High Performance Internal Transport Barriers in Alcator C-Mod

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Abstract

Internal transport barrier plasmas with average pressure greater than 1 atmosphere have been obtained in Alcator C-Mod using two techniques. In one method, high magnetic field (6.3T) and high plasma current (1.3 MA) are combined with 3 MW off-axis ICRF power to optimize the performance. In the other, high off-axis power (> 2.3 MW) is used to create an ITB plasma which is then heated with central ICRF power. To form an ITB in the pressure channel, particle and thermal flux is reduced in the barrier region which then allows the Ware pinch to peak the central density while maintaining the central temperature. Gyrokinetic code simulation suggests that steepening of the density profile destabilizes TEM modes inside the barrier, ultimately driving sufficient outgoing particle flux to balance the inward pinch and halt further density rise. Experimentally, increasing levels of density fluctuations are observed as the central density peaks, although the location of these fluctuations is not resolved. This report will examine the recent high power operation and explore the implications of increased turbulent transport on high power operation.
Internal Transport Barriers (ITBs) in C-Mod arise from steady H-mode plasmas lasting 2 or more energy confinement times when the central power input is low: they are seen in both Ohmic and Off-axis heated ICRF plasmas.

C-MOD plasmas are a unique platform for ITB study:
- No particle or momentum input
- Monotonic q profiles
- Collisionally coupled ions and electrons with $T_i = T_e$

Reduction in particle and thermal transport in the barrier region and core allows the Ware pinch to dominate the transport resulting in strongly peaked pressure and density profiles. Ion thermal transport reduces to neoclassical.

Control of particle and impurity accumulation is achieved through application of central ICRF heating: TEM stability plays a role. *Ernst, IAEA 2004*
Recently, improved performance has been demonstrated through:

- Maximizing RF input power to the plasma at high field, high current
- Tailored use of central to off-axis rf power input to optimize central plasma parameters.
- Previously obtained limits for adding central power into an ITB were surpassed.

Operation of C-Mod at even higher plasma current and rf power could extend the performance even further.

However: Work by Ernst, et al. suggests that transport driven by fluctuations from collisionless TEM modes will overcome inward neoclassical pinch once a sufficient value of $a/L_n$ and electron temperature is achieved.

Question: Is there a limit to the central pressure and stored energy that can be reached in CMod ITB plasmas from gyrokinetic stability considerations, and have we reached it in current operation?
Internal Transport Barriers (ITBs) observed in Alcator C-Mod have strongly peaked pressure and density profiles.

The ITB arises gradually after the H-mode is established in off-axis heated ICRF; 0.02 < $\tau_E$ < 0.03 s.

The square root of the visible bremsstrahlung emission yields $n_e \sqrt{Z_{\text{eff}}}$; 1 < $Z_{\text{eff}}$ < 2.

Core electron pressure from Thomson scattering increases.

3MW off-axis ICRF power, 1MA plasma current gives high pressure in ITB.
Adding central ICRF power to an established ITB halts the central density rise; the central temperature and pressure double.

Pressure and RF power profiles are shown: The highest pressure peaking occurs with combined central and off-axis power.
$\chi_{\text{eff}}$ often increases before the density stops peaking during the ITB.

ITB foot is at $r/a=0.5$
ITB plasmas were formed at low field (2.8 T) using 50 MHz ICRF off-axis heating in order to extend the field and current scaling of the ITB foot location which had been done in previous run campaigns using 70 and 80 MHz on both the low and high field sides. Results were consistent with the previous q-scaling results.

Further studies of temperature critical gradient and linear stability in the barrier region were pursued. See K. Zhurovich, KP1.00006

Improvements in time and spatial resolution of the Thomson scattering system yielded better electron density, temperature and Zeff profiles for use in transport analysis.
Internal Transport Barriers (ITBs) observed in Alcator C-Mod exhibit reduced core thermal transport to ion neoclassical level.

\[ \chi \text{ in core } (< r/a=0.5) \text{ decreases with the application of off-axis ICRF.} \]

At \( r/a=0.25 \), \( \chi_i, \chi_{\text{eff}} \) reach neoclassical when density peaking becomes noticeable.

The ITB arises gradually after the H-mode is established if the central power density is lower than the power density at half radius. Core power < 30% of total during ITB in this case.
$\chi_{\text{eff}}$ decreases in the core after H-mod onset even in non ITB cases, but to a lesser degree.
\( \chi_{\text{eff}} \) decreases with ITB onset; sometimes forms well inside of the barrier foot during the ITB.
ITB foot position is not dependent on the location of the ICRF peak power location.
The ITB foot location narrows with increasing toroidal magnetic field, decreasing plasma current.
Recent Results of Ernst GS2 Studies

Internal Transport Barriers (ITBs) in C-Mod arise from steady H-mode plasmas when outward particle diffusion due to micro-instabilities (ion temperature gradient, trapped electron modes) are suppressed in the core after the transition into H-mode. The Ware pinch then dominates the particle transport and the central density rises.

Steepening Density Gradients in the core region causes $a/L_n$ to exceed a critical value for the growth of TEMs. For the cases studied, critical $a/L_n$ is $\approx 1.3$.

Control of particle and impurity accumulation is achieved through application of central ICRF heating causing an increase in $T_e$: Particle diffusivity was found to increase as $T_e^{3/2}$. Thus the diffusive outflow balances the inward pinch and the central density no longer increases. Energy transport should also increase due to TEM driven turbulence.

Suggestion: There should be self quenching of ITBs observed in some cases, even without application of central ICRF

*Ernst, IAEA 2004
It is often seen that the central temperature starts to decline while the density is still peaking during the ITB.

In this case shown here, the electron and ion temperatures begin to drop at 1.2 s, while the density continued to increase until 1.3 s. Collapse of the ITB occurred at 1.31 s.

Such a decline has been blamed on radiative collapse due to accumulated impurities in the center. What if that is not the true cause?
$a/L_n$ exceeds typical critical value for most ITB cases throughout most of the ITB lifetime.

$a/L_n$ critical was 1.3 for Ernst case study at 4.5 T.

Density rise halts without addition of central ICRF in a few rare cases.
Te collapse before the end of the ITB is very common.

The electron temperature just at the point where it begins to decline is shown from a selection of ITB plasmas.

Examination of radiated power and Zeff did not show a clear correlation with the ITB temperature collapse.
Te collapse before the end of the ITB is very common.

The electron temperature just at the point where it begins to decline is shown from a selection of ITB plasmas.

The plasmas in the Ernst study are circled. The indication is that most ITBs are in the range of $a/L_n$ and $T_e$ such that the TEM induced transport should be an issue, even without additional central heating.
Density fluctuation level in an ITB plasma increases at addition of central rf

• Chordal data from PCI (phase contrast imaging) is shown.

• k value is found for 2 frequency bins as a function of time: from 20 kHz to 70 kHz, then from 70 kHz to 150 kHz (includes QC mode).

• Fluctuation amplitude increases with addition of central RF in an ITB plasma.
Density rise is halted; Central Te begins to decrease
Density fluctuation level in an ITB plasma increases as central density peaks.

Central temperatures decline. Is this caused by the fluctuation increase?
Caveats on interpreting PCI Data

• Non-localized chordal measurement

• The measurements shown are not corrected for density and scattered power will increase with increasing density without an actual change in the fluctuation level.

• i.e. if the fluctuation is outside of the barrier where the density is not rising, then it might be increasing in intensity just as the signal indicates.

• If the fluctuation is at the core where the density is increasing, it may not be changing in intensity even though the scattered power is increasing.

• Measured frequency will be shifted by poloidal rotation for non-central fluctuations.
Conclusions:

• Scaling of ITB foot radius appears linear with $I_p/B_t$ suggesting $q$ dependence

• There is evidence that the ITB phase of the plasma may be terminating from the onset of micro turbulent transport. If so, it may not be possible to push ITB performance in C-Mod to levels much higher than already achieved since the TEM driven diffusion scales as $T_e^{3/2}$.

• Much more work is needed in refining and interpreting PCI data to study the instability. Localized PCI measurements may be available in another year.