Internal transport barriers (ITBs) can be routinely produced in C-Mod steady enhanced $D_α$ (EDA) H-mode plasmas by applying ICRF at $|r/a| \geq 0.5$ (off-axis heating). They are observed primarily in electron particle channel and are marked by the steepening of the density profile following the L-H transition. The triggering mechanism of these ITBs is under consideration. The importance of the magnetic shear and the critical scale length $a/L_T$ are being explored. Preliminary results from TRANSP analysis suggest that the ITB triggering could depend on the magnetic shear. At the same time $a/L_T$, which has been seen to decrease as the ICRF resonance position is moved outward by raising the magnetic field, is likely to play a role in suppressing ITG turbulence. These effects are studied using a kinetically constrained EFIT model as well as the gyrokinetic code GS2. Recent experimental results as well as the results from the analysis are presented.
$T_e$ and $n_e$ are measured by Thomson scattering diagnostic

Profiles are mapped onto midplane along the surfaces of constant poloidal flux using EFIT
Density fit

- Many transport analysis codes like TRANSP require smooth profiles as an input
- Fit core and edge regions separately
- Edge fit: tanh (polynomial) function, including some core points
- Core fit:
  - for L- and H-modes: unconstrained third order B-spline with 4 knots, including edge points inside pedestal
  - for ITB: constrained third order B-spline with 6 knots
- Combine core and edge regions using cubic fit matching values and slopes
- Combine Visible Bremsstrahlung (VB) and TS measurements to derive $Z_{\text{eff}}(r,t)$
- Resultant $Z_{\text{eff}}$ profiles are smoothed radially to minimize artifacts
- $Z_{\text{eff}}(r,t)$ profiles are used in TRANSP
Temperature fit

- Combine all available $T_e$ measurements from core and edge TS as well as various ECE diagnostics
- Fit core and edge regions separately
- Edge fit: tanh (polynomial) function, including some core points
- Core fit: constrained third order B-spline with 6 knots
- Combine core and edge regions using cubic fit matching values and slopes
Plasma parameters (ITB vs. non-ITB)

- $I_p$ scan, constant magnetic field
Temperature scale length

- Temperature scale length is calculated from high resolution ECE measurements.
- There is no obvious difference in temperature scale length in ITB (pre-ITB phase) vs. non-ITB discharges (especially if include data from many shots).
Magnetic shear (TRANSP)

- Magnetic shear is calculated based on TRANSP equilibrium calculations
- Magnetic shear is systematically lower for ITB cases throughout most of the discharge
- This trend is observed in the core plasma region up to R~81 cm (approximately the position of ITB foot later in the discharge)
- This trend holds for various assumptions about $Z_{\text{eff}}$ and $T_i$
Magnetic shear (Kinetic EFIT)

- Magnetic shear calculated by magnetic EFIT does not reveal the difference between ITB vs. non-ITB discharges.
- Kinetic EFIT calculations show the same trend in the magnetic shear as TRANSP results do.
Linear GS2 analysis (ITG modes)

- Stability analysis by linear runs of the gyrokinetic code GS2
- ITG modes are identified and found unstable in the outer plasma region
- ITG growth rate profiles and k spectra look similar for ITB vs. non-ITB cases
- Using different assumptions about $T_i$ yields different growth rate profiles, but without major differences between ITB vs. non-ITB cases

### Graphs

**Shot 1040310005 (non-ITB)**
- $t=1.0$ s (H-mode phase)
- $k_p$ spectrum peaks at $\sim 0.4$

**Shot 1040310012 (ITB)**
- $t=1.0$ s (right before ITB phase)
- $k_p$ spectrum peaks at $\sim 0.4-0.5$
Linear GS2 analysis (ETG modes)

- There is a change in ETG growth rate profile and $k$ spectrum between L- and H-modes.
- ETG growth rate profiles and $k$ spectra look similar for ITB vs. non-ITB cases.
Temperature profiles

- $T_e$ is from the temperature fit
- $T_i$ is derived to match the neutron rate
- Temperature and density (not shown) profiles looks similar for ITB vs. non-ITB cases
• Linear GS2 runs do not suggest there is strong dependence of ITG growth rate on the magnetic shear for these C-Mod plasmas
• Linear runs suggest that ITG turbulence is suppressed under extreme magnetic shear values (negative, zero, 10x)
Magnetic field scan

• **Motivation:** The above analysis shows that for similar heating scheme (same magnetic field and, therefore, same ICRF resonance position in plasma) temperature profiles are very similar. This can explain the fact why linear GS2 runs do not reveal much of a difference in the ITG (and ETG) growth rate profiles for ITB vs. non-ITB cases. The role of magnetic shear is still unknown.

• **Question:** can ITB formation still be explained in the framework of suppressing ITG turbulence via increasing ion temperature scale length relative to the critical scale length?

• This idea was tested by varying the toroidal magnetic field and thus shifting the RF resonance location on shot-to-shot basis. Plasma current was adjusted proportionally to keep q95 constant. Total ICRF power was kept constant.

<table>
<thead>
<tr>
<th>$B_t$ (T)</th>
<th>$I_p$ (MA)</th>
<th>ITB</th>
</tr>
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<tbody>
<tr>
<td>6.27</td>
<td>1.0</td>
<td>yes</td>
</tr>
<tr>
<td>6.2</td>
<td>0.989</td>
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</tr>
<tr>
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<td>0.973</td>
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<td>0.957</td>
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<td>no</td>
</tr>
<tr>
<td>5.4</td>
<td>0.861</td>
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</tr>
</tbody>
</table>

Sharp threshold in the magnetic field is consistent with the previous observations.
Temperature scale length

- Temperature scale length is calculated from high resolution ECE measurements
- Averaging has been done over steady portions of the discharges
- $a/L_T$ decreases as the ICRF resonance position is moved outward by raising the magnetic field
Effect of sawteeth

- Each sawtooth period is divided into 10 ‘phases’
- For each radius temperature scale length is calculated as a function of sawtooth phase (averaging over corresponding phases)
- This gives an idea by how much $L_T^{-1}$ can change due to sawtooth crashes
- These data will be used for stability analysis
Plasma parameters (ITB vs. non-ITB)

- **Plasma line-integrated density** \((10^{20} \text{ m}^{-2})\)
- **RF power** (MW)
- **Plasma stored energy** (kJ)
- **Plasma current** (MA)

**5.8 T**
- Non-ITB

**6.2 T**
- ITB

**5.8 T**
- CMOD 1050707027
- Non-ITB

**6.2 T**
- CMOD 1050707025
- ITB

**Plasma parameters**

- **Line-integrated density** (10^20 m^-2)
- **RF power** (MW)
- **Plasma stored energy** (kJ)
- **Plasma current** (MA)
Density profiles

- Density profiles are similar
Temperature profiles

- \( T_e \) is from the temperature fit
- \( T_i \) is derived by TRANSP to match the neutron rate
- A ‘hump’ in the ion temperature profile is located further out for the off-axis heating
Ion temperature measurements

- Ion temperature is measured by HIREX (high resolution X-ray) diagnostic
- $T_i$ at $R=0.763$ is increasing when ICRF resonance is moved outward by raising the magnetic field
Linear GS2 analysis (ITG modes)

- ITG modes are found unstable in the outer plasma region
- $k$ spectra look similar for ITB vs. non-ITB cases
- ITG growth rate profile shifts outward as ICRF resonance is shifted outward; ITG modes are stable at the ITB location
• ETG modes are found unstable in the outer plasma region
• k spectra and growth rate profiles look similar for ITB vs. non-ITB cases
Conclusions

• Plasma density and temperature profiles on C-Mod are measured by Thomson scattering systems. Temperature measurements are complemented by various ECE diagnostics. Fitted profiles are used for transport analysis.

• Temperature measurements suggest that $L_T$ is similar in ITB vs. non-ITB (in otherwise similar) discharges with off-axis ICRF heating.

• TRANSP results indicate that magnetic shear is systematically lower for the discharges which develop ITBs. This trend is observed throughout most of the discharge duration. The low magnetic shear region extends radially to approximately a position of ITB foot. This suggests that magnetic shear might play an important role in ITB triggering mechanism. Magnetic EFIT results do not show any difference in magnetic shear for ITB vs. non-ITB cases. Kinetic EFIT results show similar trend as those from TRANSP.

• Stability analysis is done by gyrokinetic code GS2 (linear runs). ITG and ETG modes are found to be unstable in the outer plasma region in all analyzed discharges.
Conclusions (Cont’d)

• The results of linear GS2 runs do not reveal significant difference in the modes’ growth rates for ITB vs. non-ITB discharges
• Using different assumptions about ion temperature profile changes the ITG mode structure, but no difference for ITB vs. non-ITB cases
• The results of linear GS2 runs do not show the dependence (at least strong) of ITG growth rate on the values of the magnetic shear
• Shifting ICRF resonance by changing toroidal magnetic field produces a difference in $a/L_{Te}$, which may be related to the ITB formation. Similar trend is seen for the ion temperature
• ETG growth rate profiles and k spectra look similar for discharges with off- and on-axis heating
• Shifting ICRF resonance outward extends the region of stability for ITG modes; ITG modes are found stable in the ITB region. This suggests that ITG turbulence still can be a dominant factor in the triggering mechanisms for off-axis ICRF heated ITBs in C-Mod