EX/2-2

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

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with thanks to

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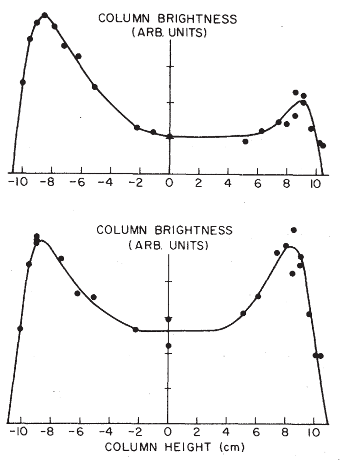
Longstanding mysteries in tokamak Ohmic plasmas:

Up/down impurity density asymmetries

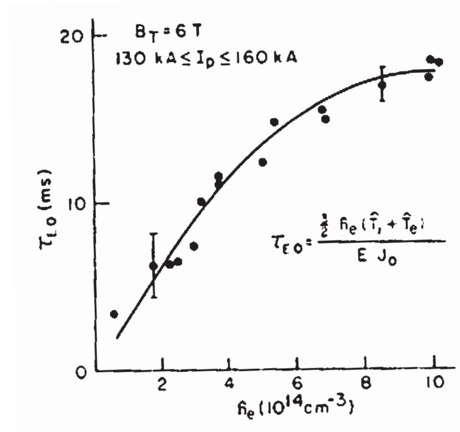
J.L.Terry et al., Phys. Rev. Lett. **39** (1977) 1615.

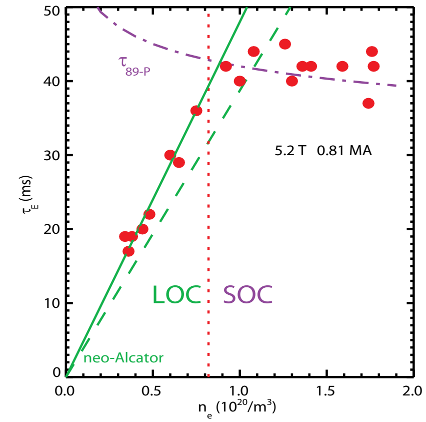


Alcator A
PDX
Alcator C
TEXT
COMPASS-C
C-Mod

Confinement saturation

A.Gondhalekar et al., 7th IAEA (1978) Vol.I 199.

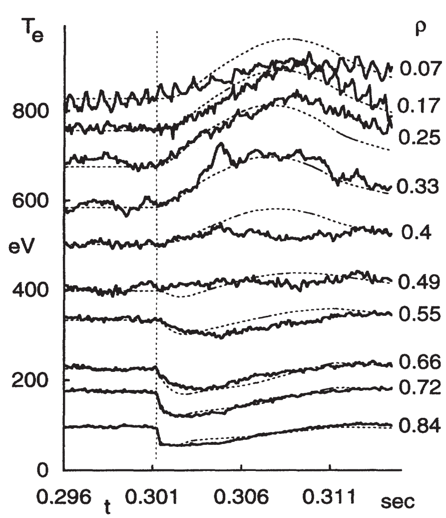




nomenclature: LOC = linear Ohmic confinement
SOC = saturated Ohmic confinement

Non-local heat transport

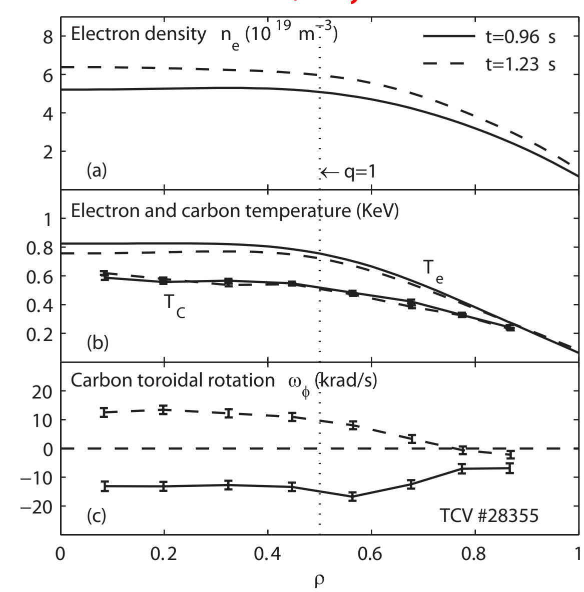
K.Gentle et al., Phys. Rev. Lett. **74** (1995) 3620.



TEXT
TFTR
RTP
AUG
HL-2A
C-Mod

Rotation reversals

A.Bortolon et al., Phys. Rev. Lett. **97** (2006) 235003.



TCV
C-Mod
AUG

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 ν_*

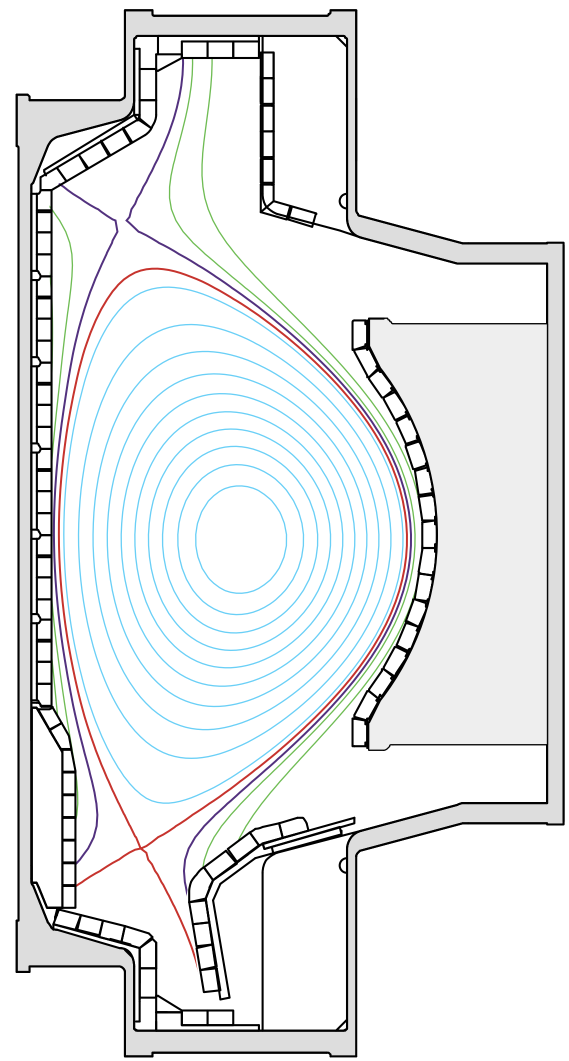
Alcator C-Mod   Fusion Sci. Technol. **51** (2007)

$R = 0.67$ m $r \sim 0.2$ m $\kappa < 1.8$

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

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

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



Rotation velocities and T_i from imaging x-ray spectrometers

A.Ince-Cushman et al., Rev. Sci. Instrum. **79** (2008) 10E302.

Cold pulse from LBO CaF_2 injection

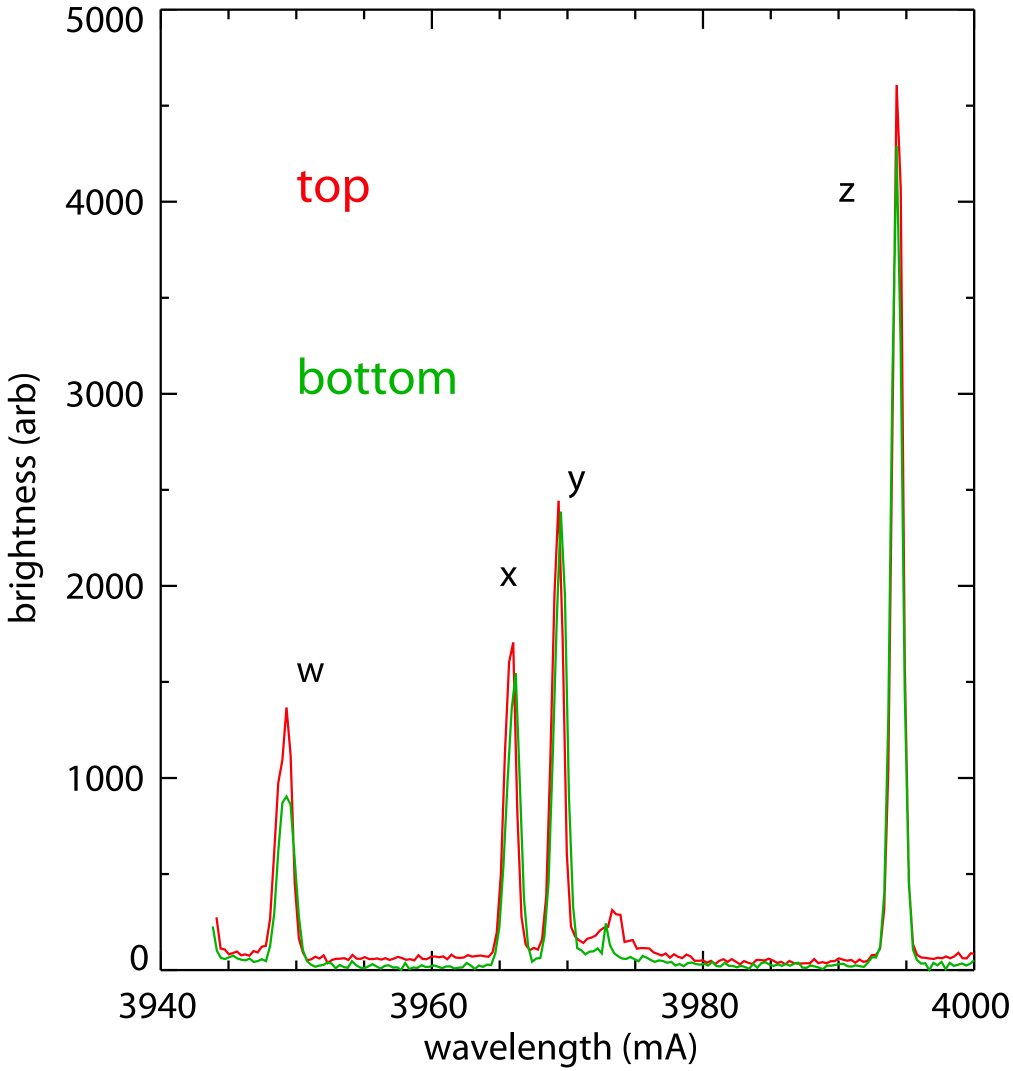
No external momentum sources   Ohmic plasmas only

Edge X-ray Spectra Show Up/Down Emissivity Asymmetry at High Density

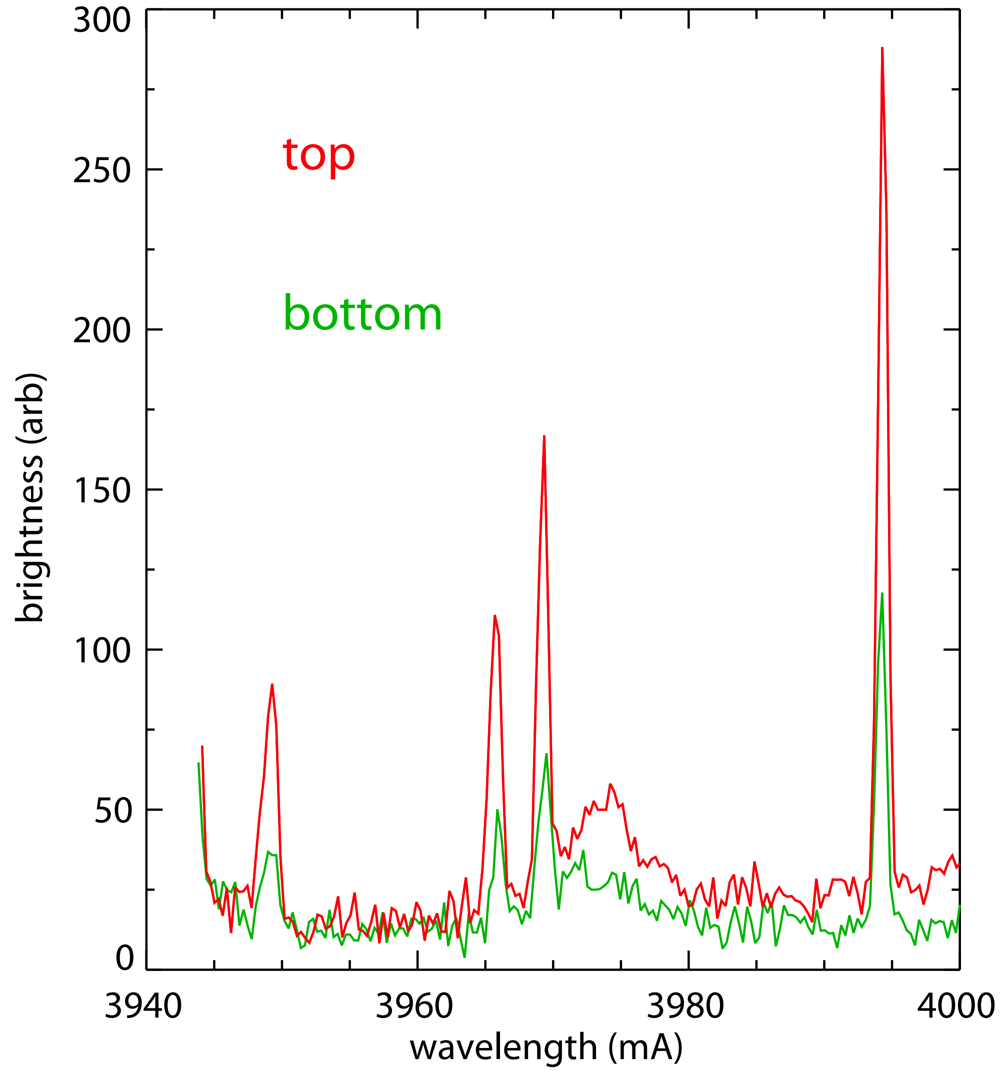
(J.E.Rice et al., Nucl. Fusion **37** (1997) 241., M.L.Reinke, Ph.D. thesis M.I.T. 2011)

Ar^{16+} x-ray spectra exhibit recombination population at r/a~0.9.

Up/down symmetric in LOC
($0.6 \times 10^{20}/m^3$)



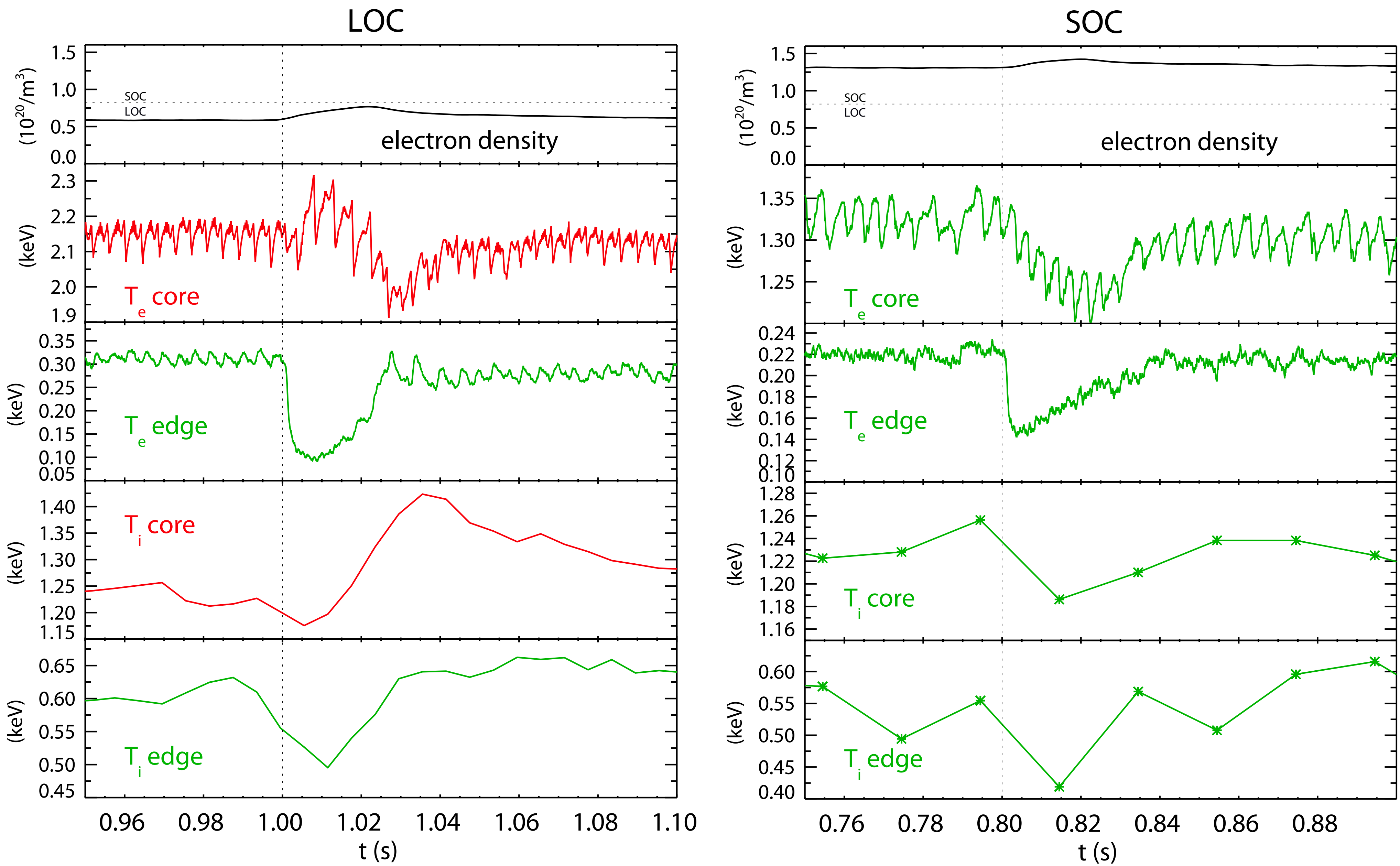
Up/down asymmetric in SOC
($1.4 \times 10^{20}/m^3$)



Cold Pulse Propagation Comparison in SOC and LOC Plasmas

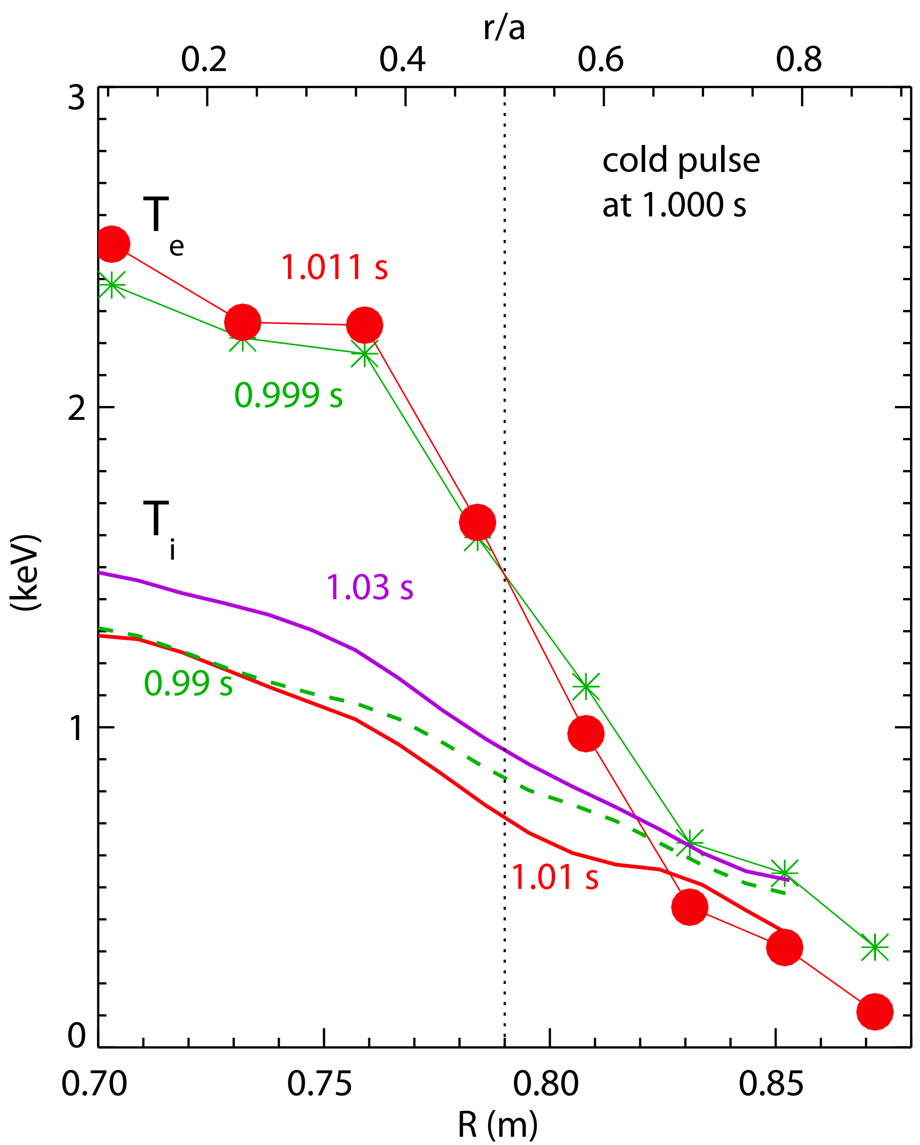
In LOC, the core electron and ion temperatures *increase* following edge cooling. Non-local, non-diffusive.

In SOC, the heat transport is diffusive. $\tau_E \sim 30$ ms.

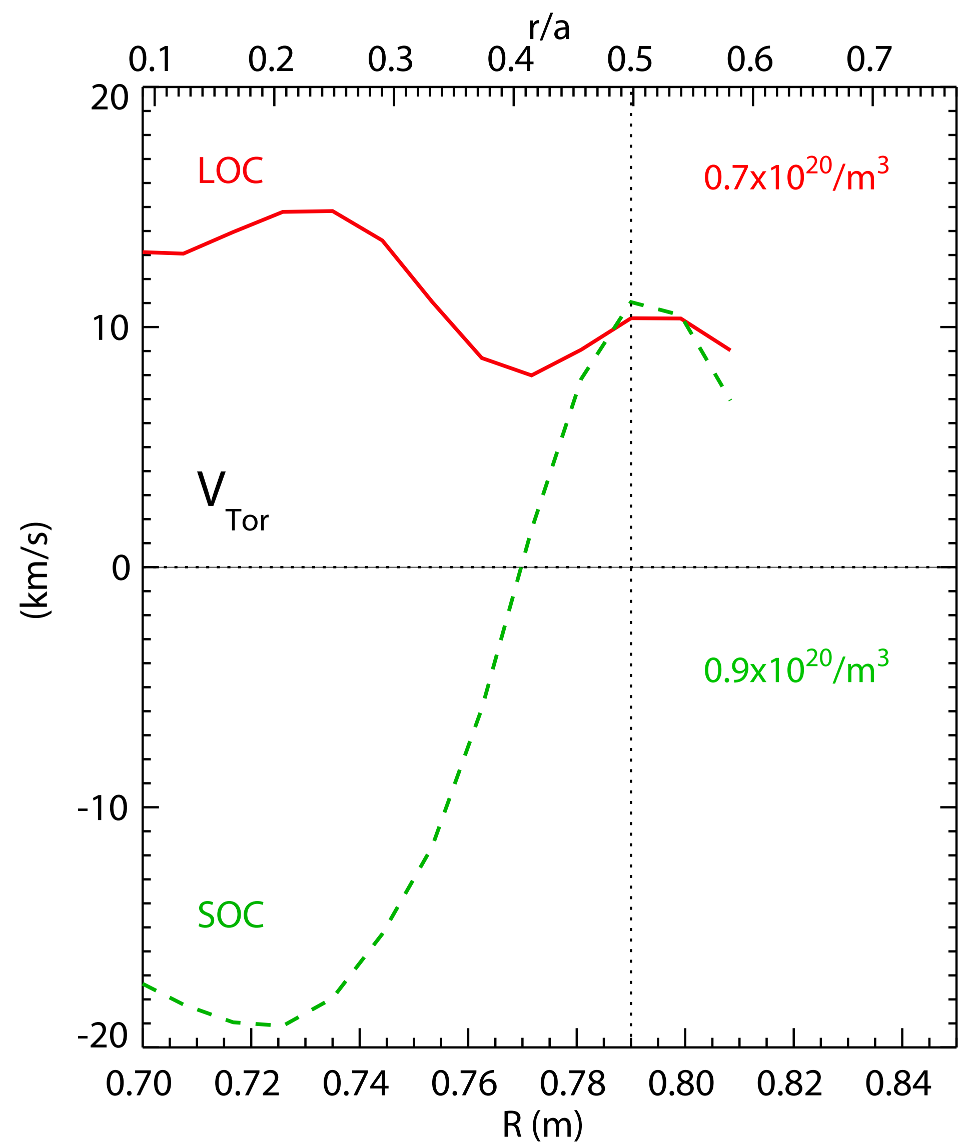


Temperature Flex Point and Rotation Reversal Anchor Point Similar

LOC temperature profiles before and during cold pulse. R/L_{T_e} changes from 11.5 to 14.0. R/L_{T_i} changes from 5.9 to 8.2. T_i profile develops more slowly.

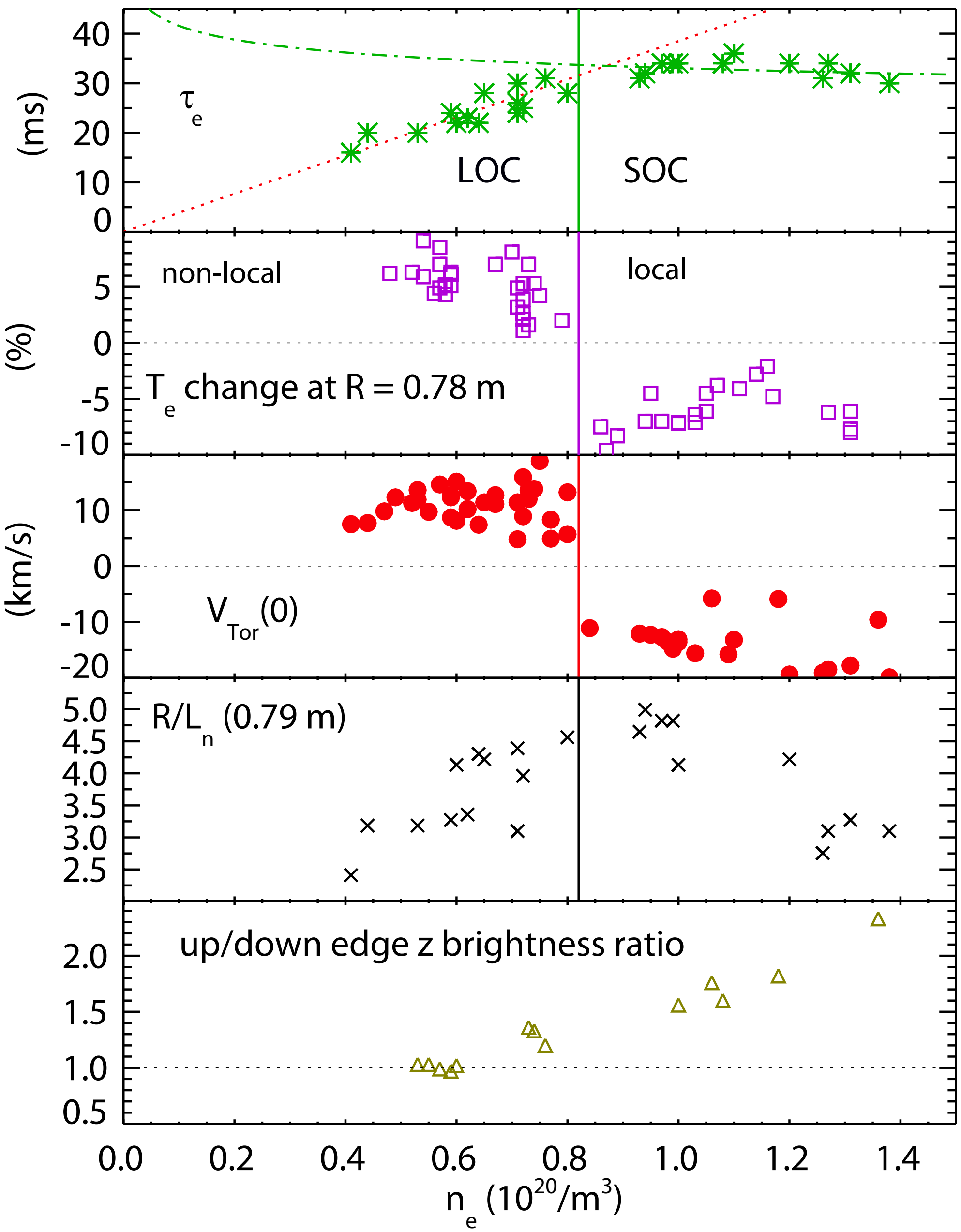


Comparison of LOC and SOC velocity profiles. Anchor point close to T_e flex point in LOC.

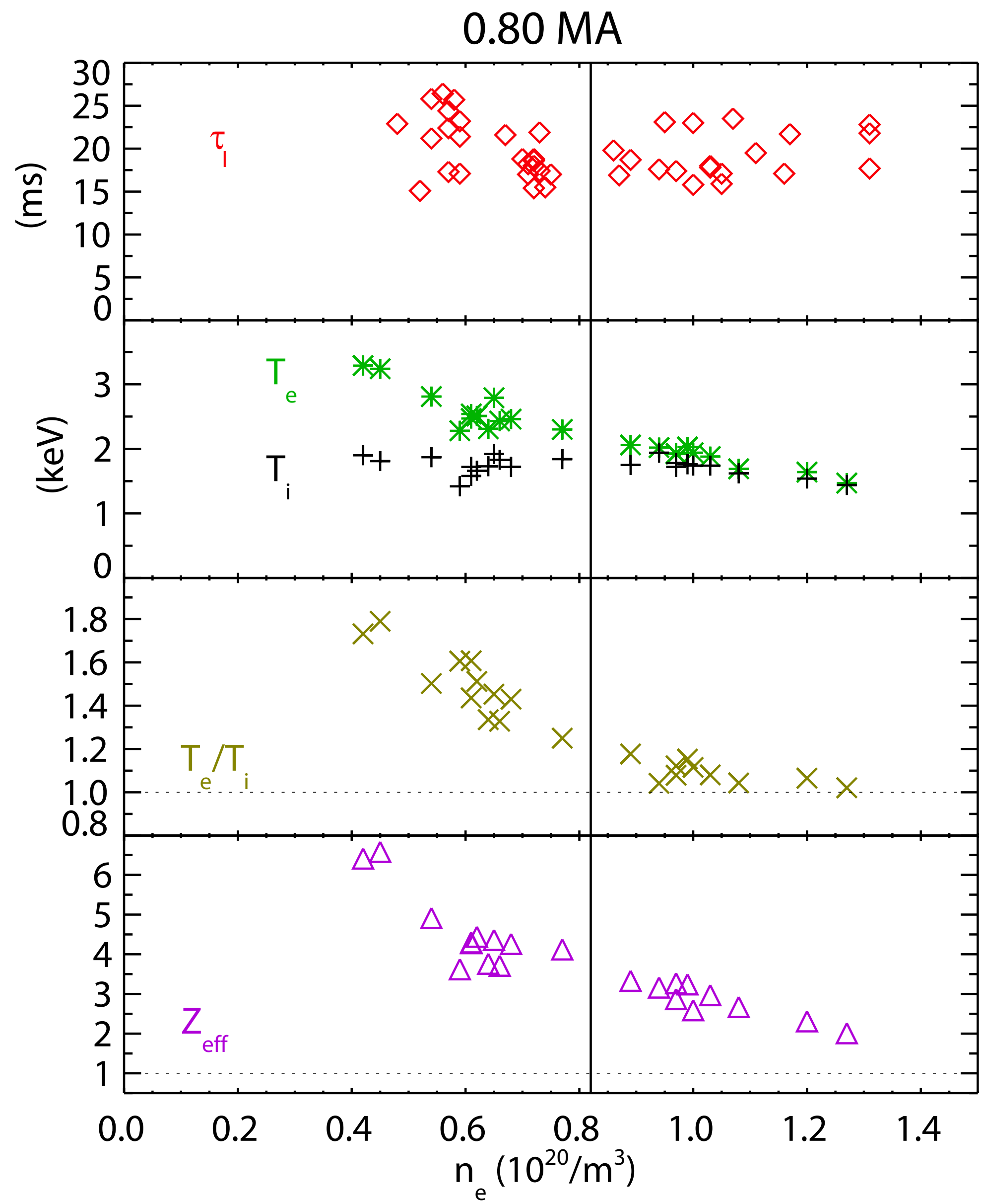


Rotation Reversal, LOC/SOC Transition, Non-Local Heat Transport and Up/Down Impurity Density Asymmetry All Related

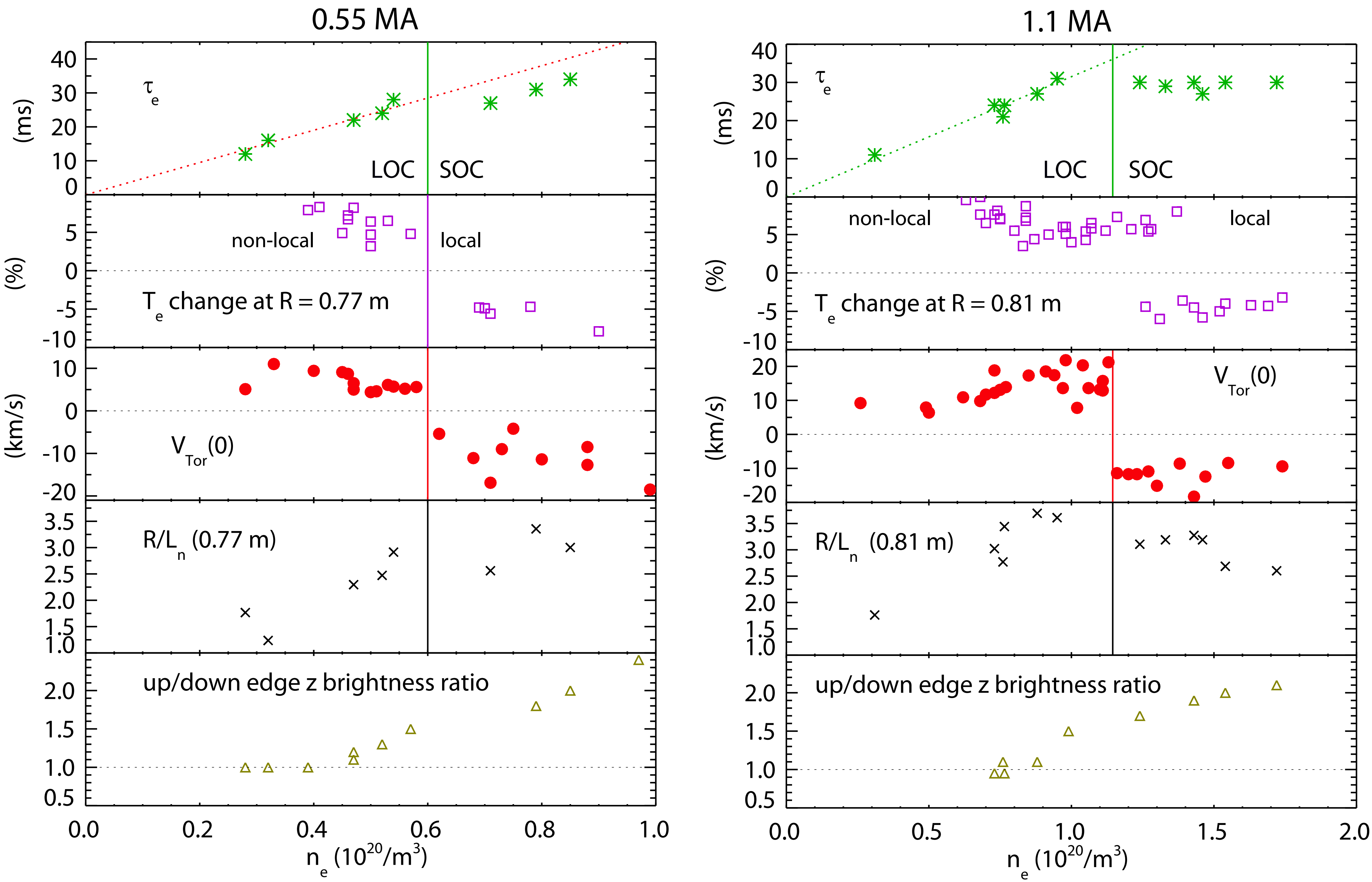
For 0.8 MA, reversal and non-local transition at exact same density.



At LOC/SOC transition, T_e/T_i ~ 1.2 for 0.8 MA.

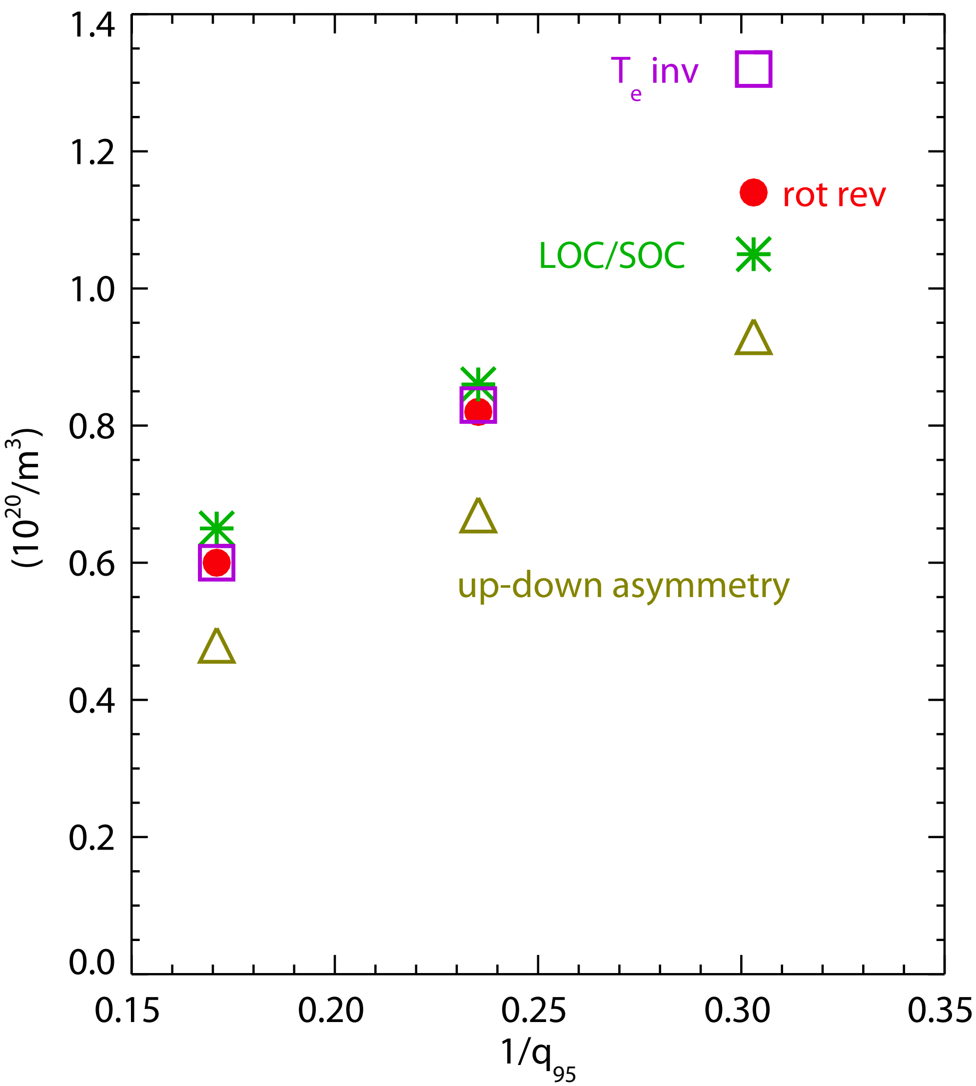


Critical Density for Rotation Reversal, LOC/SOC Transition, Non-Local Cut-Off and Up/Down Impurity Density Asymmetry Scales with Current

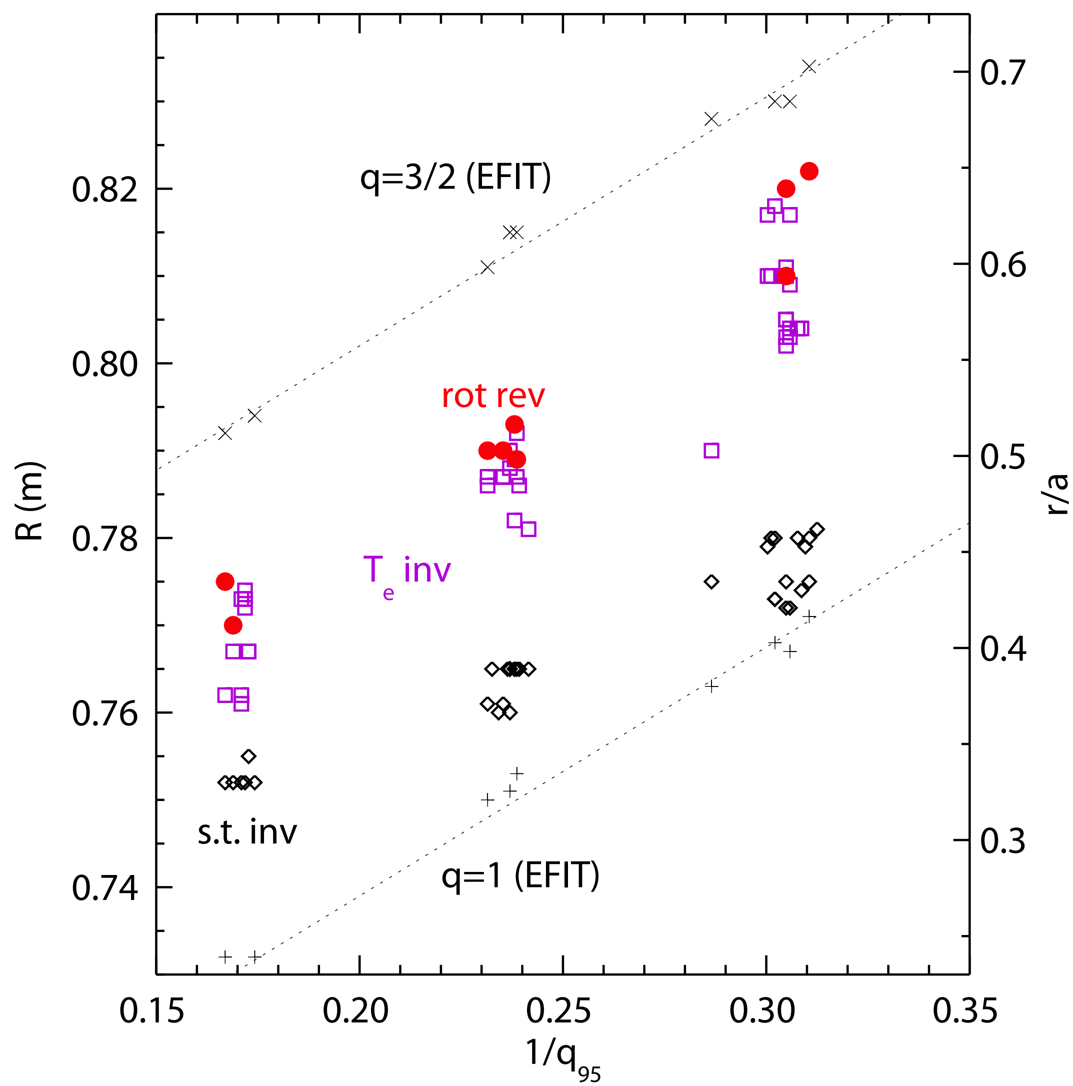


Scalings of Critical Densities and Characteristic Radii with Plasma Current

Critical densities for temperature inversion, rotation reversal, LOC/SOC transition and up/down impurity asymmetries scale similarly with plasma current.



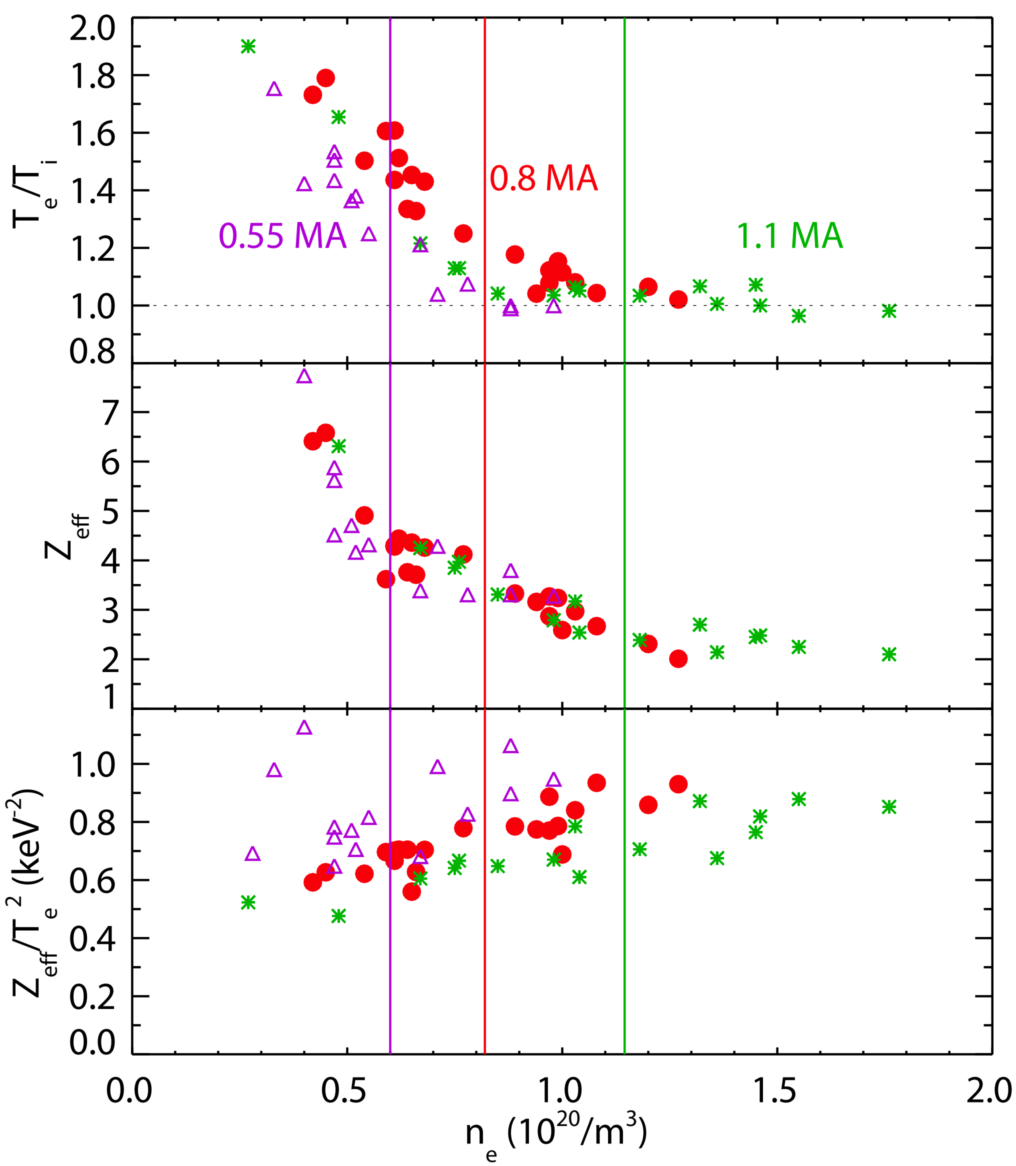
Rotation reversal anchor points and temperature flex points located inside of q =3/2.



Values of Z/T^2 and Collisionality at LOC/SOC Transition Fixed

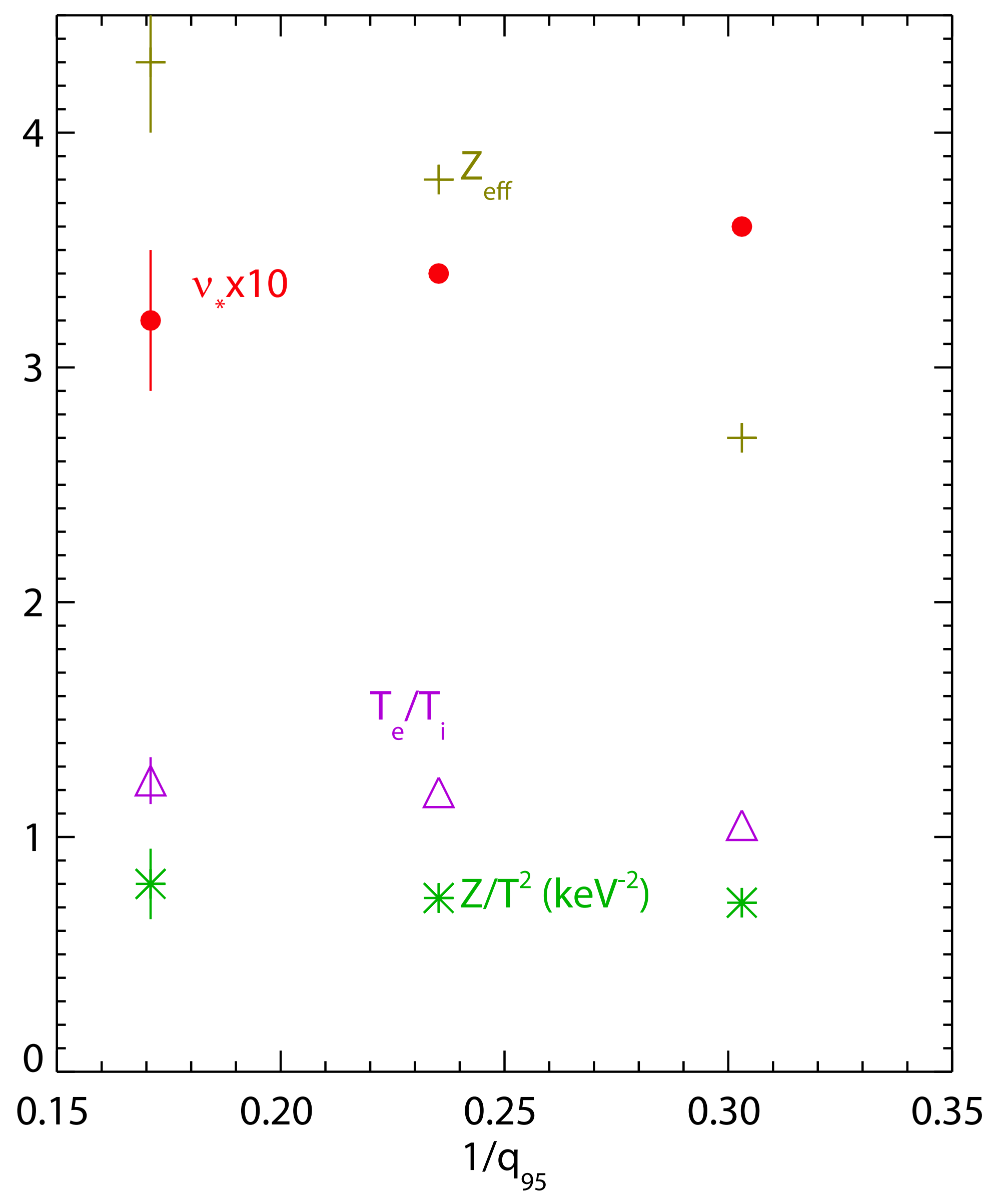
Scalings with density

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

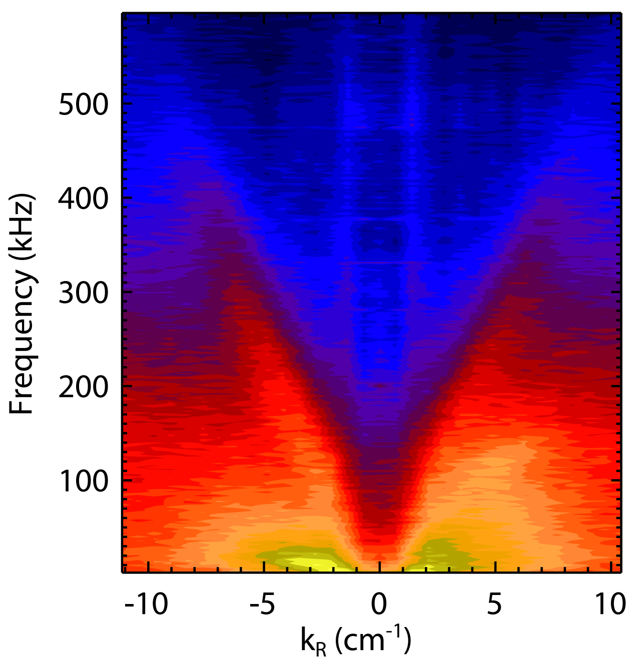
Core density fluctuations from PCI.

J.E.Rice et al., Phys. Rev. Lett. **107** (2011) 265001.

TEM?

$k_\theta \rho_s < 1$

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



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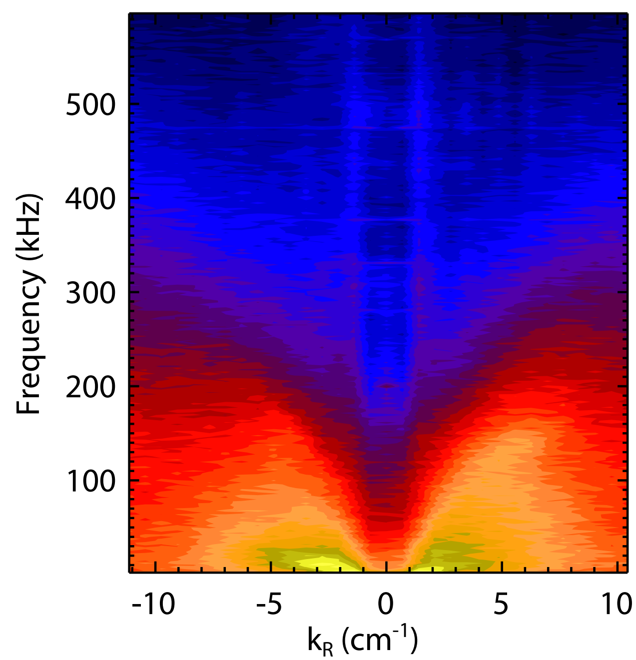
SOC $1.05 \times 10^{20}/m^3$



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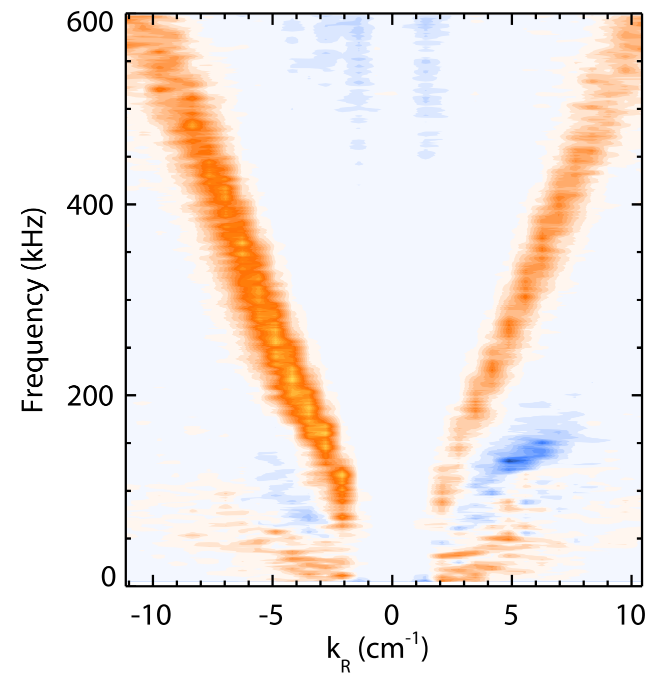
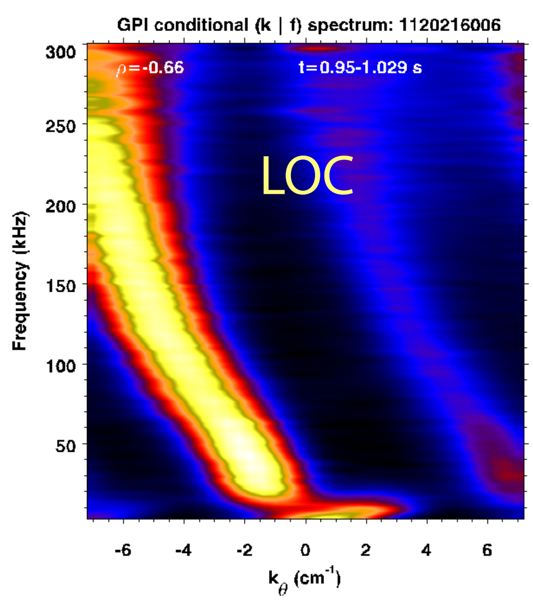
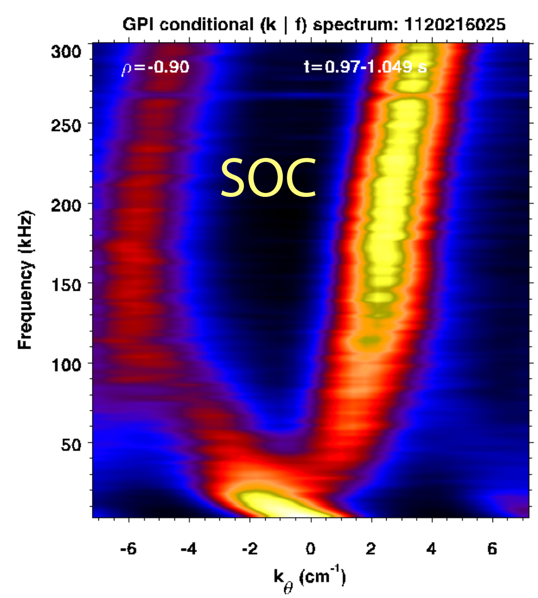


Edge density fluctuations from GPI.



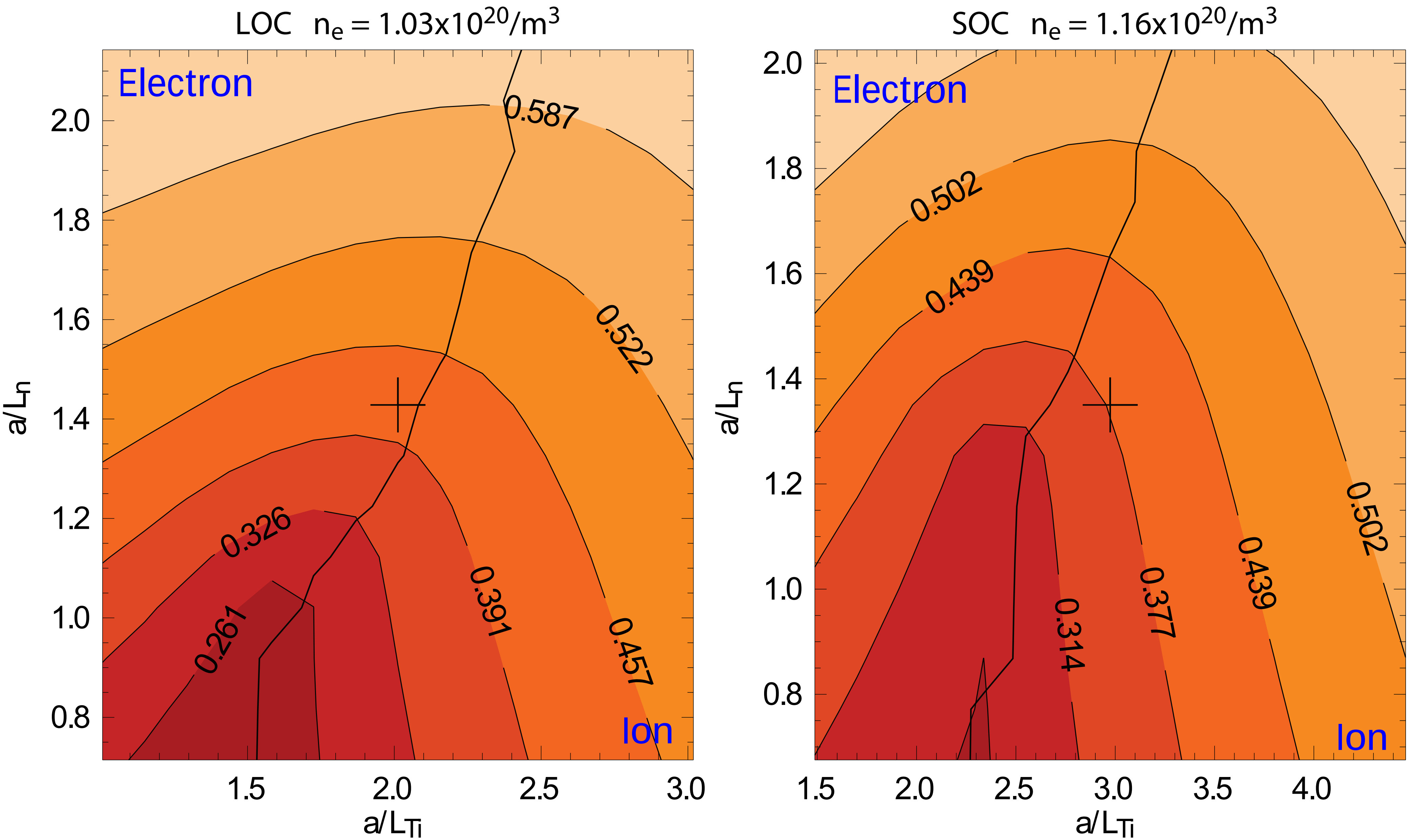


Edge turbulence propagation direction reverses at LOC/SOC transition.

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 $0.1 < k_\theta \rho_s < 0.75$



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.

A.Gondalekar et al., Proc. 7th IAEA Conf., Innsbruck (1978)
Y.Shimomura et al., JAERI-M Report 87-080 (1987)
R.L.Watterson et al., Phys. Fluids **28** (1985) 2857.

Non-local heat transport
occurs below a critical density.

K.W.Gentle et al., Phys. Rev. Lett. **74** (1995) 3620.
P.Mantica et al., Phys. Rev. Lett. **82** (1999) 5048.

Density profile peaking saturates at LOC/SOC transition.

C. Angioni et al., Phys. Plasmas **12** (2005) 040701.

Up/down impurity density asymmetries seen in SOC.

J.L.Terry et al., Phys. Rev. Lett. **39** (1977) 1615.

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

Rotation reversals occur at a critical density
which depends on q_{95} and is associated
with turbulence changes and the LOC/SOC transition.

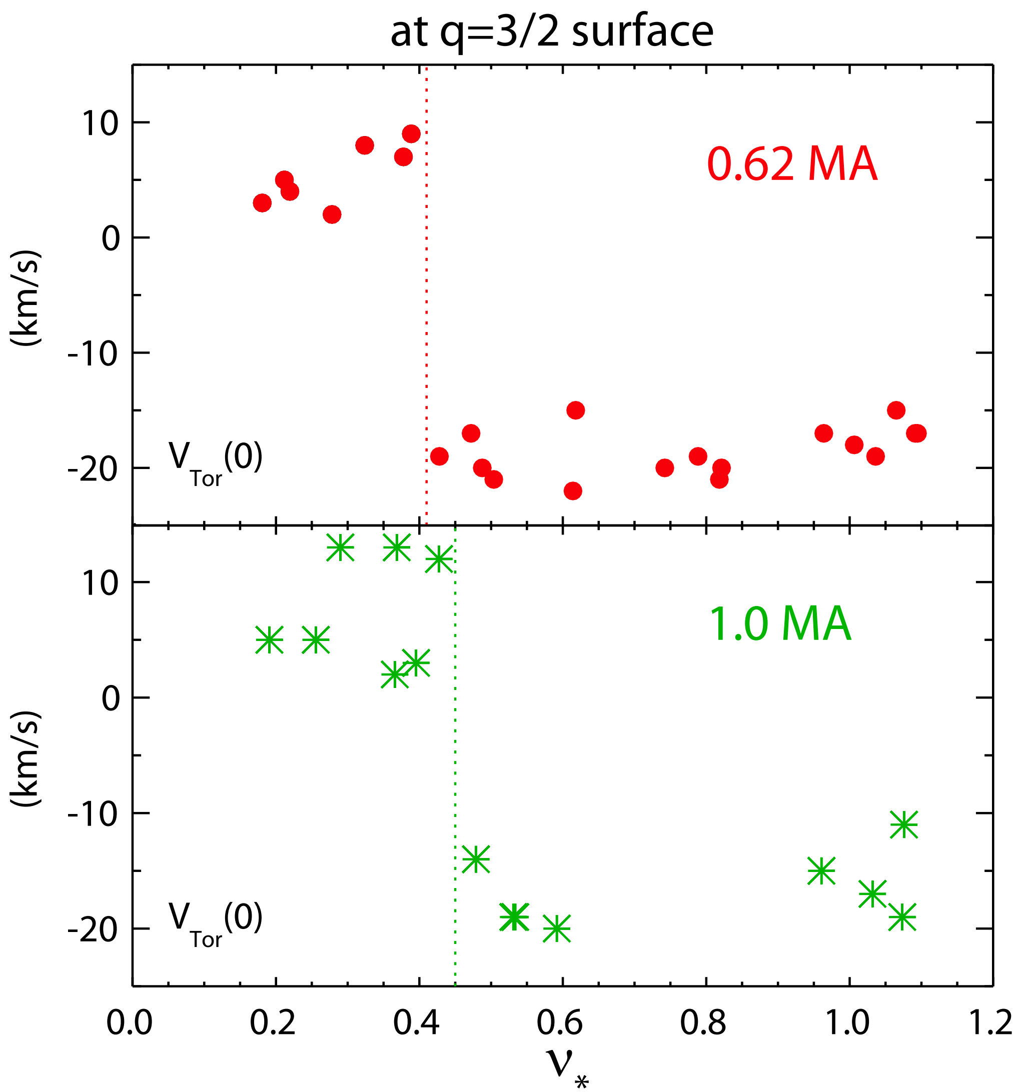
A.Bortolon et al., Phys. Rev. Lett. **97** (2006) 235003.
J.E.Rice et al., Nucl. Fusion **51** (2011) 083005.
J.E.Rice et al., Phys. Rev. Lett. **107** (2011) 265001.

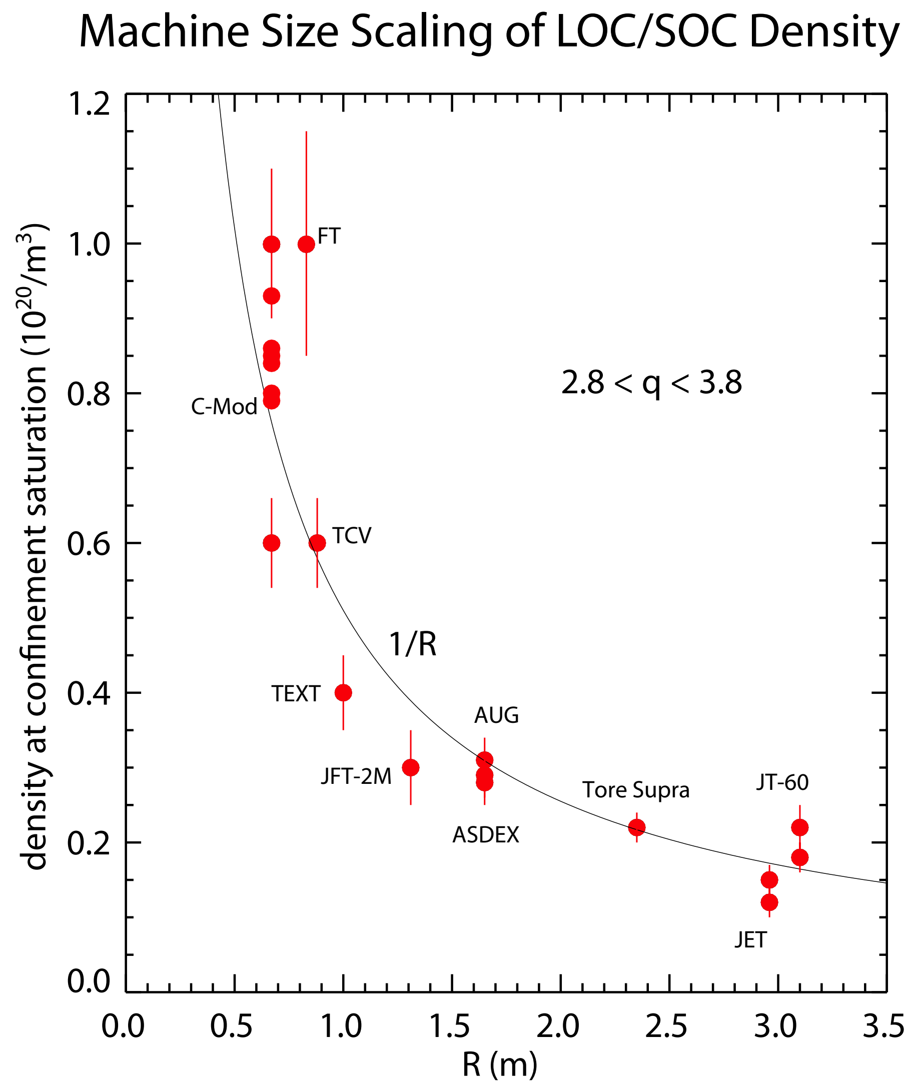
Momentum flux is proportional to the Reynolds stress: $-\chi_\phi\, dv_\phi/dr + V v_\phi + \Pi^{res}$

χ_ϕ is positive definite, quasi-linear V can change sign if dn/dr changes sign

Π^{res} can change sign if mode propagation direction changes.

Is Collisionality ν_* the Determining Parameter?





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

J.E.Rice et al., Phys. Plasmas **19** (2012) 056106.

Unifying *ansatz*:

low collsionality, 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

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 $cm^{-1} < k_\theta < 11$ 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