, while maintaining fixed beta-N, was found to modify the profiles which resulted in increased ion scale fluctuations and deteriorated the global energy confinement due to decreased flow shear

• The impact of ECH on fluctuations was also measurable at electron scales where considerable heat and particle pinches may be generated according to GYRO predictions
Recent experiments in IBS on DIII-D explored the effect of torque-free electron heating on confinement and fluctuations.

Operations in ITER and beyond will rely on torque-free electron heating ($\alpha$-heating).

ITER Baseline Scenario
Low rotation
EC heated for burning plasma mock-up

RESULTING IN
$T_e \sim T_i$
reactor relevant conditions
lower confinement
The intensity of low-frequency fluctuations is observed to increase with ECH

- ECH considerably slows down plasma rotation => lower flow shear
- TGYRO-TGLF modeling reproduces temperature profiles inside $\rho=0.8$ within experimental error for both heating schemes

- In ECH heated plasmas, the intensity of fluctuations:
  
  I. **Increases** mainly at $\rho\sim0.6$ as measured from BES and DBS
  II. **Increases** at low frequency as measured by PCI (line integral)

> Results interpreted from TGLF as flow shear damping of low-k turbulence when the heating scheme, at constant power, provides net torque

  R. I. Pinsker et al., EPJ2014

- **Decreases** at high frequencies as measured by PCI

> Result independent of flow shear
Comparison of discharges with NBI and ECH+NBI

<table>
<thead>
<tr>
<th></th>
<th>155196</th>
<th>155199</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{NB} - P_{loss}</td>
<td>2.7 MW</td>
<td>2.6 MW</td>
</tr>
<tr>
<td>P_{OH}</td>
<td>0.3 MW</td>
<td>0.2 MW</td>
</tr>
<tr>
<td>P_{ECH}</td>
<td>0.0 MW</td>
<td>3.3 MW</td>
</tr>
<tr>
<td>P_{tot}</td>
<td>3.0 MW</td>
<td>6.1 MW</td>
</tr>
<tr>
<td>W_{tot}</td>
<td>0.71 MJ</td>
<td>0.74 MJ</td>
</tr>
<tr>
<td>W_{th}</td>
<td>0.66 MJ</td>
<td>0.68 MJ</td>
</tr>
<tr>
<td>\tau_{E,th}</td>
<td>0.24 s</td>
<td>0.11 s</td>
</tr>
<tr>
<td>\tau_{E,th 98(y,2)}</td>
<td>0.20 s</td>
<td>0.12 s</td>
</tr>
<tr>
<td>H_{98(y,2)}</td>
<td>0.96</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Replacing beams with ECH reduces energy confinement time due to reduced flow shear.

Without ECH the intensity of fluctuations is seen to decrease at low k (PCI-BES-DBS).

Effect attributed to flow shear turbulence quench.

Let us now focus on the prompt response of fluctuations to ECH => high-f/high-k => Phase Contrast Imaging.
Internal reference interferometer sensitive to the line integral of density fluctuations

Large bandwidth, ideal for multi-scale physics:

- Frequency: 10 kHz - 2 MHz
- Wave vectors: 1-25 cm\(^{-1}\)

Images fluctuations on a 32-elements linear array

Fluctuations measured by Phase Contrast Imaging (PCI)
By comparing Blue vs Red time windows we look at “pure” heat flux effect (i.e., frozen profiles apart from $T_e$)
Prompt increased intensity of fluctuations at high frequency is not due to larger Doppler shift.

The increase in high frequency fluctuations at ECH turnoff significantly precedes increase in Doppler shift.

The increase in high frequency fluctuations at ECH turnoff significantly precedes increase in Doppler shift.
The prompt (sub-$\tau_E$) response of fluctuations at high-$f$ seen by the PCI is localized at outer radii.

Growth rates of electron modes (high-$f$) increase promptly only at outer radii thus indicating where fluctuations are collected along the line integral.
• Better agreement is obtained when evolving quantities separately

• Work in progress:
  – Improve profile-matching on axis & add momentum transport
• Marginal effects in TGYRO are not retained in non-linear modeling

• The model is used to gain further insights on micro-instabilities
In non-linear global GYRO runs experimental - level flow shear reduces ion scale turbulence

<table>
<thead>
<tr>
<th>Fields</th>
<th>$\gamma_E/\gamma_{E,\exp}$</th>
<th>$Q_i/Q_{i,\exp}$</th>
<th>$Q_e/Q_{e,\exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi$</td>
<td>0</td>
<td>8</td>
<td>1.5</td>
</tr>
<tr>
<td>$\Phi$ &amp; $A_{jj}$</td>
<td>0.75</td>
<td>2.3</td>
<td>0.7</td>
</tr>
<tr>
<td>$\Phi$ &amp; $A_{jj}$</td>
<td>1.25</td>
<td>1.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Experimental collisionality

Experimental profiles linearized around $r/a=0.7$

No impurity included (their inclusion should further lower $Q_i$, also according to exploratory linear runs)
Increased $R/LT_\text{e}$ at ECH turn-off enhances intermediate-$k$ modes.

The reduced inward particle pinch associated with ECH operation may explain the 'ECH density pump out'.

**Caveat:** also ELMs are affected by ECH...

...need coupled pedestal-core modeling.
Conclusions - Experiment

• Recent experiments on DIII-D executed ITER Baseline Scenario (IBS) like discharges with torque-free electron heating (ECH) to $T_e \sim T_i$ and slow rotating plasmas

• **Upon turning off ECH power:**
  - Kinetic profiles evolve to a new stationary phase
  - The Phase Contrast Imaging diagnostic observes a prompt increase of the intensity of fluctuations at high frequencies
  - After profiles evolve, low frequency fluctuations are observed by several diagnostics to decrease in amplitude

• ECH power is observed to considerably lower plasma flow
• The largest variation of ExB flow shear is around $\rho=0.75$
Conclusions-Modeling

- Ion dominated turbulence for $k_\theta \rho_s \leq 1$ and electron dominated turbulence up to electron gyro-radius scales was studied.

- TGYRO powered by TGLF+NEO evolving density and temperature of all species successfully recover profiles, but on axis values are overestimated.

- Upon turning off ECH power:
  - Linear growth rates of electron modes increase in the outer half of the minor radius, consistent with PCI measurements.
  - Non-linear GK simulations indicate:
    - Enhanced flow shear weakens ion scale fluctuations, consistent with reduced intensity of measured low-frequency fluctuations.
    - Increased $R/LT_e$ destabilizes electron scale fluctuations, causing transient outward heat flux and inward particle pinch.