Ohmic and RF Heated ITBs in Alcator C-Mod

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Internal transport barrier (ITB) plasmas can arise as a result of RF heating or spontaneously in Ohmic Alcator C-Mod plasmas. The operational prescription for the ITB includes formation of an EDA H-mode. In Ohmic ITBs, the toroidal magnetic field is ramped down and then increased. Like ITBs generated with off-axis ICRF heating, Ohmic ITBs have peaked pressure profiles which can be suppressed by on-axis ICRF heating. Recent work on onset conditions for the ICRF generated ITB (K. Zhurovich, et al., Nuclear Fusion 47, 1220 (2007)) demonstrates that the broadening of the ion temperature profile due to off-axis ICRF reduces the ion temperature gradient and suppresses the ITG-instability-driven particle flux. The object of this study is to add additional impurity transport information to the ITB description and to examine the characteristics of ITBs to find whether this model for onset is supported.
Summary

- Two ITB modes in Alcator C-Mod
  - Ohmic, no auxiliary heating
  - Auxiliary heated: off-axis ICRF
  - Common features previously identified
    » EDA H-Mode precursor required for both
    » Peaked pressure profiles evolve in both
    » Central ICRF heating suppresses peaking
- New results are for ITBs with off-axis ICRF
  - New boron impurity profiles are reported and used to study impurity transport at the onset of the ITB
    » Inward advection is enhanced over diffusion during the ITB
    » Impurity transport approaches neoclassical
  - Clear profile $T_i$ increased but cannot confidently interpret a profile broadening
  - ITB gradient for $n_z$ is inboard of gradient for $T_i$
ITB in C-Mod

- Two ITB scenarios
  - Same precursor-plasma target: EDA H-mode
  - Ohmic: requires a $B_T$ ramp
  - ICRF: Off axis deposition
- Very similar characteristics
  - Form from an H-mode
  - Strong pressure profile peaking
  - Peaking can be clamped by deposition of central ICRF power
- Results from either will apply to the other
- There are advantages of studying one in preference to the other
  - ICRF deposition complicates the transport analysis
  - ICRF deposition has more operational similarities to ITBs on other devices
Ohmic ITB

H$_\alpha$

$n_e$ peaking

TeTS

neTS

$B_T$

H-Mode Transition

Note $B_T$ Ramp

ne$_L(4)$
Auxiliary Heated ITBs

- Off-axis ICRF deposition
- ITB forms from EDA H-mode plasma
- ITB is characterized by peaking of the electron density profile. The change of the electron temperature is less dramatic
- Similar ITB can be formed in an Ohmic plasma
Off-axis ICRF and Improved Confinement

- Off-axis ICRF deposition leads to ITB formation
- For the results shown here, deposition was on the high field side. $0.55 < R \ (m) < 0.6$ (vertical dashed lines)
- Deposition can be on the low field side.
- Improved impurity transport is observed between the two vertical lines on the low field side.
- Improved impurity transport on flux surfaces in-board of surfaces on which the heating is resonant.
- $T_i$ gradient just out-board of the gradient.

ICRF Resonance  Improved boron confinement
Compare \( n_e \) and \( T_e \) for ITBs

- ITB characterized by peaking in the pressure profile for \( \rho < 0.6 \)
- Density peaking is dominant contributor
- Peaking can be clamped by deposition of central RF (Fiore, et al., POP)
Ion Temperature

ITB foot
ICRF Resonance Range

Ion temperature (eV)

major radius (m)

ITB Impurity Gradient Region

ITB
H-Mode
Ion Temperature

- $T_i$ profile changes when the plasma transitions from H-mode to ITB
- The $T_i$ gradient is just outside the ICRF deposition and clearly outside the ITB foot as defined by the electron density profile.
- In-board of the gradient, $T_i$ during ITB is larger than $T_i$ in H-Mode
- The $T_i$ increase is well developed at the location of the impurity gradient enhancements
The current work extends earlier C-Mod impurity transport research (J. W. Rice, et al., Nuclear Fusion 42, 510 (2002)) with local measurements of lighter ions.

New measurements of fully stripped $\text{B}^{+5}$ profiles with spatial and temporal resolution are reported here.

In the earlier work on C-Mod, chord-averaged measurements of puffed argon ions were reproduced in numerical simulations of impurity transport to characterize the transport.

This measurement is local. There is just one boron ion present at the measurement locations. The analysis is therefore more transparent.

Differences between light and heavy impurity transport have been observed in other experiments. (ref JET)
The boron density profile steepens during the ITB.

The deposition location for the ICRF is just outside the foot of the gradient (see the configuration).

The inset shows the MIST analysis for a similar discharge. In measurement and simulation, B$^+5$ is the only boron charge state for R < 0.87 m. B$^+5$ density for R < 0.87 is the entire boron density.
The boron density profile steepens during the ITB.

The heating location for the ICRF is predominately just outside the foot of the $n_e$ gradient (see the configuration).
The transport equation is

$$\frac{\partial n^z_j}{\partial t} + \nabla \cdot \Gamma^z_j = S^z_j$$

For quasi-linear or neoclassical descriptions of impurity transport

$$\Gamma^z_j = -D \frac{\partial n^z_j}{\partial r} + \nu n^z_j$$

Dynamic equilibrium $$\frac{\partial n^z_j}{\partial t} = 0$$

For fully-stripped boron ($B^{+5}$) $R < 0.85$ m $S^z_j = 0$

That region is "source free" so that

$$\frac{1}{n^z_j} \frac{\partial n^z_j}{\partial r} = \frac{\nu}{D}$$

Inward convection is increased over diffusion in ITB
Is $B^{+5}$ neoclassical?

- Is $B^{+5}$ neoclassical?
- or-
  Can it be shown to obey neoclassical descriptions?

- The diffusion coefficient is $D = D_{\text{neo}} + D_{\text{an}}$
- The convection coefficient is purely neoclassical $v = v_{\text{neo}}$
- Limit collisions of the impurity to collisions with the main plasma ion, $D^{+}$ in this case

$T_{D} = T_{z}$

$v_{\text{neo}} = D_{\text{neo}} \frac{Z_{I}}{Z_{D}} \left( \frac{1}{n_{D}} \frac{dn_{D}}{dr} - H \frac{1}{T_{D}} \frac{dT_{D}}{dr} \right), \quad 0.2 \leq H \leq 0.5$

$$
\frac{1}{n_{Z}} \frac{dn_{Z}}{dr} = \frac{1}{n_{D}} \frac{dn_{D}}{dr} \frac{Z_{I}}{Z_{D}} \frac{D_{\text{neo}}}{D_{\text{neo}} + D_{\text{an}}} \left(1 - H \eta_{D}\right), \quad \eta_{D} = \frac{1}{T_{D}} \frac{dT_{D}}{dr} \approx 1
$$
Is the transport neoclassical?

- $B^{+5}$ is neoclassical over a narrow range in-board of the ITB at the foot
- For this, use $D_{an} \ll D_{neo}$

\[
\frac{1}{n_Z} \frac{dn_Z}{dr} = \frac{Z_I}{Z_D} (1 - H) \approx 2.5 - 4.5
\]
Comparison with Previous C-Mod Results


present work
Comparison with JET Results

Summary

◆ Confinement of light impurities is improved during ITB
  – Inward convection is enhanced relative to diffusion, or equivalently, diffusion is reduced relative to inward convection.
  – Transport for boron is neoclassical over a limited range of the plasma radius.
  – Further confirmation of ITB particle transport similarities between C-Mod and other devices.
◆ $T_i$ profiles change during the transition from H-mode to ITB.
  – $T_i$ increases on flux surfaces connected to the ICRF resonance region.
  – $T_i$ increases out-board of the ITB foot (defined using $n_e(R)$) and of the region where the light impurity gradient steepens
◆ Additional experiments planned for the next campaign.