Supported by

Johns Hopkins University

NSTX

Studies of Improved Electron Confinement on NSTX

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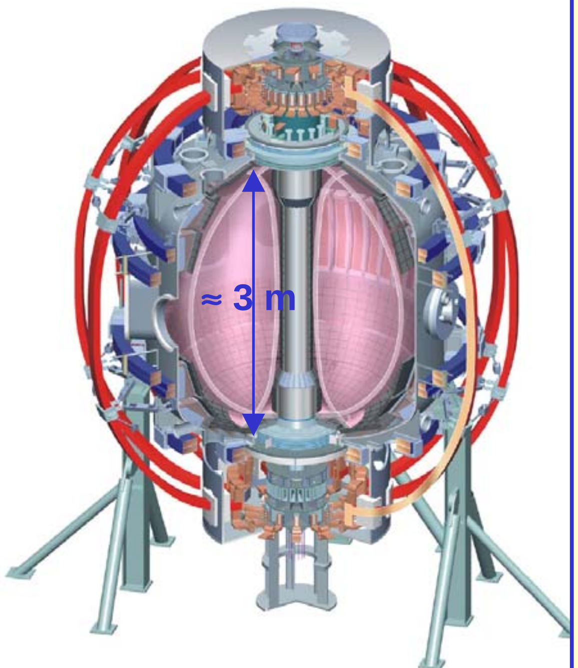


$A \approx 1.27$
$\kappa \leq 2.5$
$\delta \leq 0.8$
$R_0 \approx 0.85$ m
$I_p \leq 1.5$ MA
$B_{T0} \leq 0.6$ T
Pulse ≤ 1 s
NBI (≤ 100 keV) 7 MW
RF (30MHz) 6 MW
$T_{e0} \approx$ 1-3 keV

- Electron thermal transport is rapid in most NBI heated NSTX (National Spherical Torus Experiment) plasmas.

- Improved electron confinement is however observed in low density L-mode plasmas heated by early NBI.

- We use these plasmas to study q-profile effects on transport. The magnetic shear is modified through changes in the I_p ramp rate and NBI onset.

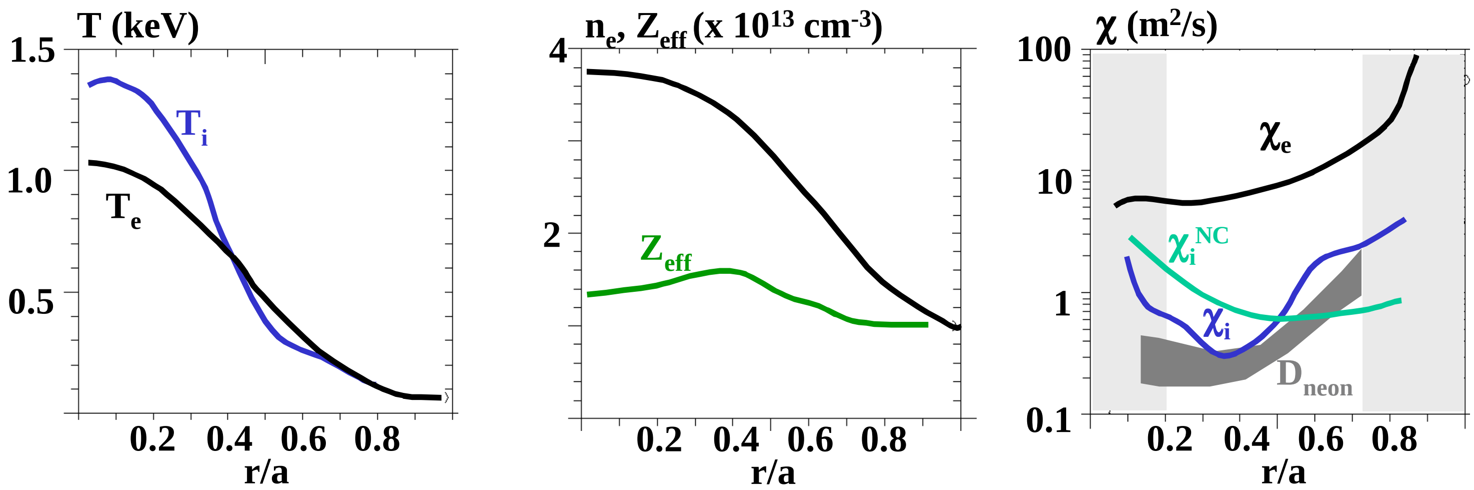
- Electron and ion ITBs form with fast current ramp and early beam injection, with $\chi_e, \chi_i \lesssim$ decreasing below 1m²/s.

- USXR measurements of double-tearing MHD activity and TRANSP current diffusion calculations indicate negative magnetic shear in these plasmas.

- The GS2 linear microstability assessment indicates that TEM and ETG growth rates are strongly reduced by the negative magnetic shear in the gradient region.

Electron transport is rapid in most NBI heated NSTX plasmas

1.6 MW NBI L-mode (108213, 1 MA, 4.5 kG, t≈ 0.3 s)



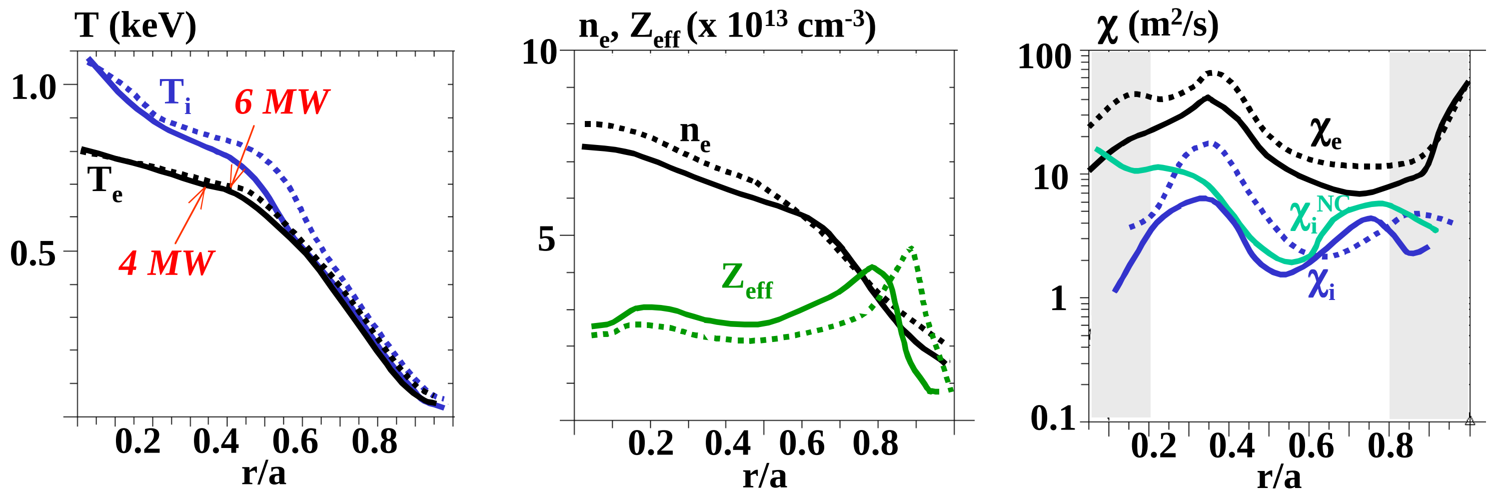
- $T_i > T_e$ although beams heat mostly the electrons (E_{beam} ≈ 80-100 keV >> E_{crit})

- $\chi_e >> \chi_i \approx D_{imp} \approx \chi_i^{NC}$ ($\chi_e \approx \chi_i \geq D_{imp} \geq \chi_i^{NC}$ in conventional A tokamak)

- Global confinement nevertheless exceeds the tokamak scaling (*S. Kaye, this meeting*)

χ_e increase can offset additional heating in H-mode

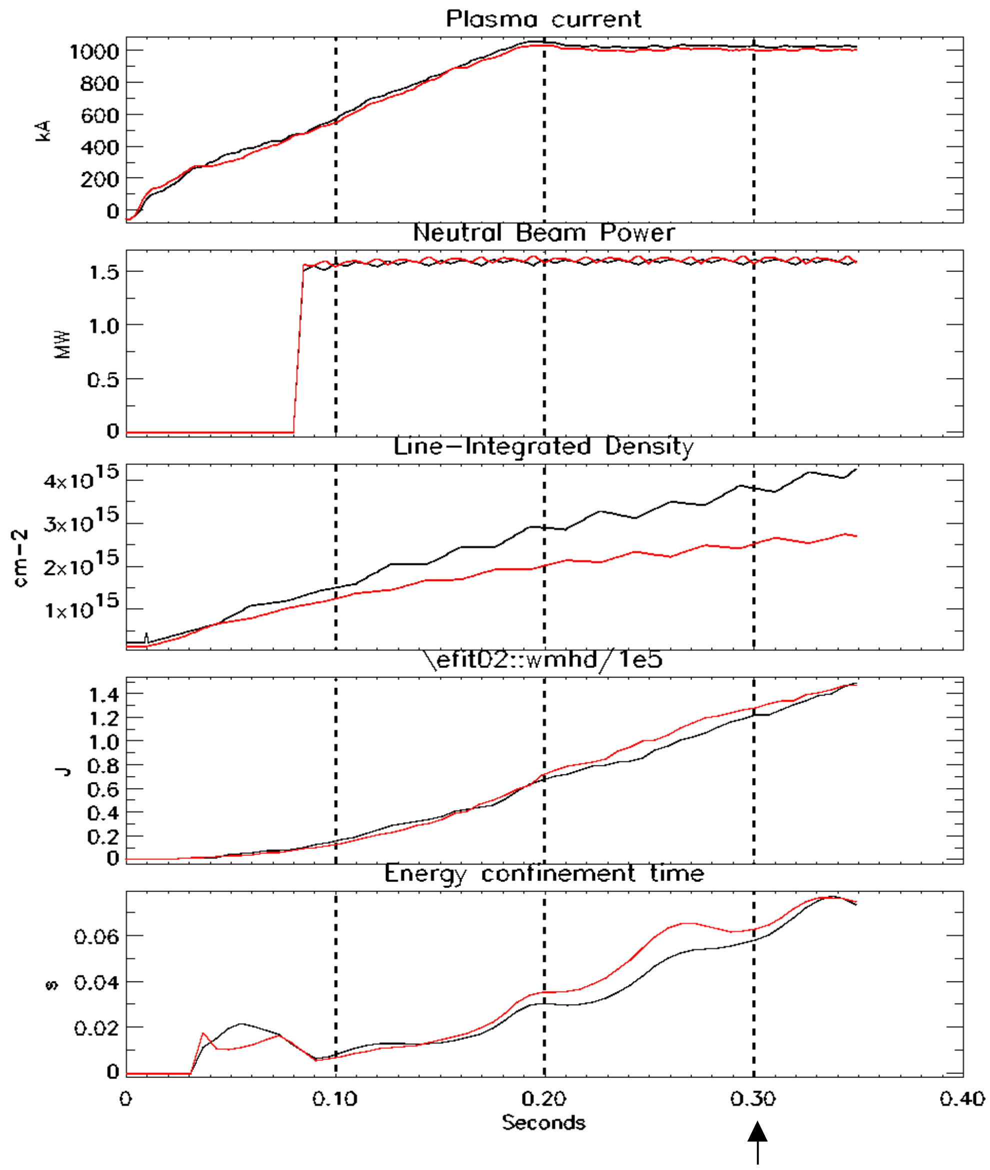
4 and 6 MW NBI H-modes (112570,112581, 1 MA, 4.5 kG, t ≈ 0.55 s)



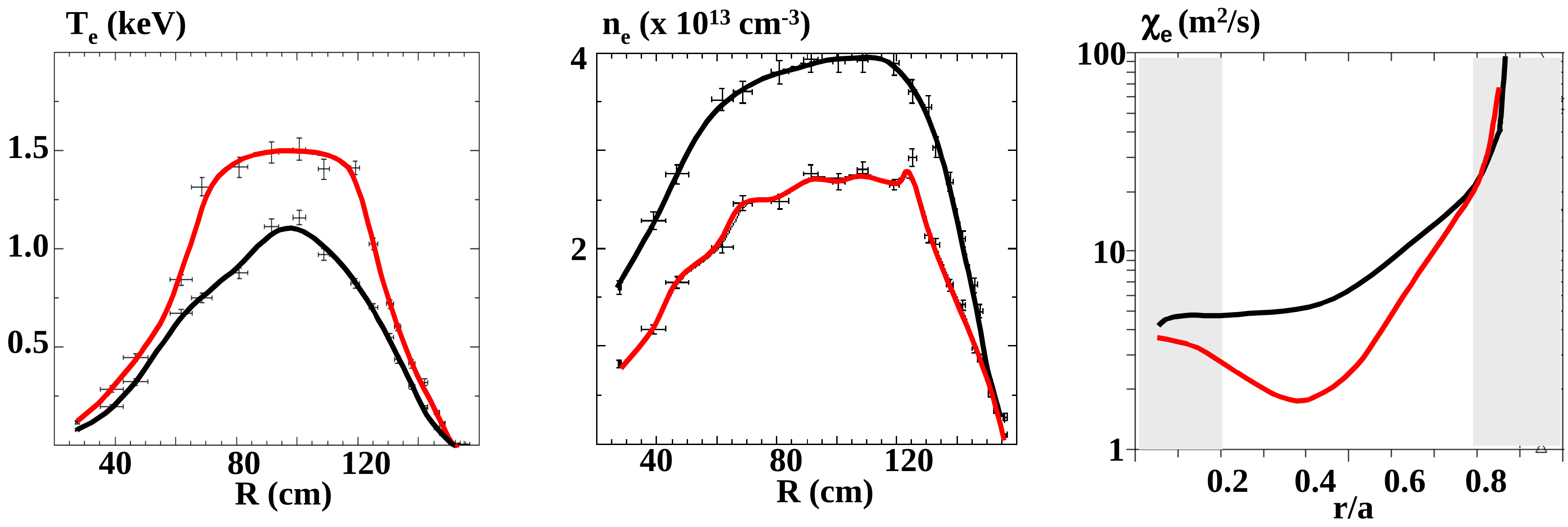
- In high power H-modes also $T_i > T_e$ and $\chi_e >> \chi_i \approx \chi_i^{NC}$
- Broad to flat core T_e profile -> very large χ_e
- Increased loss in dominant electron channel offsets additional heating

Reduced electron transport observed in low n_e L-modes

1.6 MW NBI L-modes (108213, 108918, 1 MA, 4.5 kG)



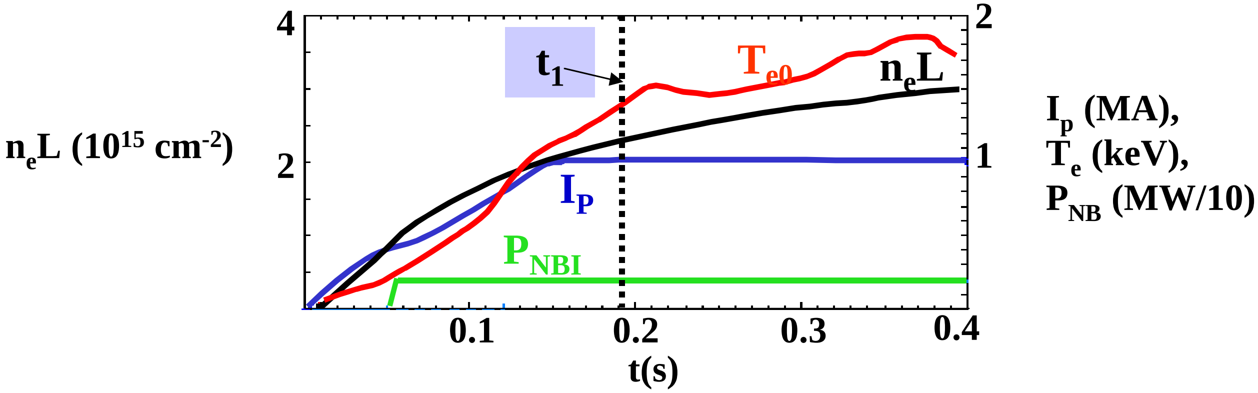
1.6 MW NBI L-modes 108213, 108918 at t ≈ 0.3 s



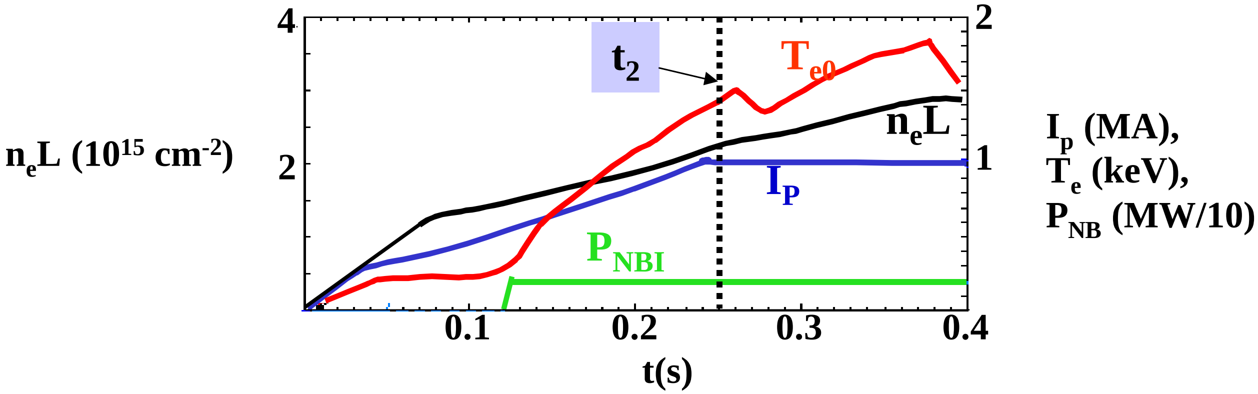
• **Evidence for reversed-q (USXR, TRANSP) -> q-profile important knob on NSTX transport ?**

I_p ramp rate and beam onset time used to modify q(r)

Fast ramp/early injection #112989 (2 MW, 4.5 kG)



Slow ramp/late injection #112996 (2 MW, 4.5 kG)

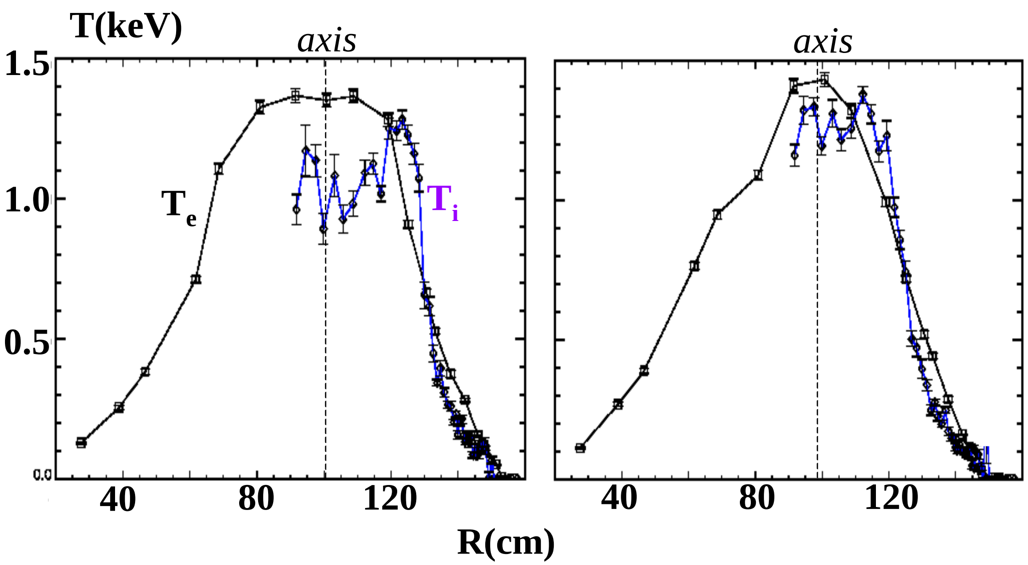


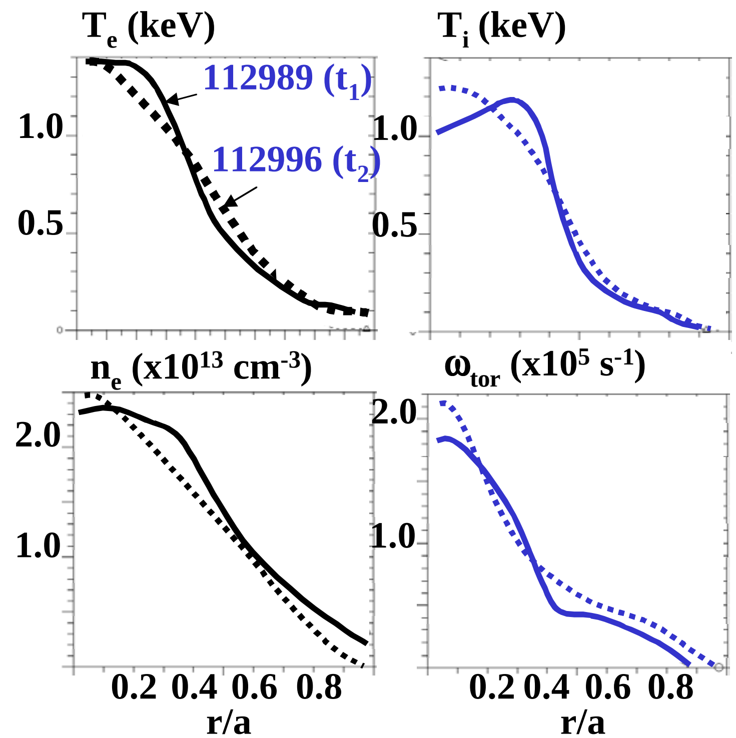
- Same low n_e condition with different q-profiles
- Similar T_{e0} , n_eL histories with respect to beam onset
- Time points t_1 and t_2 used for transport comparison (see below)

Temperature gradients increase with fast ramp at low n_e

Fast ramp 112989
$t_1 \approx 0.19$ s

Slow ramp 112996
$t_2 \approx 0.25$ s





- To highlight the effects of different q-profiles we compare thermal profiles at times t_1 and t_2 when rotation, T_i/T_e, and β are similar

- $T_{e,}T_i$ gradients are twice as steep at mid-radius in shot with apparent shear reversal

Electron and ion transport change with q-profile condition

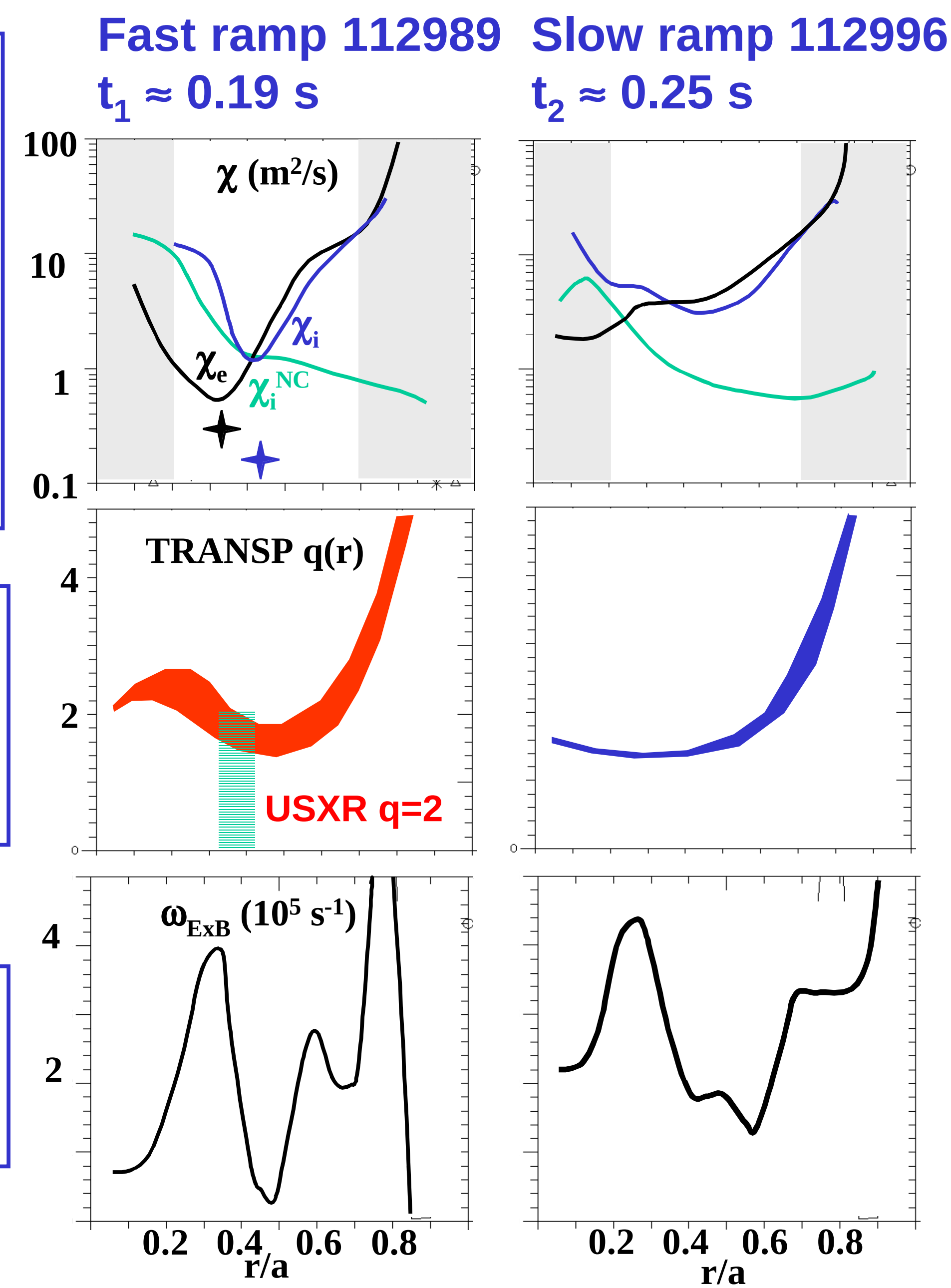
- Strong χ_e decrease at r/a≈0.3-0.45 in fast ramp case (electron ITB)

- Also χ_i decrease to ≈ neoclassical range between r/a ≈0.4-0.5 (ion ITB)

- $\chi_{e\ min}$ ≈ 0.3 m^2/s, $\chi_{i\ min}$ ≈ 0.15 m^2/s, using raw outboard temperature gradients (✦)

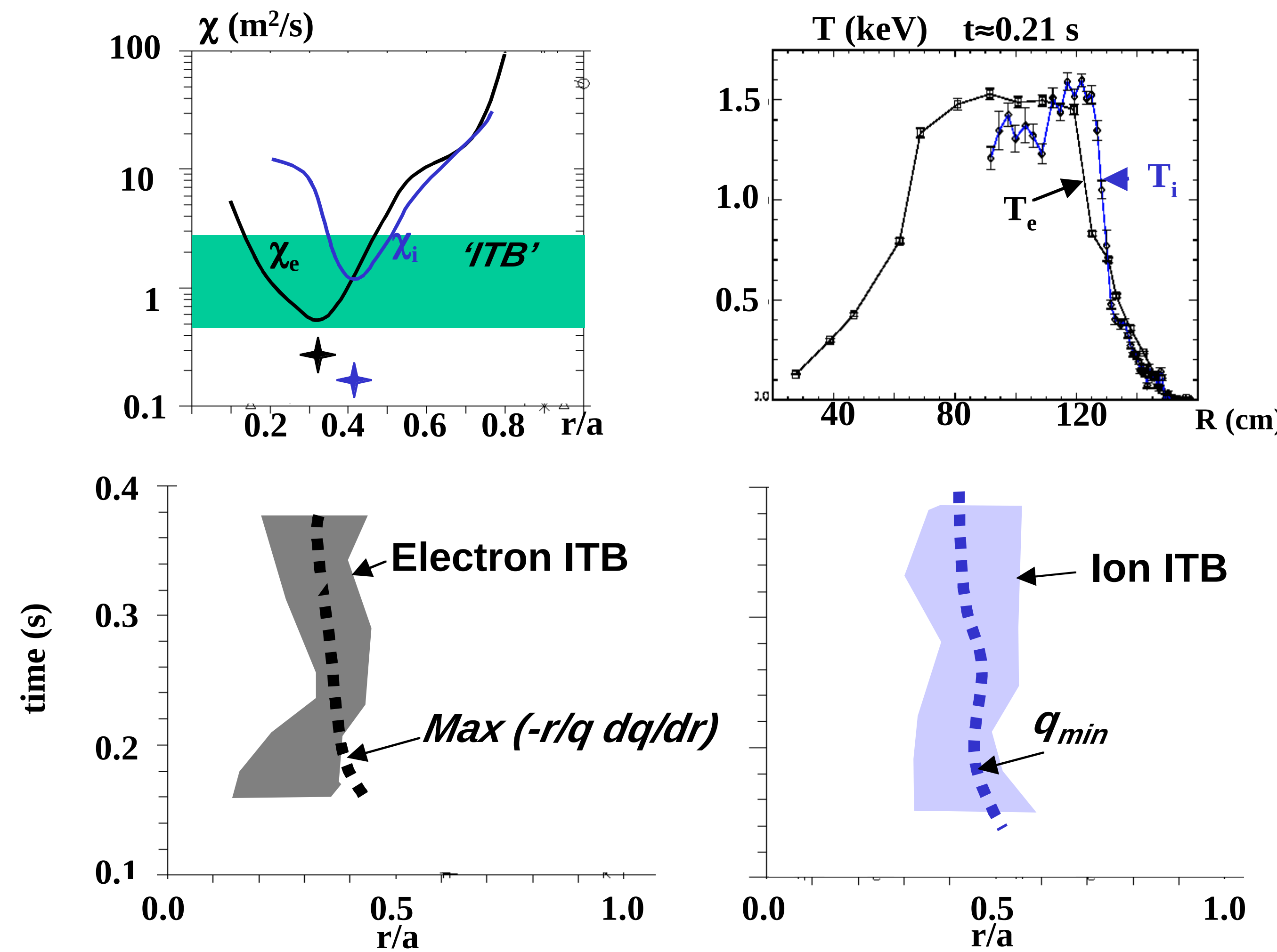
- TRANSP magnetic diffusion modeling consistently indicates shear reversal with fast ramp and monotonic q(r) with slow ramp (S. *Kaye et al, this conference*)

- ExB shear similar -> transport changes most likely due to q-profile change (ExB actually *lower* at ion barrier)



Electron and ion barriers are at different radii

Fast ramp
112989



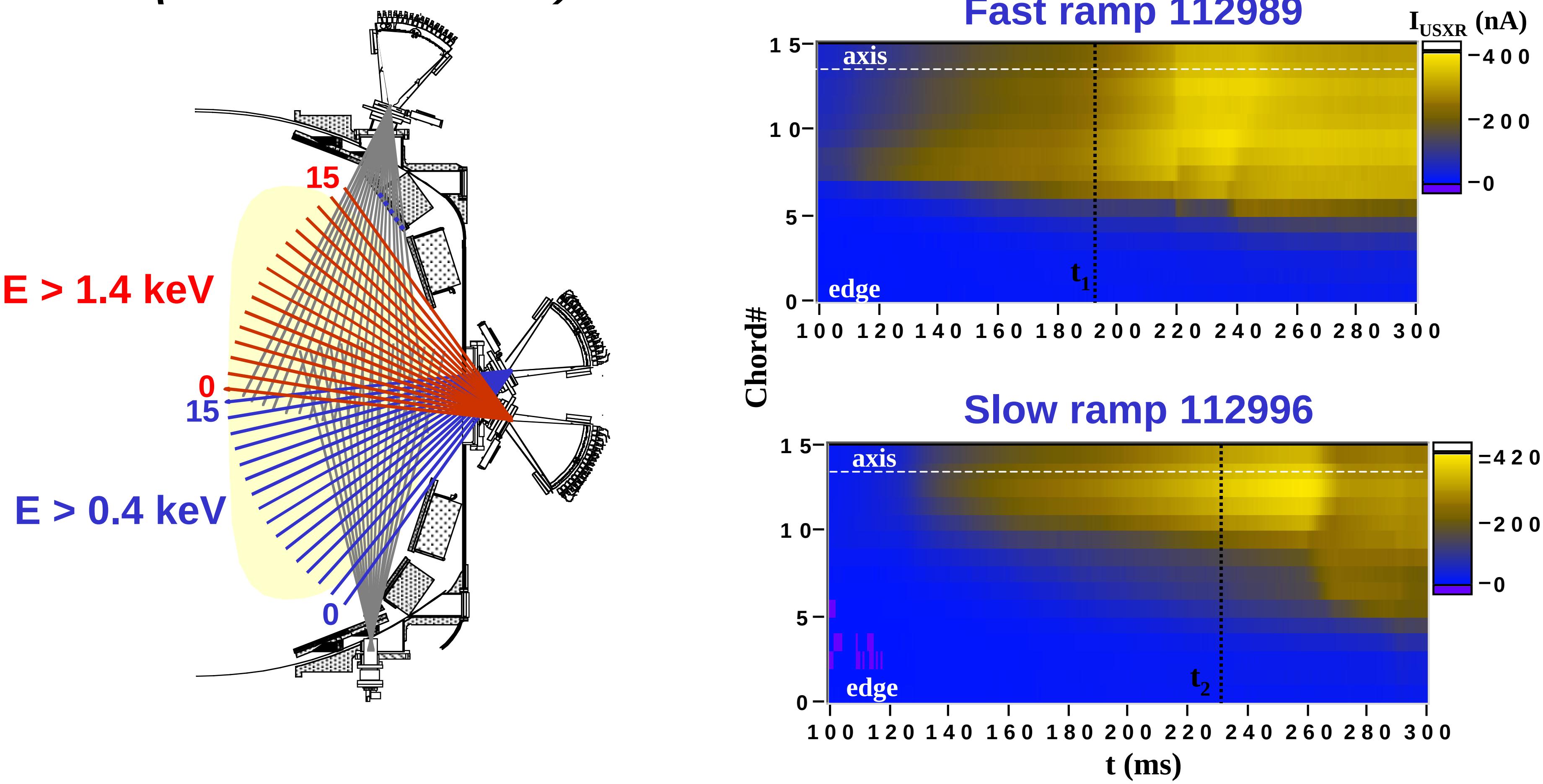
- Good transport region (ITB) taken as $\chi < 2.5$ m²/s
- Electron ITB follows path of large negative shear
- Ion ITB path follows path of low magnetic shear (q_{min})
- Different q-dependence of instability drive for electrons and ions ?

USXR shows no reconnections or MHD modes till t_1 and t_2

'Two-color' ultrasoft X-ray NSTX diagnostic

(Stutman et al RSI 99)

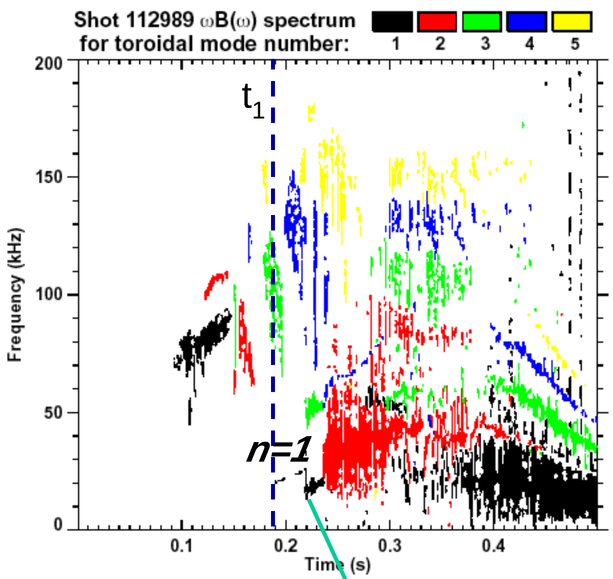
USXR profiles (E > 0.4 keV)



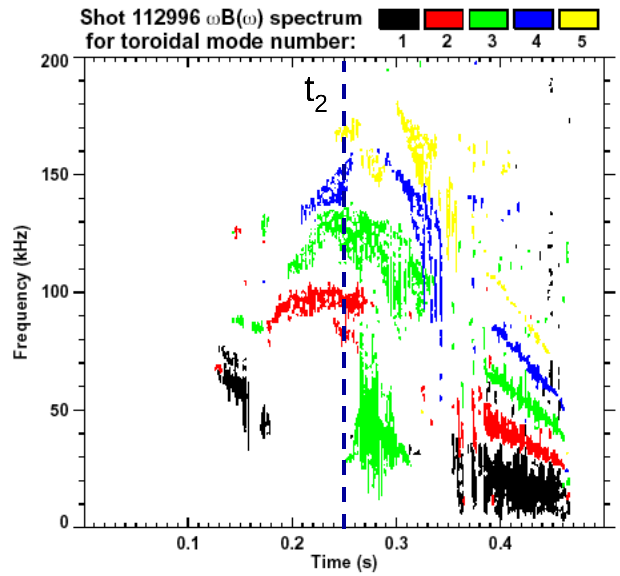
- Both shots free of large reconnections/MHD till ≈ 0.22 s in 112989 and 0.26 s in 112996
- Broader and steeper USXR profiles in faster ramp shot

Magnetic data shows no low-n activity in either case

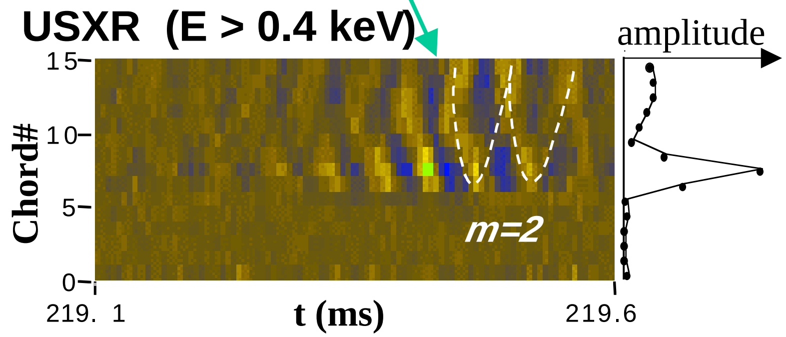
112989 - fast ramp/early beam



112996 - slow ramp/late beam



USXR (E > 0.4 keV)



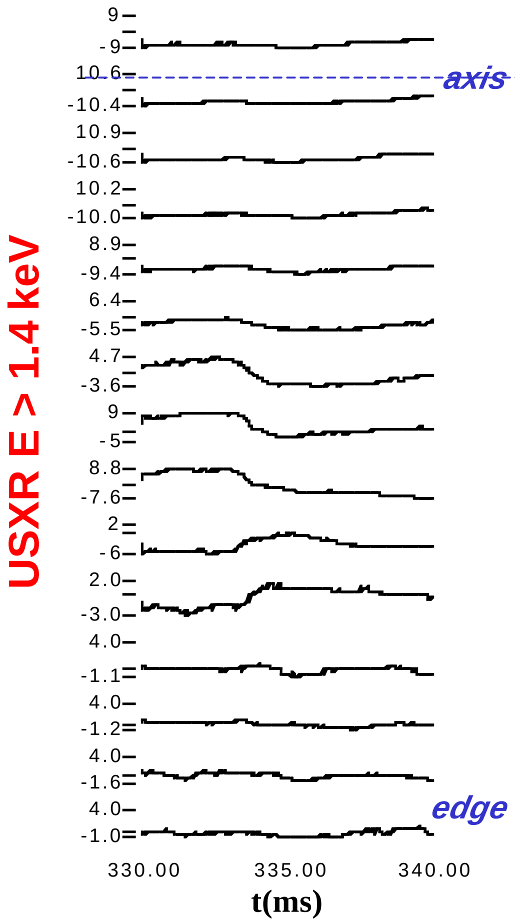
• In fast ramp shot 112989 a ≈ 20 kHz, n=1 mode briefly appears and locks in the magnetic spectrum around t ≈ 0.22 s (likely causing the V_t 'plateau' below)

• USXR data indicates it is a 2/1 mode located in the core (r/a ≈ 0.4)

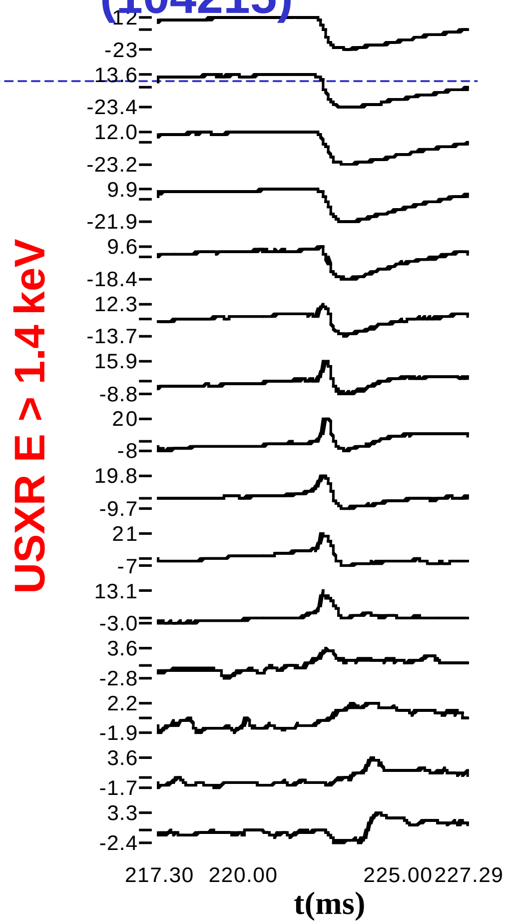
• Mode located around TRANSP predicted q=2 radius (see below)

USXR data points to q-reversal in fast ramp shots

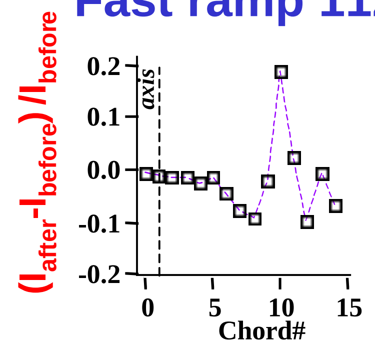
Fast ramp 112989



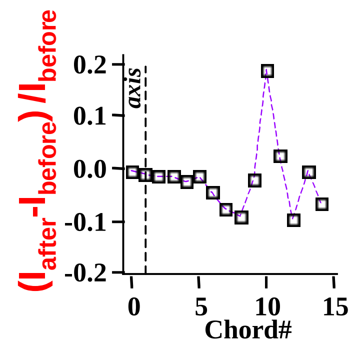
Typical q=1 sawtooth (104215)



Fast ramp 112989



q-reversed (MSE) 114139

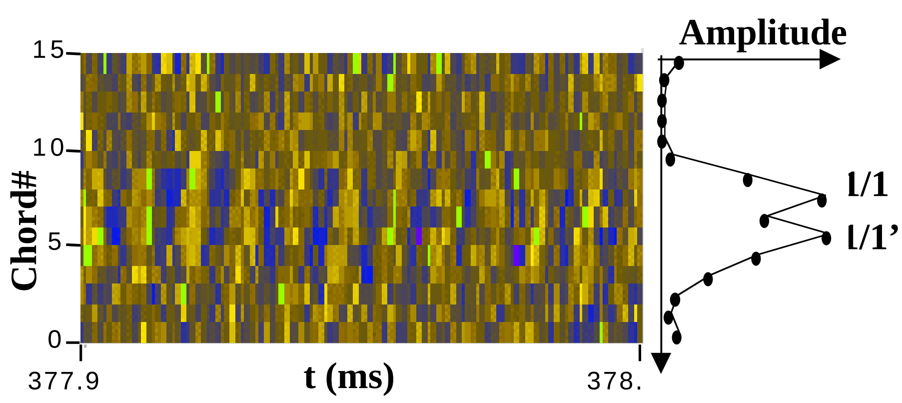


- **USXR and TRANSP magnetic diffusion calculations used to estimate q-profile changes**
- **The T_e sensitive USXR profiles show off-axis ‘sawteeth’ in the fast ramp shot**
- **Off-axis ‘sawteeth’ seen also in shots in which MSE later confirmed q-profile reversal**

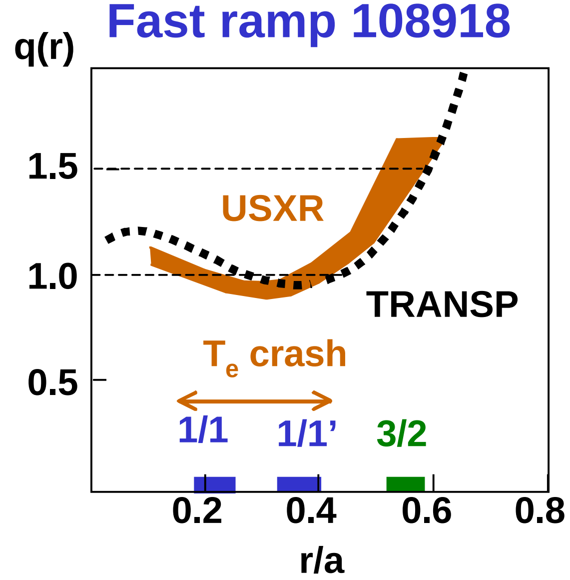
USXR and TRANSP estimated q-profiles agree

USXR E > 1.4 keV

Fast ramp 112989



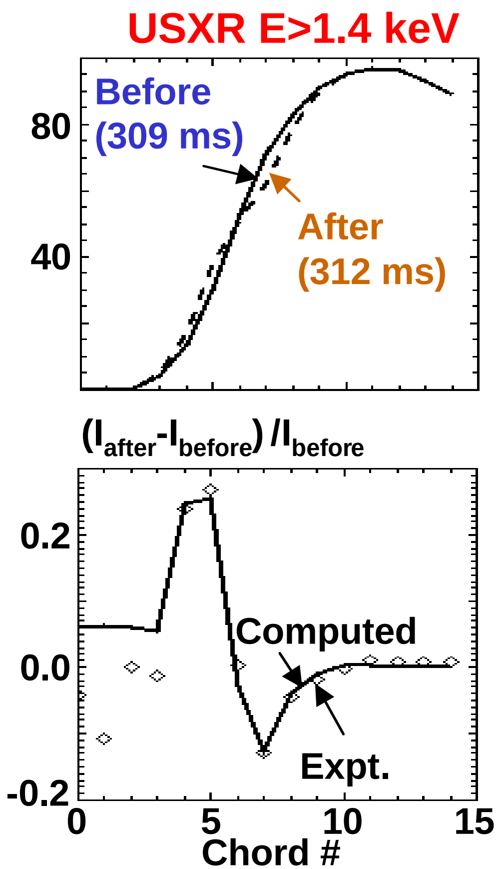
Fast ramp 108918

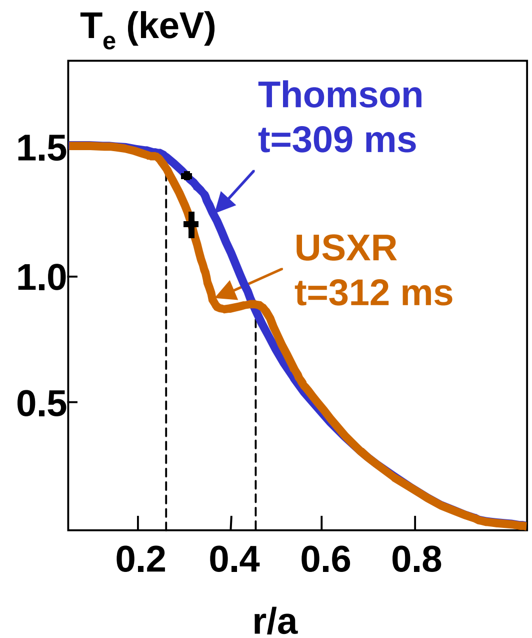


- Two 1/1 modes at different radii around time of 'sawteeth'
- In shots without large reconnections the q=1 radii from USXR corroborate the reversed q-profile predicted by TRANSP
- Slow ramp shots do not exhibit this MHD behavior
- Likely early q-reversal in fast ramp shots and more monotonic q(r) in slow ramp cases
- TRANSP magnetic diffusion calculations agree (see below)

‘Two-color’ USXR modeling supports off-axis, DT sawtooth

Fast ramp 108918





- Thomson T_e profile before crash ‘propagated’ in time using two-color modeling (Stutman et al RSI 2003)
- Similar off-axis T_e crash associated with double-tearing (DT) reconnection in reversed shear discharges in TFTR

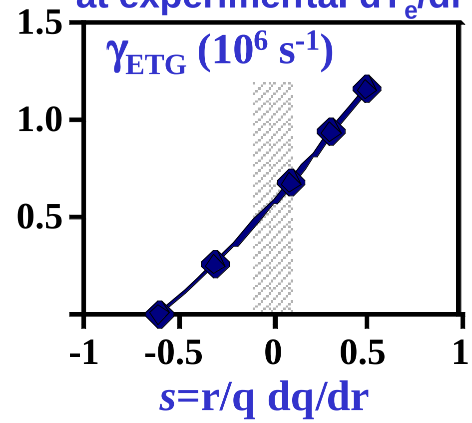
Linear microstability analysis supports the observed trends

GS2 growth rates (10^5 s^{-1}) of most unstable modes in the ITG, TEM and ETG range. Also shown the magnetic shear used in GS2 and the TRANSP ExB shearing rate (10^5 s^{-1})

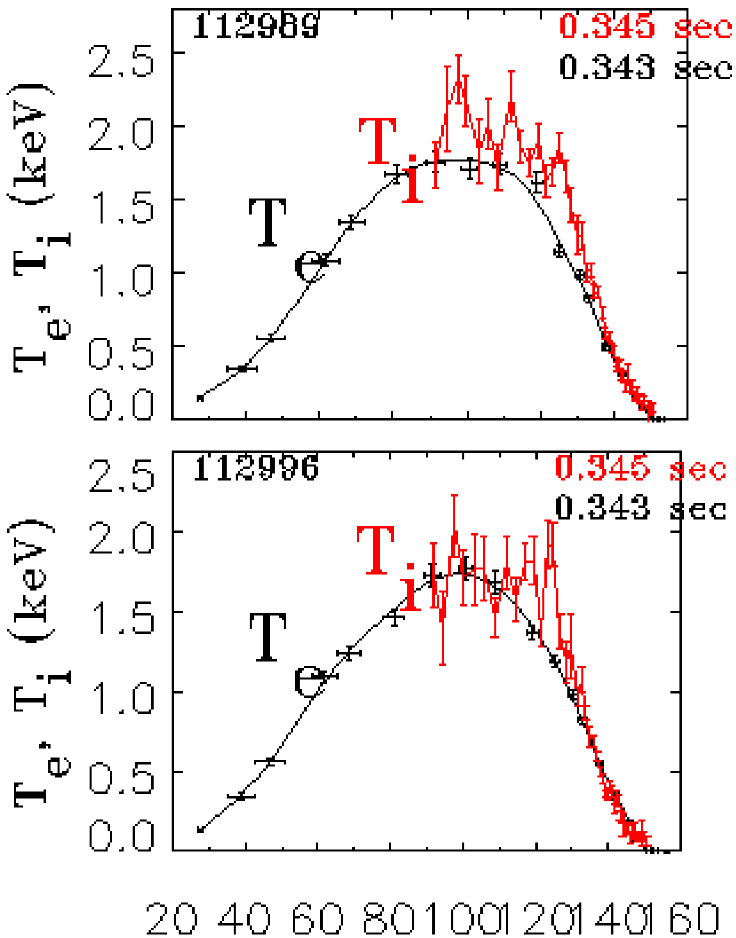
	Fast ramp 112989, t_1				Slow ramp 112996, t_2		
r/a	0.25	0.35	0.45	0.65	0.25	0.45	0.65
s	*-0.6*	*- 1.7*	*- 0.45*	*+2.3*	*-0.35*	*+0.65*	*+2.3*
ITG	0.1	0.2	0.05	1.5	0.1	0.4	1.5
TEM	0.1	0.1	0.1	2.0	stable	1.8	3.8
ETG	stable	stable	stable	7.8	stable	5.0	7.5
χ_e (m^2/s)	*0.7*	*≥0.3*	*1.6*	*12*	*3*	*4*	*13*
χ_i (m^2/s	*10*	*2*	*≥0.15*	*12*	*6*	*3*	*12*
ω_{ExB}	*2.5*	*3.8*	*0.5*	*2.0*	*4.2*	*1.7*	*2.5*

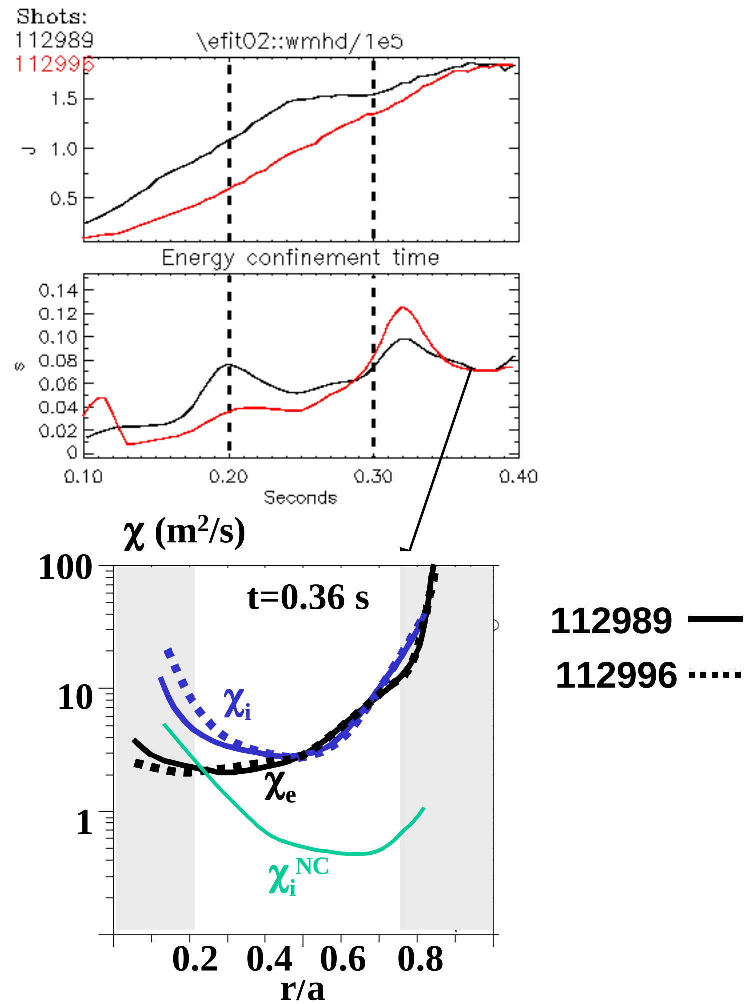
- TEM and especially ETG modes strongly stabilized by negative magnetic shear in the gradient region
- ITG modes also reduced at r/a ≈ 0.45
- All modes intrinsically stable in the core (little gradient)
- All modes strongly driven for both shots in the outer plasma, with γ larger or comparable to ω_{ExB}

GS2 shear scan at experimental dT_e/dr



Later the transport picture becomes similar in both shots





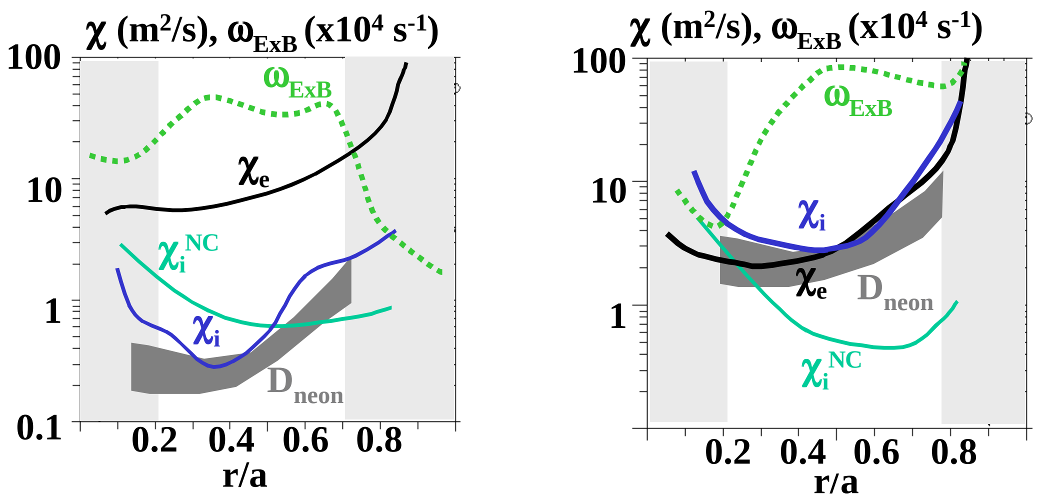
- Transport barriers 'weaken' in 112989, while $\chi_{e,i}$ improve with time in slow ramp 112996
- q-profiles likely converge to similar, more moderately reversed shape in both shots:
  - reconnections relax reversal in 112989
  - transport bifurcation to broader current and T_e profile in 112996 at $t \approx 0.26$ s ?

Puzzles from these experiments

• While core electron transport decreases with reverse shear, ion thermal and impurity transport *increase* in low n_e L-mode compared to intermediate n_e case (although ω_{ExB} large)

Intermediate density L-mode, t≈ 0.29 s (108213)

Low density L-mode, t ≈ 0.36 s (112989)



• Is there a systematic correlation between the absence of ion turbulence (excluding ITB situations) and rapid electron transport in NSTX ?

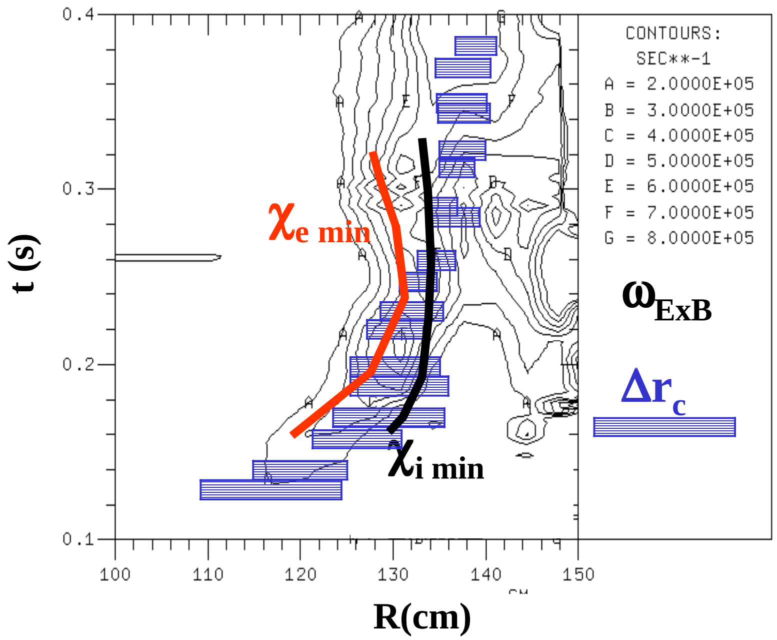
- In high density L-, H-modes, when $\chi_i \approx \chi_{i\,neo}$ (no ion turbulence) -> rapid transport electron
- In low density L-mode, when $\chi_i > \chi_{i\,neo}$ (some ion turbulence) -> $\chi_e \approx \chi_i$ (similar electron and ion transport scale)

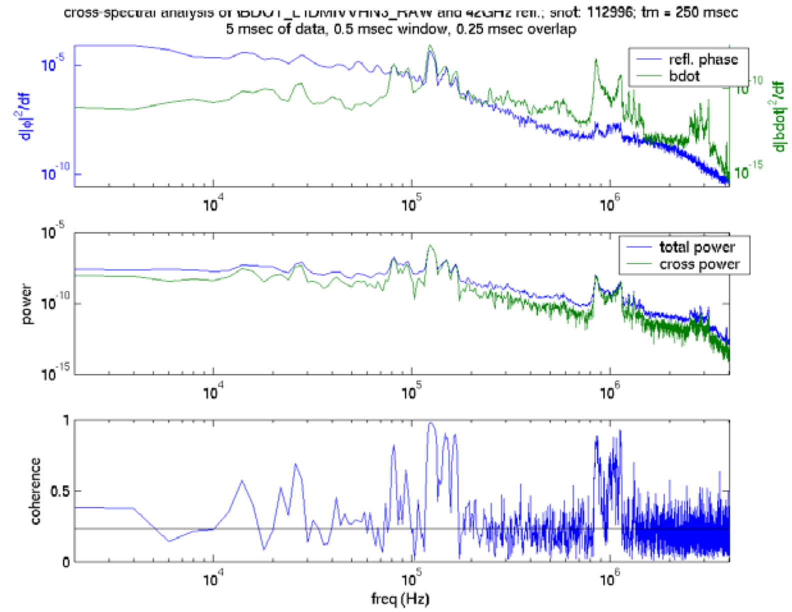
• What drives the flat T_e profile inside the electron ITB in fast ramp shots ?

Large fluctuation correlation lengths in the low n_e L-modes

Density correlation lengths Δr_c (S. Kubota, UCLA)

Fast ramp 112989 | **Slow ramp 112996**





- Large Δr_c in regions of low χ and large ω_{ExB} ($\leq$ 20 cm in slow ramp 112996)
- Spectral analysis indicates however correlation with high frequency magnetic fluctuations, including fast particle driven MHD (i.e., likely ideal modes)
- Could these nevertheless play a role in thermal transport ?

Summary

- Electron transport can be reduced to quite low levels (≥ 0.3 m^2/s) in NSTX -> large electron transport not an intrinsic characteristic of the low B_t, low A ST

- The q-reversal tool for electron transport reduction in tokamaks seems to work also in a ST

- Microstability calculations indicate medium and high-k instabilities might be involved in electron transport in the NSTX L-mode

- A possible correlation between the absence/existence of ion turbulence and strong/reduced electron transport in NSTX (excepting ITB situations)
  -> *is long wavelength ion turbulence regulating short wavelength electron transport (for instance, zonal flows limiting radial extent of ETG 'streamers') ?*

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