Edge pedestal and confinement regulation on Alcator C-Mod


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Motivation

- Obtaining high confinement regimes ($H_{98} \sim 1$) without ELMs is a priority for ITER
  - Formation of edge pedestal $\geq 4$keV needed to achieve $Q=10$ scenario
  - Simultaneous restriction on the energy release by edge localized modes (ELMs)
  - *But ELMs flush impurities, keep core radiated power controlled*
  - Must satisfy requirements of good confinement, reduced ELM activity in regimes transferrable to ITER

- Can we utilize non-ELMing regimes with good energy confinement, but some degree of particle control?
  - Examples: EDA, QH-mode, RMP-based suppression
  - Compatibility with ITER?

- By varying coupling between thermal and particle confinement, can we learn something about edge transport barrier physics?
Goal: Actively explore techniques for decoupling the particle/impurity transport from the energy transport in high-confinement tokamak discharges

- Techniques evaluated:
  - Magnetic balance optimization
  - Pedestal modification via lower hybrid waves
  - Suppression of density barrier formation via unfavorable $\nabla B$ drift operation
Is coupling of particle and thermal transport in pedestal unavoidable?

- Edge turbulence suppression typically gives rise to a strong transport barrier for both particles and energy.
- Confinement scales with plasma current: $I_P$ regulates pressure.
- On C-Mod, density pedestal (as well as $T$) regulated by $I_P$.
  - Edge relatively thick to neutrals, sometimes approaching ITER opacity.
  - Weak neutral fueling effects.
  - Resilient $n_e$ pedestal profiles.
- Cannot usually achieve arbitrary $<n_e>$ in H-mode.

ITER rampdown studies: Kessel, UO4.14
1. Magnetic balance optimization
Magnetic topology known to affect partition of pressure between $n$, $T$

- With single null dominant, pedestal behavior changes with ion $B_x \nabla B$ drift direction
  - **Toward active X-point** (typical)
    - Good confinement ($H_{98(y,2)}=1$) in stationary H-modes possible
    - Pedestal pressure roughly constant at fixed $I_p$
  - **Away from active X-point**
    - Similar pressure constraint
    - Reduced $n_{ped}$, increased $T_{ped}$, for a given L-mode target density and power
    - High confinement transiently (ELM-free)
Magnetic topology known to affect power threshold, H-mode quality

- $B \times \nabla B$ away from X-point is "unfavorable"
  - Typically gives rise to short-lived radiative ELM-free H-modes
  - High power threshold
- What is the behavior when close to double null (DN)?
  - Continuous?
  - A bifurcation?
- Is proximity to DN a potential concern for ITER?
H-modes have been studied with varied magnetic balance

- Magnetic balance characterized by the midplane radial distance between separatrices passing through lower and upper X-points: $\Delta R_{SEP} = R_{mid,XL} - R_{mid,XU}$

$\nabla \Delta R_{SEP} = -5\text{mm}$

$\nabla \Delta R_{SEP} = 0\text{mm}$

$\nabla \Delta R_{SEP} = +5\text{mm}$
Magnetic balance can be scanned while maintaining steady H-mode

- Stationary enhanced D$_{\alpha}$ (EDA) H-modes can be obtained with swept $\Delta R_{\text{SEP}}$ (LSN$\rightarrow$USN and back)
- Density typically reduces as discharge becomes USN
  - Collisionality does not always drop
- Edge quasi-coherent mode (QCM) observed on fluctuation diagnostics
  - Magnetics
  - Phase contrast imaging
  - Reflectometry
- Higher $\beta$ discharges exhibit small ELMs in addition to the QCM
Magnetic balance regulates edge pedestal and confinement

- Scans of magnetic balance near DN were executed
- Obtained variation of $|\Delta R_{SEP}|$ within characteristic scale lengths near edge
  - Near SOL $\lambda_p \sim 2-3\text{mm}$
  - H-mode pedestal width: 3—5mm
- Leading results
  - Natural H-mode density reduced for $\Delta R_{SEP}>0$, for sufficiently high power
  - Energy confinement time (absolute and normalized) significantly improved for $\Delta R_{SEP}<0$
- Global changes are directly related to pedestal effects
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Scale ITER $\Delta R_{SEP}$ to C-Mod: $\sim$-5mm
Sufficient power required to observe several effects of magnetic balance

- **Major question for ITER:** How is H-mode performance impacted for power just above threshold power?
  - As $P_{\text{net}} = P_{\text{loss}} - P_{\text{rad}}$ decreases toward threshold for H-L back-transition, *favorable energy confinement lost*
  - Pedestal density and core particle inventory increases dramatically at low $P_{\text{net}}$
  - Generally poorer particle and energy confinement observed in USN: correlates with higher H-mode threshold
  - General observation of pedestal “stiffness” in EDA may require minimum $P_{\text{in}}/P_{\text{th}}$

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Cryopumping helps ameliorate the confinement degradation at low $P_{\text{net}}$

Upper chamber cryopump

![Graph showing $\tilde{n}_e$ (10^20 m^-3) vs. $P_{\text{net}}$ (MW) for unpumped and pumped conditions.](image)

![Graph showing $H_{\text{ITER-98-Y2}}$ vs. $P_{\text{net}}$ (MW) for unpumped and pumped conditions.](image)
Results of magnetic balance studies

• Near DN operation has shown sensitivity of pedestal parameters, confinement to magnetic balance
  – Strong pedestal density reduction in slightly USN configurations, with sufficient net power
  – However, typically obtained pedestal $\nabla p$, $\tau_E$ are lower
  – Best confinement obtained in slightly LSN, with $\Delta_{SEP} \approx 5\text{mm}$
  – Cryopumping generally improves performance

• Pedestal optimization studies have opened up new pathways for other experiments
  – Small ELM regime readily accessed in the near DN discharges with good confinement
  – Low collisionality targets for studies of density peaking (Greenwald APS07)
  – Low-density H-mode targets developed for LHCD $\rightarrow$ an additional actuator for pedestal behavior identified
2. Pedestal modification via lower hybrid waves
EDA H-mode target demonstrates clear response to LHRF

- **Modest ICRF heating**
  - H-mode triggered in LSN
  - Shift to USN with cryopumping used to obtain minimum possible density prior to lower hybrid turn-on ($n_||=2.3$)

- **Results include:**
  - Core density reduction
  - Substantial increase in core $T_e$
  - Net increase in $W_p$
  - Effect sustained for multiple $\tau_E$, $\tau_{CR}$

- Data and modeling suggests relatively low current drive ($f_{CD}<4\%$) in this target
  - Likely a combination of SOL interaction and low single-pass absorption

**LH in SOL: Wallace GO4.8, Wilson PP8.7**
Significant modification to pedestal profiles leads to global change

- Steady state $n_{PED}$ reduction is observed: as much as 30% in 600kA discharges
- Relaxation of $n_e$ gradient, boost in SOL $n_e$
  - Beneficial for LH coupling, wave penetration into core plasma
- $T_{PED}$ increases by up to 50%
  - Beneficial for LH damping in core
- Pressure pedestal nearly invariant, with $p_{PED}$ constant or slightly increasing
- ~50% increase in $D_{eff}$ at LCFS
- Pedestal collisionality drops from ~4 to ~1 in this case ($v_{95}$)
  - EDA H-mode is maintained throughout
Time behavior shows effects propagating in from edge

- Prompt edge response observed upon application of LH
  - Changes in Ly$_{\alpha}$ emissivity profile indicate fast changes in edge/SOL profiles
  - Divertor probes measure prompt increase in particle flux
  - Changes in QCM observed
- Global density decrease continues after initial edge modification
- H-modes stay in EDA H-mode throughout LH phase
- QCM mode characteristics altered → more particle transport drive?
Dynamics of $n_e$ pedestal relaxation can be observed over $\sim 100$ms
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Edge and core rotation modified on different time scales

- Natural pedestal toroidal rotation co-\(I_p\) in H-mode
- LHRF introduces a counter-\(I_p\) change in pedestal toroidal rotation
  - Precedes most other pedestal modification
  - Followed \(\sim 100\)ms later by change in central \(V_{tor}\)
- Is the pedestal rotation influencing the transport?

![Graph showing changes in plasma parameters over time](image)
Outstanding questions

• Behavior of EDA H-mode plasmas can be dramatically impacted by application of lower hybrid waves
  – Still early stages of evaluation; future experiments will explore range of effect at varied $P_{\text{LH}}$, $n_{||}$, plasma characteristics
• Effects, though mysterious, are generally beneficial
  – LHCD is more efficient in low density, high temperature targets
  – Application of LH directly produces an edge effect which promotes core coupling!
• Measurements, and promptness of edge effects, suggest a direct interaction of LH waves with pedestal/SOL
  – Direct effect of waves on transport?
  – Electron heating effect?
  – Direct momentum input?
• How large a role does (small, but finite) LH damping in core in sustainment of $n_e$ gradient relaxation?
3. Suppression of density barrier formation via unfavorable $\nabla B$ drift operation
Edge transport barrier should be an energy barrier, not a particle barrier

- H-like thermal transport and L-like particle transport would give:
  - Reduced impurity confinement leading to lower core radiation
  - Reduced density gradient in pedestal provides less bootstrap current to drive peeling-ballooning modes
- Can thermal transport and particle transport in the pedestal be fully (not just partially) decoupled?
- Can we reliably prevent formation of H-mode density barrier altogether?
- Unfavorable $\nabla B$ drift operation allows us to do this
  - Improved L-mode (Ryter 1998)
  - a.k.a. “I-mode” (McDermott, APS 2008)
Improved L-mode provides high thermal, low particle confinement

- Improved L-mode consistently obtained with ion $\nabla B$ drift directed away from X-point ($P<P_{L-H}$)
- Two-phase transitions reported, with $\chi_{\text{eff}}$ decrease preceding bifurcation in edge particle confinement [Hubbard APS 2007]
- Making progress in sustainment of first phase only
  - Shaping, $I_p$ optimization
  - Cryopumping
  - Determining H-mode power threshold

More discussion of I-mode: Marmar GO4.2
High thermal, low particle confinement readily demonstrated

- Edge profiles demonstrate the formation of temperature pedestal in I-mode
  - Experimental $\chi_{\text{eff}}$ in pedestal closer to that in H-mode than in L-mode
- Density profile L-mode like
  - $n_e$ very high in the far SOL, even to the limiter radius
- Pedestal $\nu^*$ less than 0.1 possible at high $\rho_{\text{ped}}$
  - *But very few ELMs are observed*
- When triggered, ELM-free H-mode that follows has larger $\tau_E$, transiently
  - Short-lived due to rapid impurity accumulation
Impurity confinement time confirmed to be very favorable in I-mode

Impurity confinement time measured with timed CaF$_2$ injections.

Multi-pulse laser blow off diagnostic: Howard PP8.11
A weakly coherent mode is generally observed in the sustained I-mode

- EM mode observed in turbulence diagnostics
- Features:
  - Spins-up in $f$ at I-mode onset
  - Not extant in H-mode
  - Unlike QCM in EDA H-mode, thrives at low $\nu^*$
  - May play a role in density and/or impurity control, as QCM has been demonstrated to do
I-mode results

• I-mode discharges are being optimized using unfavorable ion $\nabla B$ drift
  – Enhanced $T_e$ pedestals (up to ~1keV) without strong particle barrier
  – *Density and core radiation kept low; $H_{98}\sim1$ in many cases.*
  – Low $v^*$, high $\nabla p \Rightarrow$ ELMs possible, although not necessary for sustained impurity transport
  – Sustainment demonstrated for several $\tau_E$ while staying slightly below L-H power threshold

• Physical mechanism for suppressing thermal transport with elevated particle flux not entirely clear
  – $E_r$ well is significant in I-mode (1/2 of that in EDA H-mode), but does not suppress particle transport! Details of edge flows important?
  – Transport likely regulated in by a minimally coherent fluctuation (f~200kHz in lab frame)
  – Optimization so far involved *increasing H-mode power threshold* via shaping effects, running *higher $I_p$ for improved confinement.* [Marmar GO4.2]
  – Cases also exist in favorable $\nabla B$ drift direction and are being investigated
Pedestal regulation: Looking forward

- Study of edge flows in and around the pedestal
  - Known sensitivity of SOL flows, core rotation, to magnetic topology [LaBombard APS04, Rice IAEA04]
  - Edge pressure gradients in L-mode plasmas reported to be sensitive to magnetic topology, correlated with rotation [LaBombard APS07]
  - Can decoupling of particle and thermal transport be partially linked to changes in rotation shear, relative strength of $v_\phi$ vs. $v_\theta$? Already there is potential evidence for this
- Fluctuation diagnostics provide means of directly correlating fluctuation characteristics with transport
- Linear and non-linear calculations of MHD stability (including resistive)
  - What (typically) stabilizes many of these discharges to ELMs, and can the physics extrapolate to ITER?
  - What are the conditions for existence, saturation of the weakly coherent modes in EDA and I-mode. What relative levels of transport do they drive?
Overall Summary

- Studies of influence of magnetic balance on pedestal and confinement reveal a rich behavior in near DN configurations
  - With sufficient power, little or no degradation of confinement for LSN discharges approaching DN; not true for USN
  - Some of our highest $H_{98}$ values achieved in slightly LSN, with cryopumping assist
- We have developed low-density LHCD targets, and allowed demonstration of pedestal modification with lower hybrid waves
  - Operation with relaxed $n_e$ pedestal, invariant pressure pedestal, reduced collisionality
  - A possible actuator for modulating pedestal transport, rotation
- Unfavorable ion $\nabla B$ drift operation is being optimized for improved L-mode, or I-mode
  - USN with strong cryopumping has led to high normalized confinement, sustained for many $\tau_E$
  - Clear experimental demonstrations of the decoupling of thermal confinement and particle/impurity confinement
Other Alcator C-Mod presentations happening this week

• Monday AM
  – BI3.5. Istvan Cziegler (next): Advanced edge fluctuation studies

• Tuesday AM
  – GO4. C-Mod Contributed Oral Session (13 talks)

• Tuesday PM
  – KI3.2. Liang Lin: Turbulent electron transport

• Wednesday PM
  – PI2.6. Dennis Whyte: Runaway e-s in mitigated disruptions
  – PP8. C-Mod Posters

• Thursday AM
  – TI3.3. Syun’ichi Shiraiwa: FEM modeling of lower hybrid waves

• Thursday PM
  – UO4. ITER Research Oral Session: Reinke, Lipschultz, Kessel