Access to high-confinement regimes on Alcator C-Mod and the complex influence of divertor geometry

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Abstract

The placement of X-point and strike points in a diverted tokamak can have a remarkable impact on properties of the discharge, including thermal and particle confinement. The distinctive divertor of Alcator C-Mod allows us to demonstrate these effects experimentally, as we vary equilibrium shaping to obtain substantial variation of divertor leg length, field line attack angle and divertor baffling. In response to these changes, we observe differences in both L-mode confinement and access to high-confinement regimes (i.e. ELMy H-mode and I-mode). With the ion grad-B drift directed toward the divertor, scanning the strike point can induce ~2x reductions in H-mode power threshold, and can produce a window for I-mode operation with $H_{98}>1$. Recent and ongoing experiments seek to explore these effects using improved diagnostics, taking data over a range of plasma density and input power. Detailed high-resolution measurements, spanning the last closed flux surface, provide profiles of quantities of likely importance in determining whether a discharge evolves an edge transport barrier, or remains in an L-mode state. New tests of models for H-mode access are enabled by these data, especially those attempting to explain the density dependence of the H-mode power threshold.

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POWER THRESHOLD FOR H-MODE
Existing scaling laws for H-mode power threshold lack predictive capability

- Power law regression incapable of capturing non-monotonic dependences, e.g. with density
  - ITER $P_{th}$ scaling law derived from a conditioned data set that excluded data in the low-density branch
  - Which branch will burning plasmas access?

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Several hypotheses exist to explain the non-monotonicity of $P_{th}$ with density

- Critical ion heat flux in pedestal required to achieve threshold ExB shear
  - Decoupling of electrons + ions at low density $\rightarrow$ reduced $Q_i/Q_e$ [Ryter NF 2014, Malkov TTF 2015]

- Density dependence in dominant modes in edge turbulence requiring ExB shear suppression
  - i.e. ITG/TEM vs. RBM [Bourdelle, TTF 2015]

- Change in the character of turbulent energy transfer into mean flows
  - Intrinsic density dependence of seed flow shear available [Schmitz, TTF 2015]

- SOL heat transport impacting upstream balance of perp/parallel heat transport
  - Transition between sheath- and conduction-limited regimes [Fundamenski 2012]
  - Makes a tentative connection to divertor influence on $P_{th}$
Existing scaling laws for H-mode power threshold lack predictive capability

- Hidden variables can introduce great variability in $P_{th}$ magnitude
  - Divertor configuration: hidden in plain sight
  - X-point, strike point positioning has a significant effect on multiple machines

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C. Maggi, NF 2014
C-Mod divertor allows comparison of highly contrasting configurations

Changes in elongation and triangularity are subtle (give numbers)

Poloidal Outer Leg Length ranged from approx. 10cm to 25cm

Y. Ma, PPCF 2012
Variation of $P_{th}$ with outer leg length is substantial

- Minor variations of multiple shaping parameters ($i.e.$ $\kappa$, $\delta_U$, $\delta_L$) present in data set
- No clear correlation of $P_{th}$ with shaping parameters, absolute $X$-point position, midplane or divertor pressures
- Data suggest the reduction in $P_{th}$ may occur suddenly upon transitioning from the vertical plate to the divertor floor

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Density dependence affected by transition from vertical plate divertor to slot divertor

- Local $T_e$ at threshold very similar in both configurations
- Suggests differences in L-mode confinement
- Indeed, kinetic measurements indicate $\tau_{E,\text{th}}$ in moderate-density Ohmic plasma increases $\sim 30\%$ with slot divertor

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Targets for new experiments

1. Revisit divertor effect on L-H power threshold with improved diagnostic coverage
   - Midplane scanning probes
   - GP-CXRS
   - GPI

2. Gather data for improved validation of $P_{th}$ models
   - Full core kinetic profiles
   - Upstream and downstream SOL profiles
   - Edge turbulence

Green ovals = experimental targets

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Two experimental run days contributed to this proposal

- >40 useful plasma discharges
- Trial-and-error needed to optimizing scanning probe plunges, develop RF program that gave repeatable transitions
- Got good sets of data for both “slot” and “vertical-plate” strike at multiple densities
- Mirror Langmuir probe (MLP) plunges, CXRS D₂ puffs, GPI He puffs obtained
- Focus here will be initial observations from scanning probes
  - MLP provides highly accurate profiles of $n_e$, $T_e$, $V_f$, and derived quantities, with high temporal resolution [LaBombard, PoP 2014]
Ongoing experiments exploring possible causes for $P_{th}$ behavior

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Example mirror Langmuir probe scans

- In- and out-going probe motion overlay, giving \(\sim 18,000\) measurements of each parameter.
- \(\rho\) is the distance from the last-closed flux surface mapped to the outer midplane.
- The black curves result from smoothing the raw data over a 200 \(\mu\)s time window.

LaBombard, PoP 2014
Comparing slot and vertical plate: plunges into Ohmic plasma

Vertical lines = probe plunges
Comparing slot and vertical plate: plunges into heated L-mode

Vertical lines = probe plunges
Mirror Langmuir probe plunges

Probe plunges (pre L-H), 1140801

$P_{\text{loss}}$ [MW]

$\bar{n}_e [10^{20} \text{m}^{-3}]$

Vertical plate

$P_{\text{th}}$ fits from Ma 2012

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Examples of MLP plunges into Ohmic and pre-L-H discharges

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Vertical plate configuration, L-mode power scan

- Inferred plasma potential profiles near LCFS show evolution as auxiliary power added to L-mode

- Sharper gradients in kinetic profiles evident as L-H approached
  - Actual L-H occurred with $P_{rf}=1.8\text{MW}$

- Peaking in $\phi$ more prominent as L-H transition approached $\rightarrow$ stronger ExB shear in edge region

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Slot configuration, L-mode power scan

- Power window between Ohmic and L-H shrinks considerably
- Little change in kinetic profiles
  - Scan with RF taken ~15ms prior to L-H
- Peaking in $\phi$ more prominent as L-H transition approached → stronger ExB shear in edge region

$P_{rf} = 0.25\ \text{MW}$

$P_{rf} = 0$
Vertical plate vs. slot configuration, Ohmic

- Hypothesis: More ExB shear exists intrinsically in slot divertor case
  - i.e., less distance to go

- Observation: Peaking in $\phi$ less prominent with slot divertor $\rightarrow$ weaker ExB shear

- Kinetic profiles similar, as in [Ma 2012]
Vertical plate vs. slot configuration, RF-heated L-mode

- Peaking in $\phi$ less prominent with slot divertor $\rightarrow$ weaker ExB shear

- **Slot case** had L-H transition shortly after probe plunge

- **Vertical plate** case had L-H transition with 1.8MW ICRF

- Critical ExB shear criterion for L-H? Need to evaluate full profile using CXRS for inside LCFS
MHz scale fluctuations observable using MLP

\[ P_{\text{rf}} = 0.25 \text{ MW} \]

\[ P_{\text{rf}} = 0 \]

Pre L-H

Ohmic

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ONGOING WORK ON H-MODE AND I-MODE ACCESS
Extreme shaping can be used to access I-mode with $B_x \nabla B$ toward X-point

“Standard” equilibrium for accessing ELMy H-mode

“Grazing” equilibrium
$P_{LH}$ increased in grazing shape; L-mode improves before transition

"Slot" strike $\Rightarrow$ easy H-mode access

Grazing strike $\Rightarrow$ I-mode precedes H-mode

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I-mode phenomena evident even at low power

- Decrease in mid-frequency edge fluctuations
- Appearance of weakly coherent mode (WCM) accompanies formation of \( T \) pedestal
- Fluctuation spectra shows signs of WCM even in Ohmic cases!

**Good candidates for probe plunges!**

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“Favorable” drift I-mode compatible with high normalized confinement

D. G. Whyte NF 2010.

\[ \tau_{E,98,y2} \sim I_p^{0.93} n^{0.41} P_L^{-0.69} B^{0.15} \]

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Forward field I-modes at low power suitable scanning probe targets

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{Pth fits from Ma 2012}
\end{figure}
Take-away: Divertor configuration has prominent impact on access to high confinement regimes

- Data from multiple tokamaks, including C-Mod, show that H-mode access can be strongly affected by divertor configuration
- ITPA joint experiment PEP-28 is ongoing to attempt to understand these effects
- Some variables under consideration
  - X-point location
  - Strike point incidence
  - Proximity to neutral sources, pumping
- On C-Mod, there is a significant reduction in $P_{th}$ for H-mode when moving outer strike point from vertical plate (typical) to the divertor floor
- $P_{th}$ rises again when shaping is made more extreme, resulting in an I-mode access window at relatively low power
Planned work

• Assemble database of upstream/downstream profiles in L-mode, leading to L-H transition
  – existing data set includes mainly moderate-density cases

• Evaluate local “macroscopic” models for L-H threshold
  – Critical ion heat flux in pedestal [Ryter 2014]
  – Balance of perpendicular and parallel transport near separatrix [Fundamenski 2012]

• Connection to “microscopic” L-H dynamics
  – GPI measurements allow characterization of turbulence/flow interactions [Cziegler 2014, also poster in this session]
  – MLP measurements characterize fluctuations in $n_e$, $T_e$, $\phi$ for turbulent mode identification

• Further experiments possible
  – Fill in low and high density branches of L-H
  – Diagnose low-power I-mode to compare kinetic profiles, flows
  – Measure fluctuations in $n_e$, $T_e$, $\phi$ in WCM – mode identification and transport estimates
References

- C. Bourdelle, this meeting
- M. Malkov, this meeting