Effect of pedestal fluctuations on inter-ELM pedestal recovery and ELM characteristics in ECH dominated discharges in DIII-D

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Working hypothesis

Enhanced $\nabla T_e$

Exciting TEM/MTM like modes at the pedestal

Delayed pedestal recovery towards criticality

Enhanced transport; Ref. Da

Decreased ELM frequency

Heating changed from pure NBI to predominantly ECH
Takeaway message: Enhanced $\nabla T_e$ excites MTM and/or TEM in the pedestal

- Hence increased turbulence driven transport
- Resulting in delayed gradient recovery and thereby
- Reducing ELM frequency in ECH dominated discharges
Motivation: ELMs – the peeling ballooning instability

• Sharp pressure gradients, and consequent large bootstrap currents at the pedestal, can destabilize peeling and ballooning modes

• The dominant modes are referred as coupled ‘peeling–ballooning’ modes and are driven by both parallel current ($J_{\text{ped}}$) and the pressure gradient ($p'_{\text{ped}}$)

• These intermediate – $n$ (4~40) peeling–ballooning modes impose constraints on the pedestal height

Peeling-ballooning (PB) model for ELMs
Motivation: ELMs – the peeling ballooning instability

• ELMs can be mainly type I, II or III: we will focus on type I (giant) ELMs
  – As per the definition of type-I ELMs:
    • frequency of type I ELMs increases with the power input crossing the edge plasma
    • ELM characteristics do not depend on the power deposition location or the heating mix

• Several experiments have observed conditions where ELMs are not triggered even though pedestal gradients have reached critical PB gradients and continue in a long metastable state prior to an eventual onset of ELM
  – in most cases, in the inter-ELM period, some turbulent mode appears that alters transport and hence affects pedestal recovery
  – PB model may not be sufficient to describe the inter-ELM pedestal recovery – no comprehensive understanding till today

• Role of turbulence and interplay of turbulence and gradient recovery after ELMs leading towards the next ELM is quite crucial
Motivation: Pedestal gradient recovery has strong impact on ELM characteristics

- Modifying the pedestal gradient recovery in the inter-ELM phase can lead to very different ELM characters – both amplitude and frequency wise
  - Pedestal recovery can be influenced greatly by tweaking the underlying turbulence and transport
  - Turbulence and transport in the inter-ELM regime can be modified by changing several factors like $\nabla T_e$, $T_e/T_i$ ratio and collisionality

- Adding ECH can modify the pedestal $\nabla T_e$ as well as lower collisionality

- Here we focus on the pedestal density, temperature and pressure recovery in the pure NBI and ECH dominated discharges
  - Along with the associated fluctuations
This poster: in a nutshell

• ELM frequency reduced by 40% when heating is changed from pure NBI to predominantly ECH in DIII-D
  – At similar or even a bit higher total injected power

• The question is: why does the ELM frequency change so drastically?
  – While the major plasma parameters, like \( I_p \), shape, \( q_{95} \), remain similar

• Excitation of quasi-coherent modes and turbulence driven transport play a vital role in the inter-ELM pedestal recovery

• What are the implications for ITER and beyond?
  – Emphasize importance of turbulence driven transport in determining ELM behavior and to propose electron heating as a tool to modify ELM frequency through the modification of \( \nabla T_e \) in the pedestal for ITER and beyond
  – Also, self-sustained ignition in ITER is envisaged through thermal electron heating by \( \alpha \)-particles and better insight of pedestal behavior with electron heating is essential
  – Provide important inputs for optimizing the codes for predicting pedestal behaviour
ELM dynamics: 40% reduction in ELM frequency in ECH dominated shots as compared to pure NBI

- LSN discharge; ECH deposition at $\rho = 0.2$; balanced torque; $P_{\text{tot}} \approx 3\text{~MW}$
- Much higher ELM frequency ($f_{\text{ELM}} \approx 46 \text{~Hz}$) in pure NBI shot (#153100); $P_{\text{inj}}$ is 3 MW
- More regularly spaced, lower frequency ELMs ($f_{\text{ELM}} \approx 27 \text{~Hz}$) in ECH shot (#153116); Higher total power ~4MW

Lower $f_{\text{ELM}}$ with higher input power: does not agree with type-I ELM definition
Average pedestal profiles: ELM synced; 70-99% of ELM cycle

- In ECH shot: majority of NBI is replaced by ECH
- $n_e$ pedestal lower, $T_e$ pedestal higher in ECH; $p_e$ pedestal slightly lower in ECH shot
- $T_i$ is comparable at pedestal for both shots
- Absolute $\nabla T_e$ higher for the ECH shot as compared to NBI shot at steep gradient
- Some variation in the $E_r$ well; Bootstrap current fraction similar
Both NBI and ECH dominated shots are similar on the stability diagram

- Both the ECH and NBI shots are close to the Peeling Ballooning inflection point (nose); ECH shot is inside the peeling-balloonng boundary while the NBI shot it just outside
- In terms of normalized edge current and normalized pressure gradient both shots are similar
ELM synchronized analysis of Thomson Scattering data – ELM at $\Delta t = 0$

- Example of the ECH shot where ELMs are detected above the threshold – red broken horizontal line
- Each large type –I ELM crash is followed by one or two small spikes in $D\alpha$
Pedestal recovery following ELMs: Gradients recover much faster in NBI shots

- Pedestal decay with ELMs is smaller in NBI case compared to ECH case
- Initial recovery of gradients similar in NBI and ECH shots
- Sharp drop in gradients for the ECH shot at ~13 ms: due to the small $D_\alpha$ spike(s)

![Graphs showing gradient recovery](image)
Pedestal recovery following ELMs: Gradients recover much faster in NBI shots

- Closer look at $\nabla n_e$ from profile reflectometry – data with high time resolution
- Steady recovery of both $n_e^{PED}$ and $\nabla n_e$ in NBI shot
- Several phases in $\nabla n_e$ recovery in ECH shot, mainly due to $n_e$ pedestal width recovery; $n_e$ pedestal height increases rather monotonically
Distinct low frequency magnetic modes (in $\dot{B}_\theta$) in the inter-ELM period for the ECH shot

- 2 MHz acquisition in fast-magnetics
- $\sim$150 kHz mode prior to each ELM is present in both cases (white arrows)
- Low frequency quasi-coherent modes (13$\sim$116 kHz) present in the ECH case (green arrows), prior to major ELMs
Evolution of magnetic modes in the inter-ELM period of the ECH shot is correlated with $\nabla T_e$ recovery

- Mode amplitude evolution shows steady growth after $\sim 12$ ms
- Note: a small growth bump at $\sim 5$ ms: related to $\nabla T_e$ evolution

- Two possibilities:
  - Seems $\nabla T_e$ needs to reach a certain threshold to trigger the growth of the magnetic modes
  - Modes seems to grow only within a narrow-bounded value of the gradients
DBS – 400 kHz mode grows with ECH injection and density pump-out

- Distinct mode at 400 kHz; at $\rho=0.95$ and $k_\theta \rho_s \sim 0.9$ (TEM-scale)
- Mode amplitude increases following ECH at 2000 ms
- Shows correspondence with density pump-out & increased $\nabla T_e$ due to ECH at 2000 ms

- This mode is localized at the steep gradient region of the pedestal
  - With ECH, chord-averaged density decreases leading to inward movement of higher frequency DBS channels. But lower frequency channels don't move
  - Lower frequency channels see an increase in mode amplitude whereas higher frequency channels don't see these modes following ECH injection
DBS spectra: Evolution of the two modes is correlated with the large ELMs and small $D_\alpha$ spikes

- Fig. (e): DBS Frequency spectrogram at $\rho = 0.95$
  - Following an ELM crash: mutually exclusive occurrence of a quasi-coherent mode at $\sim 400$ kHz and a high frequency mode at $\sim 2$ MHz

- Modes’ evolution well correlated with the ELMs and the small $D_\alpha$ spikes
- $v_{ExB}$ increase well correlated with the growth of $\sim 2$ MHz mode
Mode at \(~400\) kHz survives only when the gradients are within two horizontal red broken bounds.

- Gradients relax slightly due to small \(D_\alpha\) spike in phase \#3.

- Gradients are again within bounds in phase \#4 and \(~400\) kHz mode appears.
Transport coefficients (TRANSP) indicates that MTM/ETG/TEM are likely candidates

- $D_e \ll \chi_e$ (Fingerprints: M. Kotschenreuther et al., Nucl. Fusion 59, 096001 (2019))
  - Most likely candidate is MTM or ETG in this regime
- From pedestal top till steep gradient ($\rho=0.98$), $D_e \ll (\chi_i + \chi_e) \& \chi_i \sim \chi_e$ – TEM also possible
TGLF simulations predict that frequencies are in the electron direction at ion scale

- Linear gyrofluid simulations performed with TGLF from $\rho = 0.8 \sim 1.0$
  - For most dominant mode, growth rate peaks at $\rho = 0.98$, steep gradient region;
    Growth rate is much higher for ECH dominated discharge
  - Frequency is positive and hence, in the electron direction for $k_y \rho_s < 1$
  - Observed fluctuations in magnetics could be MTM as MTM is ion-scale, electron temperature gradient driven and frequencies in electron direction
Both electron and ion energy and particle fluxes increase with $a/L_{Te}$
- electron and ion density profiles expected to flatten with increase in $\nabla T_e$

This observation either rules out ETG or demands co-existence with other modes responsible for the particle flux
- ETG mostly electrostatic, rather small scale ($k_q\rho_s \approx 10$) and not trivial to access experimentally with diagnostics like DBS

Large increase in the ion momentum flux - toroidal rotation profile expected to flatten with increase in $\nabla T_e$
Increasing $a/L_{Ti}$ will decrease both the ion and electron particle transport, thus steepening the density profiles.

Will have negligible effect on energy and momentum fluxes:
- indicates that the plasma is ITG stable at this radius as the electron and ion thermal transport is not increasing with increase in $a/L_{Ti}$.

Turbulent transport is mostly dominated by $\nabla T_e$ driven fluctuations:
- Hence, the increased turbulence observed in the ECH dominated discharge is most likely of the MTM and/or TEM nature.

ECH discharge: $(a/L_{Ti})$ scan in TGLF at $\rho = 0.98$ indicates plasma is ITG stable at this radius.
Variation of heating mix (NBI vs ECH) and ECH deposition location affects ELM frequency

- Shots compared have total input power ~3 MW and ~net zero torque injected

- **A**: Shot #184429 is a pure NBI shot (balanced)

- For core ECH injection ($\rho = 0.4$), ELM frequency increases with increase of ECH to NBI ratio
  - **B**: 3-4s ($P_{ECH}/P_{NBI} \sim 0.5$)
  - **C**: 4-5.5s ($P_{ECH}/P_{NBI} \sim 0.9$)

- For edge ECH injection ($\rho = 0.8$), ELM frequency decreases with increase of ECH to NBI ratio
  - **D**: 3-4s ($P_{ECH}/P_{NBI} \sim 0.5$)
  - **E**: 4-5.5s ($P_{ECH}/P_{NBI} \sim 0.9$)

- ELM frequency increased by ~40%, compared to the pure NBI discharge, when 1:1 heating mix ratio (NBI:ECH) is applied with the ECH at $\rho = 0.4$.

- On the other hand, the ELM frequency reduced by ~50% when 1:1 heating mix ratio is applied with the ECH deposition at $\rho = 0.8$
Quasi-coherent modes observed in DBS phase spectrogram for cases D (occasionally) & E (regularly)

A: #184429; Pure NBI

B: #184437; NBI:ECH ~ 2:1  
ECH @ $\rho = 0.4$

C: #184437; NBI:ECH ~ 1:1  
ECH @ $\rho = 0.4$

D: #184431; NBI:ECH ~ 2:1  
ECH @ $\rho = 0.8$

E: #184431; NBI:ECH ~ 1:1  
ECH @ $\rho = 0.8$
• Type I ELM frequency decreases by 40% in ECH (at $\rho = 0.2$) dominated plasmas compared to pure NBI
  • May be a mixed ELM regime in the ECH shot
• Fast-magnetics show distinct MTM-like modes in inter-ELM period
  – $\nabla T_e$ needs to be within a narrow-bounded value for growth of these modes
• DBS shows growth of 400 kHz TEM-like quasi-coherent mode and high frequency $\sim$2 MHz broadband turbulence in the inter-ELM period
  – Well correlated with the pedestal $\nabla T_e$ evolution
  – 400 kHz coherent mode also appears within narrow bounded value of gradients
    • May be responsible for enhanced transport and holding gradients lower for the ELMs to occur, for a longer period of time
• Transport coefficients suggest MTM and/or TEM are the most likely candidates for observed fluctuations in the ECH shot
• Linear eigenmode analysis corroborates this inference
  • Frequency of most dominant mode peaks at ion-scale in the steep gradient region
  • Propagates in electron direction
• Enhanced $\nabla T_e$ excites MTM and/or TEM and hence increased turbulence driven transport – resulting in delayed gradient recovery and thereby reducing ELM frequency in ECH dominated discharges

Summary – I