Core Internal Transport Barriers in Alcator C-Mod

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Presented to the joint APS DPP/ICCP meeting
10/24/00

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Supported by DoE grant DE-FC02-99ER54512
Core Internal Transport Barriers (ITBs) have been observed in Alcator C-Mod for a number of different operating conditions.

* At transition from H to L mode (Enhanced Neutron mode)  
  UP1.091
* Following pellet injection (PEP mode)
* Peaked density H-modes  
  J01.003
* Off-axis ICRF heating  
  J01.002, UP1.093, UP1.103

All but the PEP mode are accomplished without external particle or momentum sources!
Density Profiles in the 4 types of core ITBs in Alcator C-Mod.

Off-Axis ICRF generated core ITBs

Spontaneous ITBs at H- to L-mode transition (EN mode)
   a) Characteristics
   b) Plasma scale lengths

Transport Parameters

Summary and Future Work
The density is peaked at $r/a < 0.4$ following the pellet.

The neutron rate peaks after the rf power is turned on.

rf power is turned on at $t=1\text{s}$
Density Profile and Neutron Rate Peak during H to L Transition

**Graph 1:**
- **X-axis:** Major Radius (m)
- **Y-axis:** Electron Density (10^{20} / m^3)
- **Graph Labels:**
  - H-mode
  - Transition
  - Neutron rate peak
  - L-Mode

**Graph 2:**
- **X-axis:** t (s)
- **Y-axis:** Neutron Rate (10^{13} n/s)
- **Graph Labels:**
  - Neutron rate peak
  - H-mode
  - Transition
  - L-Mode
The Core Electron Density Increases in These Internal Transport Barrier Cases in Alcator C-Mod

ICRF power is input with the H minority resonance off axis on the high field side, at \( r/a = 0.5 \)

During Ohmic H-mode plasmas the central density sometimes spontaneously peaks.

**Peaked Ohmic H-Mode**
The Decrease in the Toroidal Rotation Velocity Decrease May Trigger an ITB during Off-Axis ICRF Heating

Rotation velocity starts decreasing at 0.87s for $B_t=4.5$ T

$B_t=4.9$ T

$B_t=4.5$ T

Density Peaking starts to rise
TRANSP Calculations Show RF Absorption is Off-Axis; $\chi_{\text{eff}}$ Decreases with Rotation Decline.

Core $\chi_{\text{eff}}$ decreases as ITB forms, toroidal rotation decline
Enhanced Neutron Mode

An increase in the neutron rate is seen following nearly all H to L mode transitions on Alcator C-Mod (up to a factor of 8) are observed within 20 to 40 ms of the back transition.

The increase lasts typically < 40 ms, about 1 energy confinement time.

The electron density collapses outside the center region of the plasma, with little or no change at the center.

The steep density gradient region forms an internal transport barrier in the core.
The Neutron Rate, $T_i_0$, and the Density Peaking Factor Increase at the H- to L-Mode Transition

H-Mode Ends

H-mode resumes
The Local Density Scale Length Decreases During H- to L-mode Back Transition

$r/L_n = r(|d \ln n_e/dr|)$ reaches a maximum as the neutron rate peaks.

$r/L_n$ increases to between 0.5 and 1 during the H to L back transitions.
Core Density Gradients During H- to L-mode Back Transitions are Steepest at $\sim r/a=0.4$

As the density profile steepens, a local maximum in $r/L_n$ appears in the ITB region.

The steepest part of the gradient in the plasma core occurs between $0.3 < r/a < 0.5$ for most H to L mode ITBs.
The Ion Temperature Increases at the H to L Mode Back Transition

Ti at the highest following the H to L mode is plotted versus Ti at the time the back transition starts. The blue line represents no change, and the red line represents a 40% increase. Nearly all the data lies between these limits.
The Temperature Profile Width Does Not Change at the H- to L-mode Back Transition
\( \eta_e \) decreases during the presence of the ITB which forms at the H- to L-mode Transition.

\[ \eta_e = \frac{d \log T_e}{d \log n_e} \]

\( \eta_e \) reaches a minimum value between 1 and 2 while the ITB is present.
Central temperatures increase without apparent change in their profile width.

The inverse density scale length, $1/L_n |1/n_e \, d \, n_e/dr|$, reaches a maximum value in the region $0.3 < r/a < 0.5$ at the same time.

$\eta_e$ decreases and reaches a minimum value between 1 and 2 concurrent with the neutron rate peak.

These are observed both in ohmic and RF heated discharges.
Neutron Rate Peak Lasts Longer following H- to L-mode Transition if Sawteeth are Suppressed
Confinement Parameters Improve in the Core Region Following the H- to L-mode Transition

The graphs illustrate the evolution of various confinement parameters across the normalized radius (r/a). The top graph shows the neutron rate peak and $\chi_{eff}$ in H-mode, demonstrating a noticeable improvement in confinement as the radius increases. The middle graph highlights the bootstrap current density, with a pronounced peak in the core region transitioning to H-mode. The bottom graph depicts energy confinement times, reducing with increasing radius in both modes.

This data underscores the significant enhancement of confinement parameters in the core region post-H-mode transition, contributing to improved plasma stability and efficiency in tokamak operations.
Summary

* It has been established that confinement parameters improve in the core plasma when an Internal Transport Barrier, noted by peaked density profiles, forms in Alcator C-Mod.

* These can be reliably produced by:
  a.) Injecting deuterium or lithium pellets.
  b.) Forcing H- to L-mode transitions.
  c.) Injecting ICRF power near the base edge of the ITB region.

* The lifetime of the ITB can be extended by operating at reduced field (high $q_0$?) conditions.
Further Research

* Diagnostic neutral beam related measurements will be available for

a.) Investigation of the presence of core turbulence and its role in ITB formation in Alcator C-Mod

b.) Measuring and exploring the role of the current density in ITB formation and maintenance.

c.) Detailed ion temperature profile measurements.
Further Research

* With upcoming RF enhancements the ITB formation will be explored using:

  a.) Dual frequency ICRF to simultaneously provide power to the ITB region and to the plasma center.

  b.) Use IBW current drive to control the current density profile.

  c.) Use LH current drive to control the current density profile with simultaneous central ICRF power input.
Further Research

The demonstration of controlled ITB production without an externally provided particle or momentum source is particularly exciting for Advanced Tokamak studies.