Non-Local Heat Transport, Core Rotation Reversals and Energy Confinement Saturation in Alcator C-Mod Ohmic Plasmas

J.E.Rice

Plasma Science and Fusion Center, MIT

with thanks to


H.J.Sun    SWIP

P.H.Diamond, I.Cziegler    CMTFO UCSD

R.M.McDermott, C.L.Angioni    IPP Garching

L.Delgado-Aparicio, D.Mikkelsen    PPPL

W.L.Rowan    IFS UT

B.P.Duval, A. Bortolon    EPFL

IAEA   San Diego    Oct. 9, 2012
Longstanding mysteries in tokamak Ohmic plasmas:

**Up/down impurity density asymmetries**

**Confinement saturation**
A.Gondhalekar et al., 7th IAEA (1978) Vol.1 199.

**Non-local heat transport**

**Rotation reversals**

Rotation reversals, the LOC/SOC transition, non-local heat transport and up/down impurity density asymmetries are related.
Outline

Cold pulse propagation and connection to rotation reversals
Relation with LOC/SOC transition, up/down impurity asymmetries
Associated turbulence changes during reversals
Modeling and discussion, role of $\nu_*$

Alcator C-Mod

**Fusion Sci. Technol. 51 (2007)**

$R = 0.67 \text{ m} \quad r \sim 0.2 \text{ m} \quad \kappa < 1.8$

$B_T = 2-8 \text{ T} \quad I_p = 0.3-2.0 \text{ MA}$

$n_e = 0.1-10 \times 10^{20}/\text{m}^3 \quad T_e \sim T_i = 1-8 \text{ keV}$

$\beta_N = 0.2-1.8 \quad \nu_* = 0.01-20 \quad 1/\rho_* = 170-500$

Rotation velocities and $T_i$ from imaging x-ray spectrometers


Cold pulse from LBO CaF$_2$ injection

No external momentum sources Ohmic plasmas only
Ar$^{16+}$ x-ray spectra exhibit recombination population at $r/a \sim 0.9$.

Up/down symmetric in LOC
(0.6x10$^{20}$/m$^3$)

Up/down asymmetric in SOC
(1.4x10$^{20}$/m$^3$)
Cold Pulse Propagation Comparison in SOC and LOC Plasmas

In LOC, the core electron and ion temperatures *increase* following edge cooling. Non-local, non-diffusive.

In SOC, the heat transport is diffusive. \( \tau_E \sim 30 \text{ ms.} \)
Temperature Flex Point and Rotation Reversal Anchor Point Similar

LOC temperature profiles before and during cold pulse. R/L\textsubscript{Te} changes from 11.5 to 14.0. R/L\textsubscript{Ti} changes from 5.9 to 8.2. T\textsubscript{i} profile develops more slowly.

Comparison of LOC and SOC velocity profiles. Anchor point close to T\textsubscript{e} flex point in LOC.
Rotation Reversal, LOC/SOC Transition, Non-Local Heat Transport and Up/Down Impurity Density Density Asymmetry All Related

For 0.8 MA, reversal and non-local transition at exact same density.

At LOC/SOC transition, $T_e/T_i \sim 1.2$ for 0.8 MA.

For 0.8 MA, reversal and non-local transition at exact same density.
Critical Density for Rotation Reversal, LOC/SOC Transition, Non-Local Cut-Off and Up/Down Impurity Density Asymmetry Scales with Current

![Graphs showing critical density parameters](image-url)
Critical densities for temperature inversion, rotation reversal, LOC/SOC transition and up/down impurity asymmetries scale similarly with plasma current.

Rotation reversal anchor points and temperature flex points located inside of $q = 3/2$. 
Values of $Z/T^2$ and Collisionality at LOC/SOC Transition Fixed

Scalings with density

Transition occurs at fixed $Z/T^2$ but not $T_e/T_i$. 

Values at LOC/SOC transition

(0.55 MA)  (0.8 MA)  (1.1 MA)
Turbulence Characteristics Very Different in LOC and SOC

Core density fluctuations from PCI.

LOC  $0.99 \times 10^{20}/m^3$

SOC  $1.05 \times 10^{20}/m^3$

Edge density fluctuations from GPI.

Edge turbulence propagation direction reverses at LOC/SOC transition.
Linear GYRO Simulations Indicate Dominance of TEMs at Low Collisionality, ITG Modes at High Collisionality

(for non-linear simulations see M.Porkolab et al., EX/P3-13 Wed. AM)

Contour plots of the linear growth rate ($c_s/a$) of the most unstable mode with $0.1 < k_0 \rho_s < 0.75$

LOC $n_e = 1.03 \times 10^{20}/m^3$

SOC $n_e = 1.16 \times 10^{20}/m^3$
Rotation Reversals, LOC/SOC Transition, Non-Local Heat Transport, Density Profile Peaking and Up/Down Impurity Density Asymmetries Correlated

Pieces of the puzzle have been around for many years:

LOC/SOC transition occurs at a critical density which depends on current and is correlated with turbulence changes.

Non-local heat transport occurs below a critical density.

Density profile peaking saturates at LOC/SOC transition.

Up/down impurity density asymmetries seen in SOC.

Rotation reversal is the most sensitive indicator of the LOC/SOC transition:

Momentum flux is proportional to the Reynolds stress: \(-\chi_\phi \frac{d v_\phi}{d r} + V v_\phi + \Pi^{\text{res}}\)

\(\chi_\phi\) is positive definite, quasi-linear \(V\) can change sign if \(dn/dr\) changes sign

\(\Pi^{\text{res}}\) can change sign if mode propagation direction changes.
Is Collisionality $\nu_*$ the Determining Parameter?

Machine Size Scaling of LOC/SOC Density

Unifying ansatz:

low collisionality, LOC, co-rotation, TEM turbulence, non-local heat transport, peaking density profiles

high collisionality, SOC, counter-rotation, ITG turbulence, diffusive heat transport, stable density profiles

$$\nu_* = 0.018 \ n_e q R \ Z_{\text{eff}} / T_e^2 \ e^{3/2} \sim nqR = \text{const.}$$

Conclusions and Discussion

Non-diffusive, non-local heat transport has been observed below a critical density.

$T_e$ profile flex point coincides with the rotation reversal anchor point, inside of the $q = 3/2$ surface.

Critical densities for $T_e$ inversion, rotation reversal and LOC/SOC transition are very close.

Radii of $T_e$ profile flex point and rotation reversal anchor point scale with $1/q$.

Critical densities for $T_e$ inversion, rotation reversal, LOC/SOC transition and up/down impurity density asymmetries scale with $1/q$.

Reversals from the co- to counter-current direction are correlated with a sharp decrease in core density fluctuations with $2 \text{ cm}^{-1} < k_\theta < 11 \text{ cm}^{-1}$ and frequencies above 70 kHz. Propagation direction of edge turbulence switches at LOC/SOC transition.

Linear GYRO simulations indicate TEM domination in LOC, ITG mode prevalence in SOC.

Unifying ansatz:

At low collisionality, in the LOC regime, the rotation is co-current, TEMs dominate, heat transport is non-local, density profiles peak and impurity density profiles are up/down symmetric.

At high collisionality, in the SOC regime, the rotation is counter-current, ITG modes dominate, heat transport is diffusive, density profile peaking saturates and impurity density profiles are up/down asymmetric.

The transition occurs at a particular collisionality, near $\nu_* \sim 0.4$. 

Alcator C-Mod