DOES FAST ION MHD DRIVE MAGNETIC ELECTRON TRANSPORT IN NSTX ?

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Outline

- Puzzle we try to solve

- Is T_e flattening genuine electron transport effect ?
  - low-f MHD
  - Fast ion redistribution due to Fast Ion MHD
  - Strong anomalous ion heating (CAE)

- Indications for magnetic electron transport

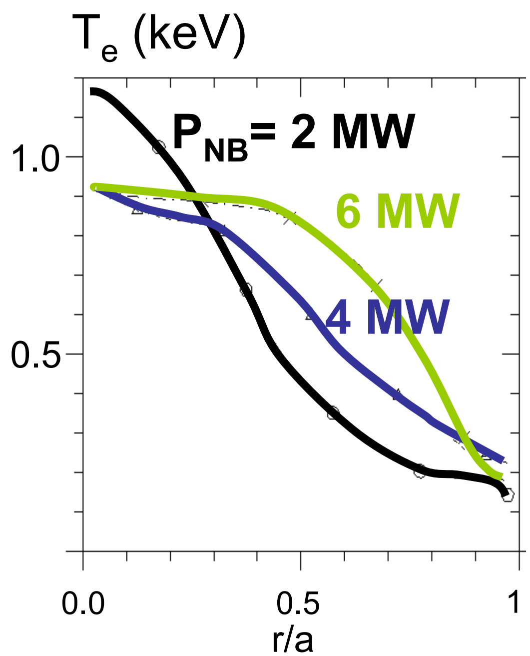
- What else fall in place if we assume magnetic transport ?

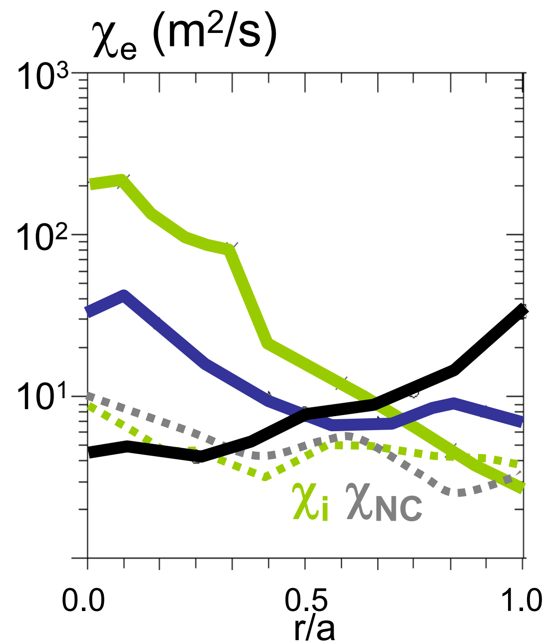
- Fast ion connection

- Possible implications, further work possible

Puzzle we try to solve : Why central T_e flattens / electron transport increases with P_b in NSTX H-modes?

'High performance' H-modes, 1 MA 4.5 kG , t=0.42 s

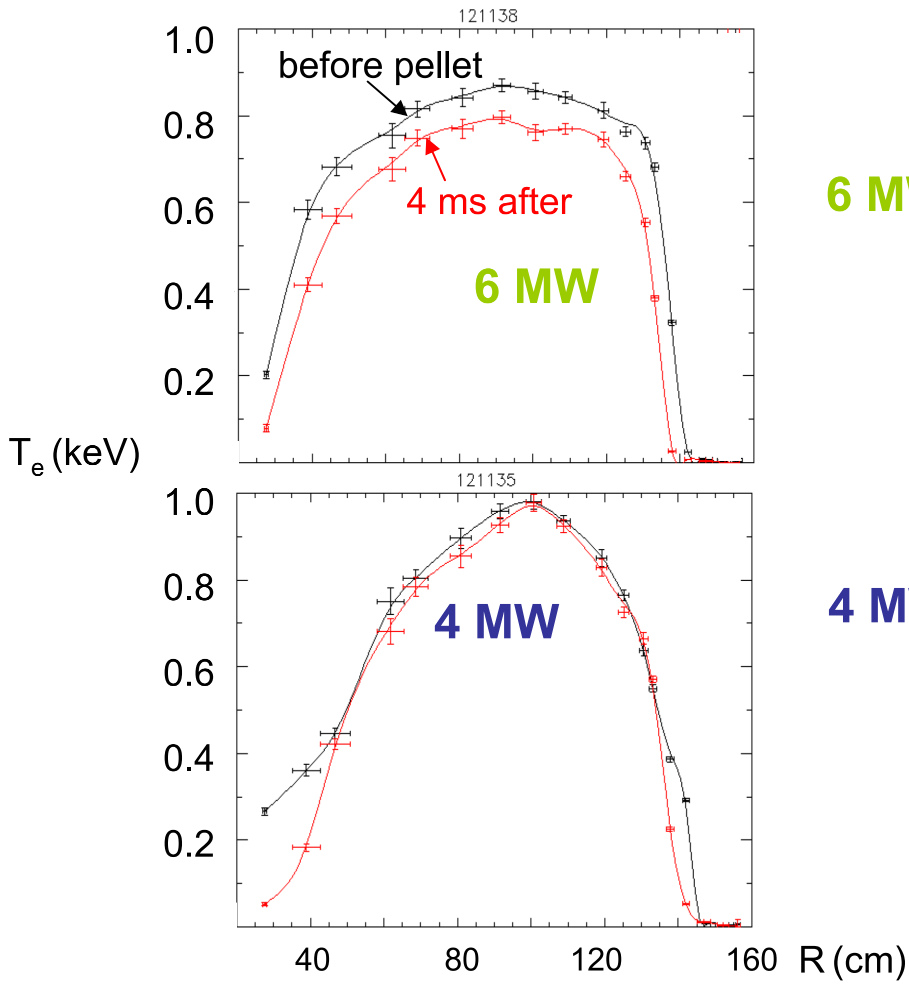




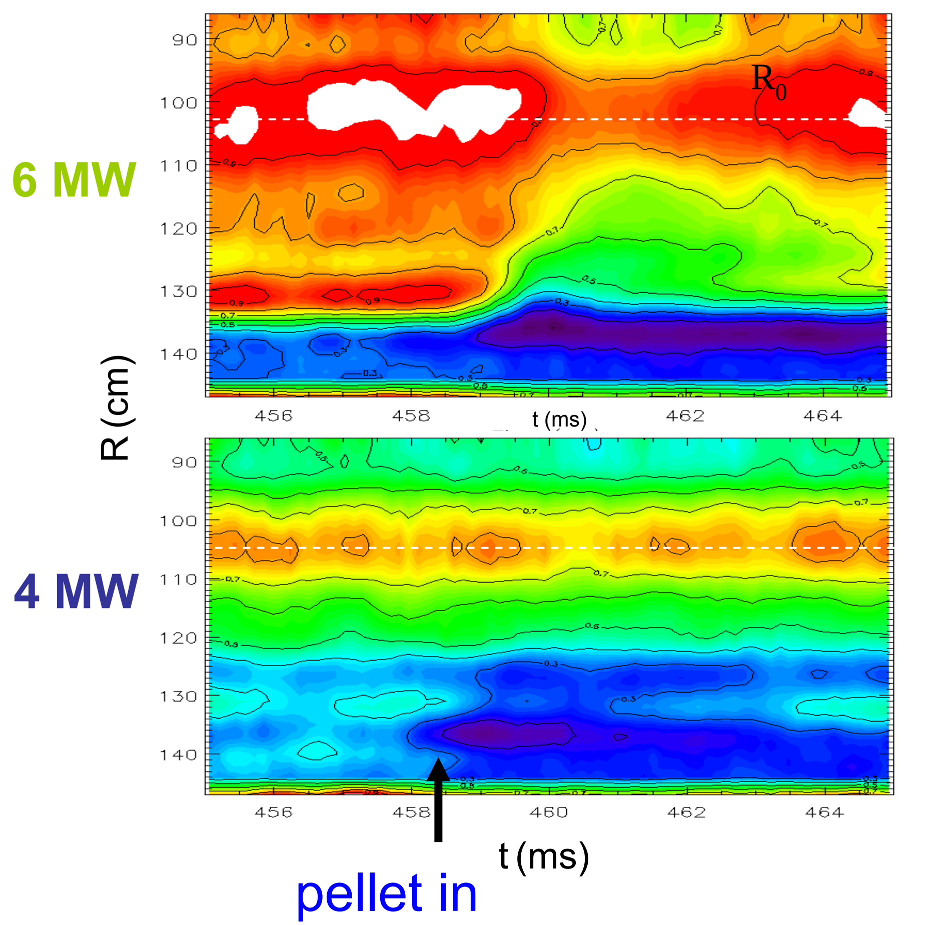
- TRANSP computes *very* rapid electron transport inside r/a ≤0.4
- Perturbed transport also very rapid (global T_e crash at Type-I ELM, pellet)
- Ion transport around neoclassical

Perturbative experiments also indicate rapid transport

T_e perturbation from 3 mg Li pellet

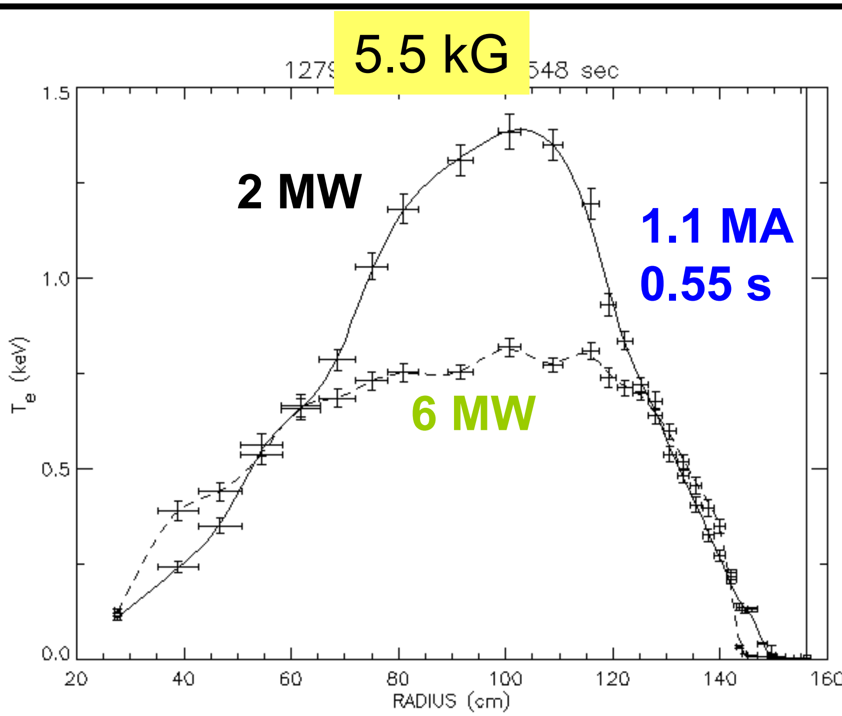


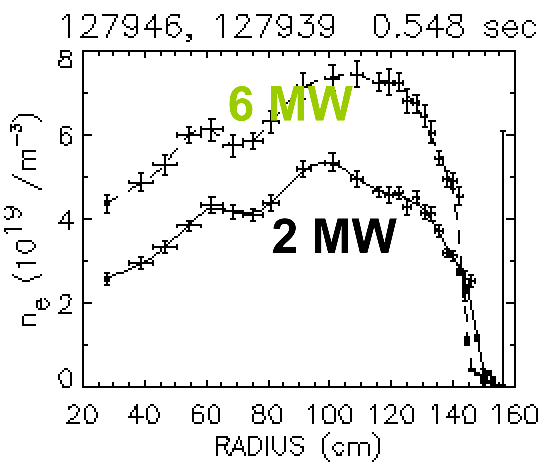
T_e sensitive SXR emission (E> 1.5 keV)

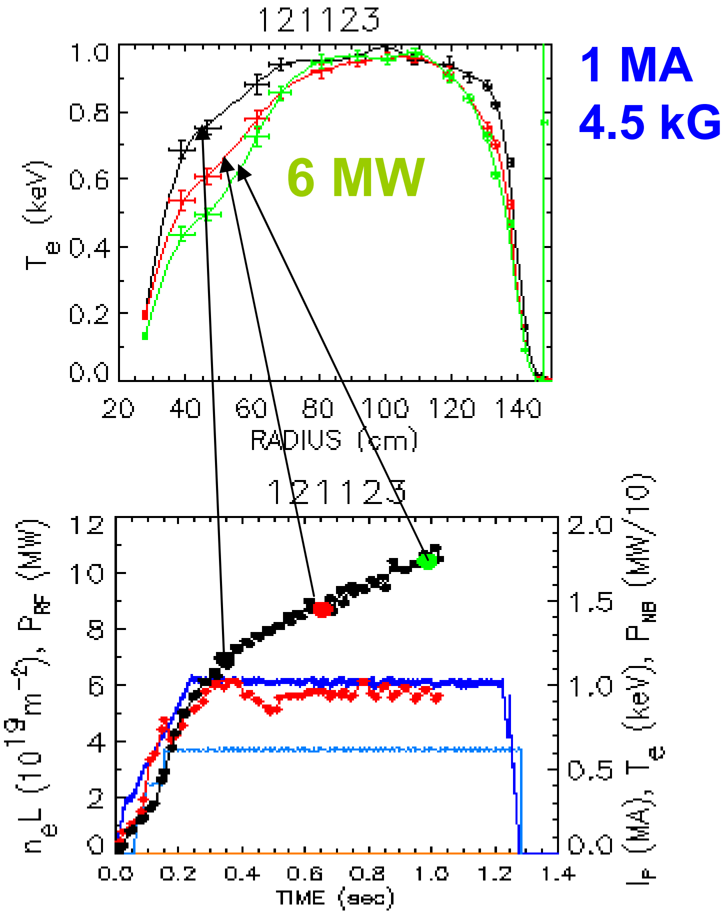


- Global, rapid T_e perturbation at high P_b
- Mostly peripheral perturbation at reduced P_b

T_e flattening persists also at higher B_t, I_p, and later in time

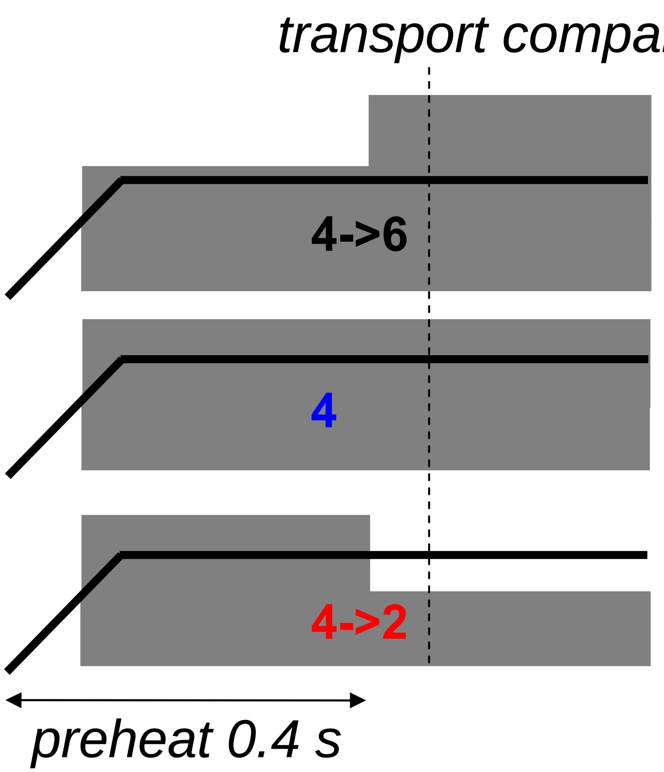


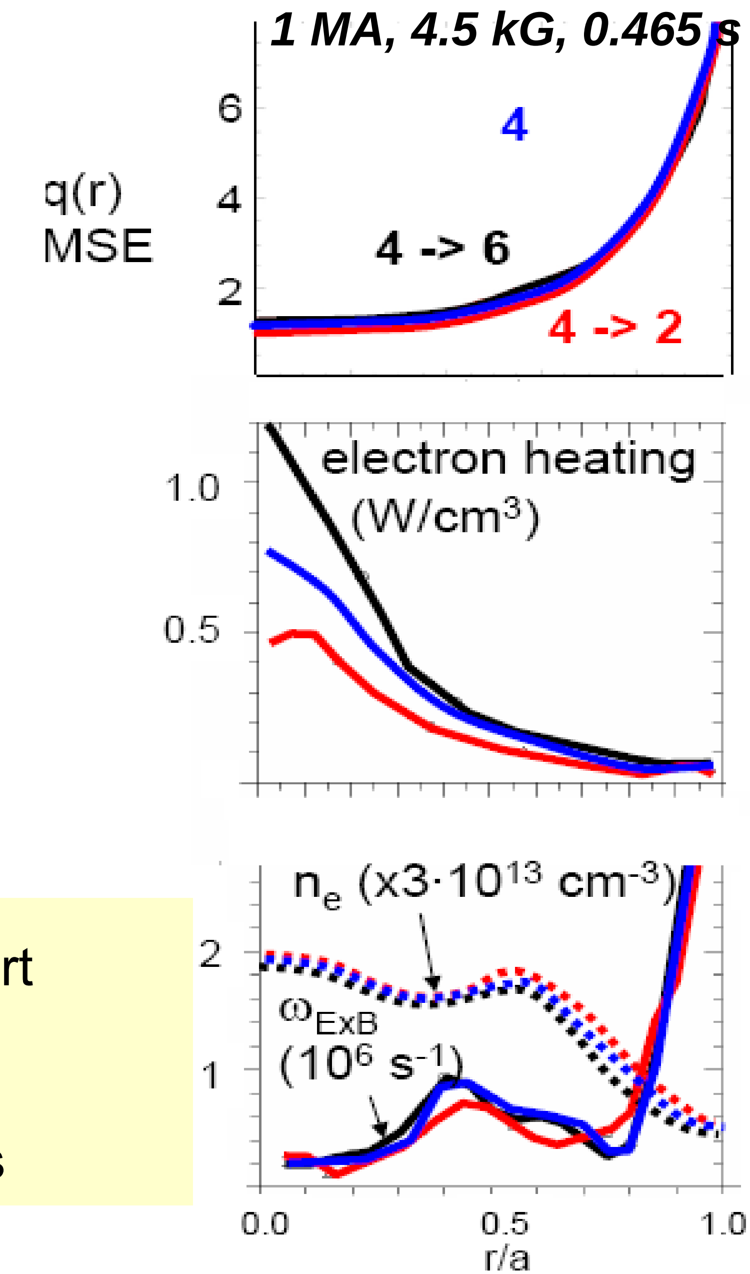




- Almost twice $T_e(0)$ at 2 MW than at 6 MW
- Only slight peaking of T_e profile late in time
- High T_e/low χ_e always at low n_e in NSTX

Technique developed to probe electron transport at fixed-q

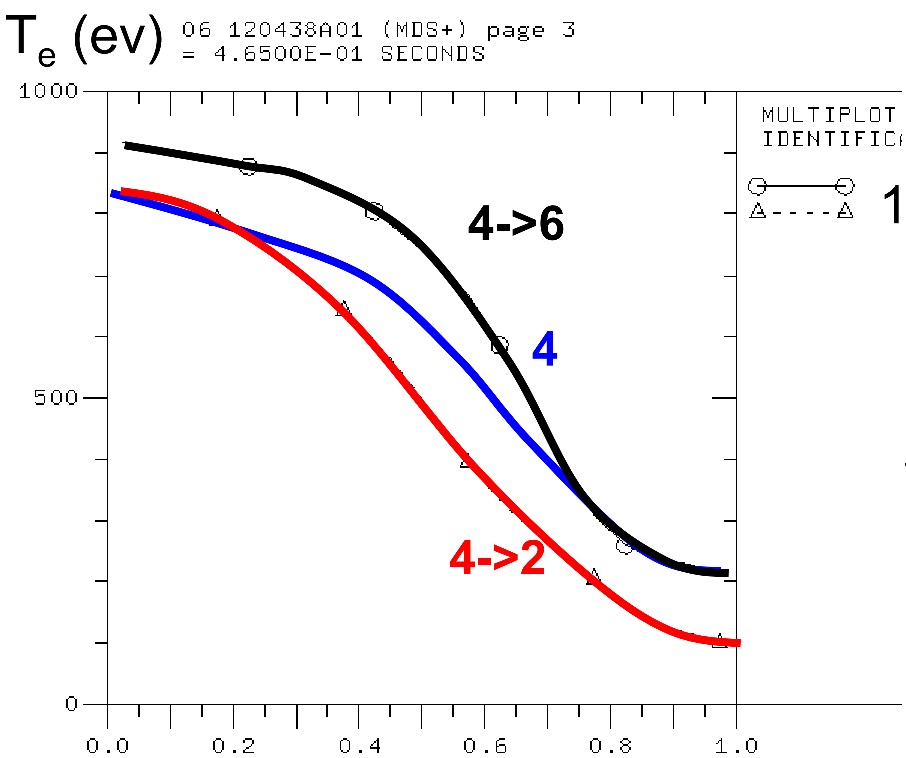


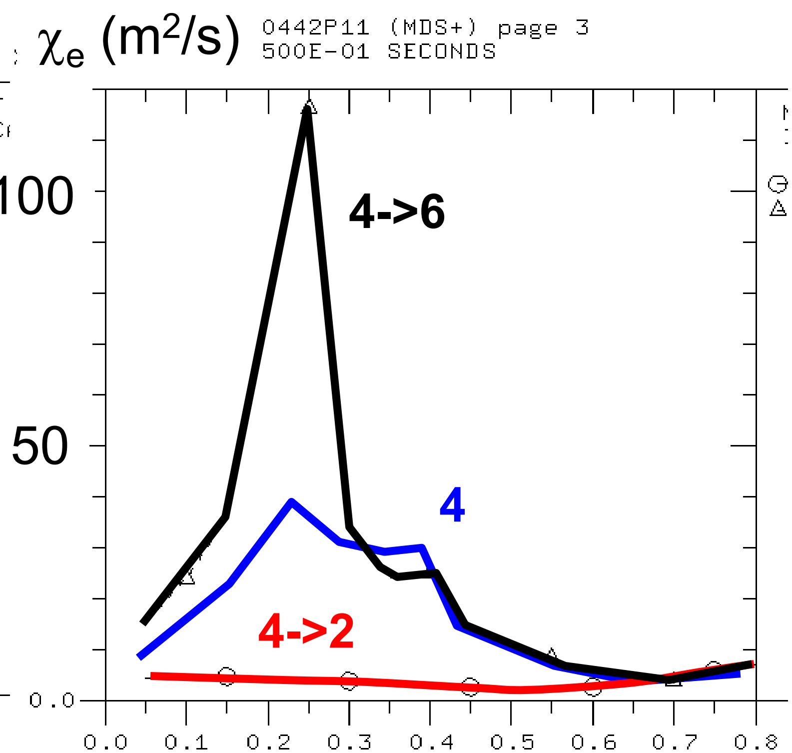


Ok

- Strong q (n_e?) effects in NSTX e^- transport
- Compare P_b effects at *same* q, n_e, ω_{ExB}
- Compare χ's at ~1.5 beam slowing times

Largest change in χ_e at 4->2 transition

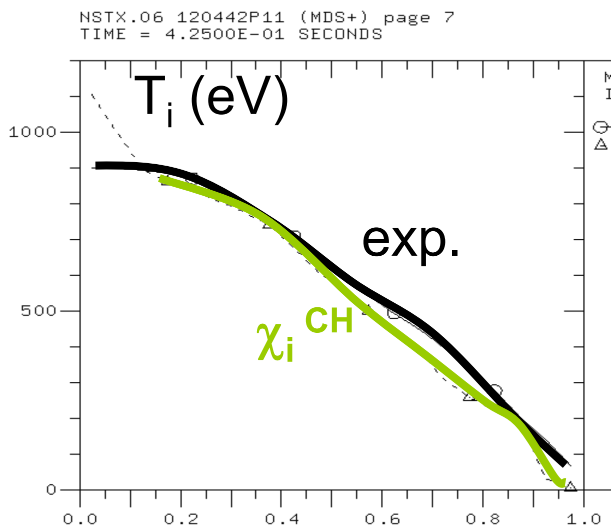


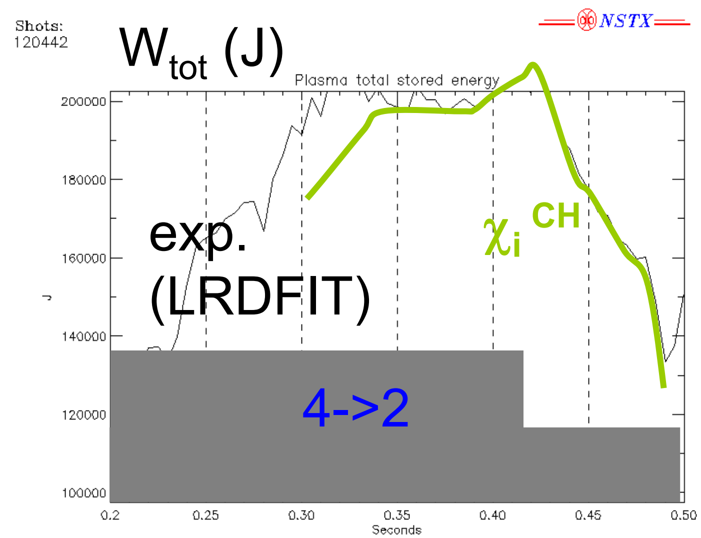


- *4->2 power balance assumes neoclassical ion transport*
  (CHERS affected by pellet puff, see below)

Why χ_e in 4->2 case assuming χ_i~χ_i^{NC} likely correct

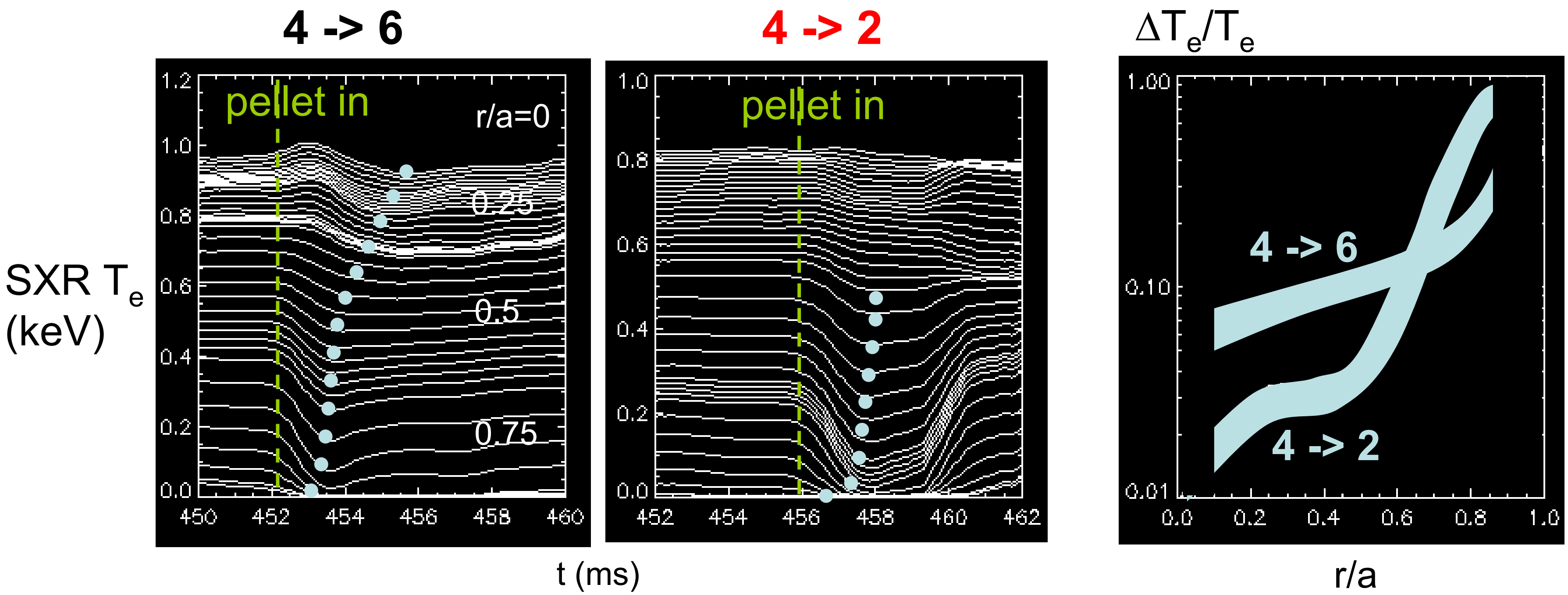
4->2 right before pellet





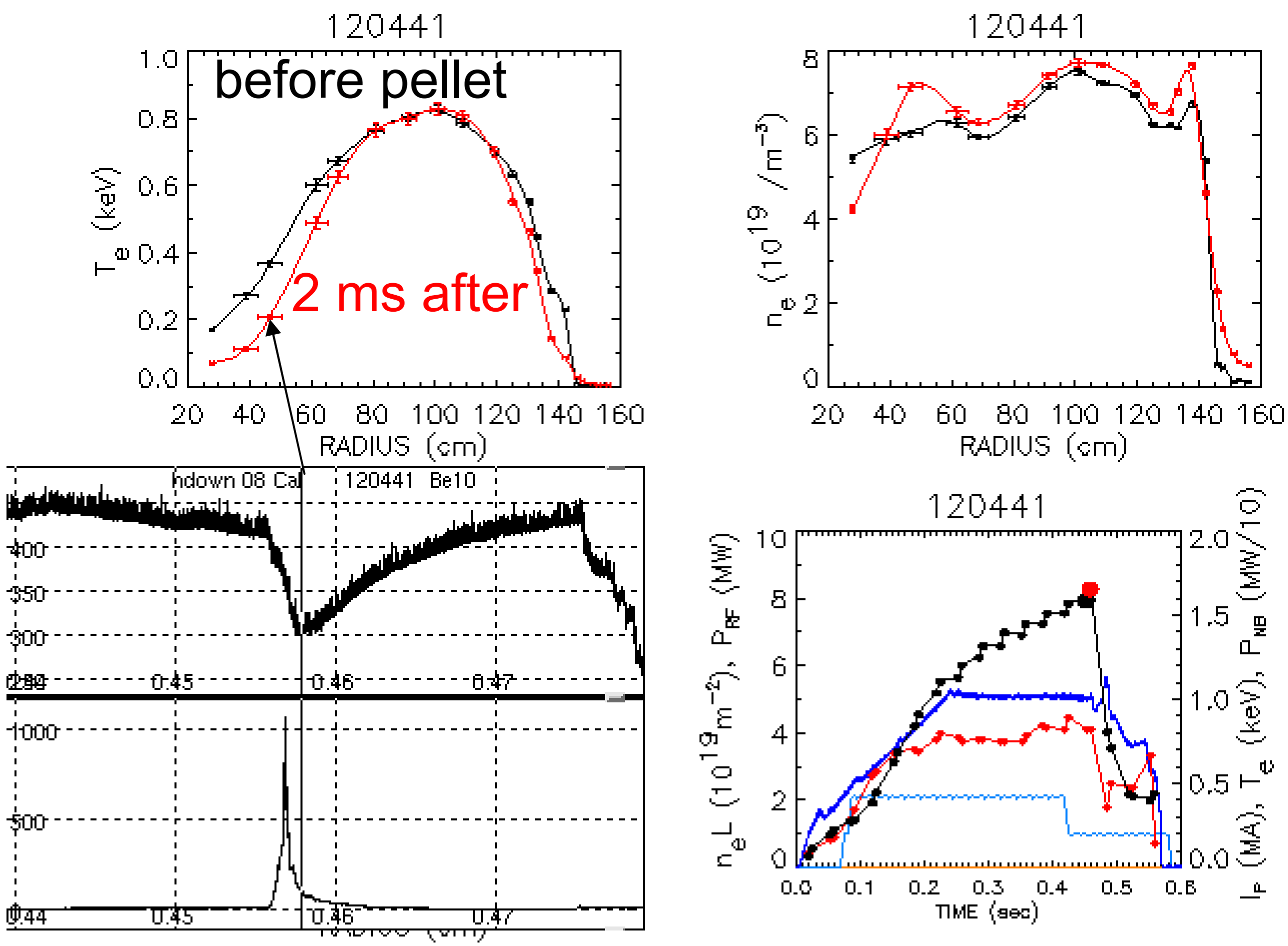
- T_i right before pellet injection, W_{tot} well reproduced with χ_i~χ_i^{NC}

Perturbative picture consistent with power balance



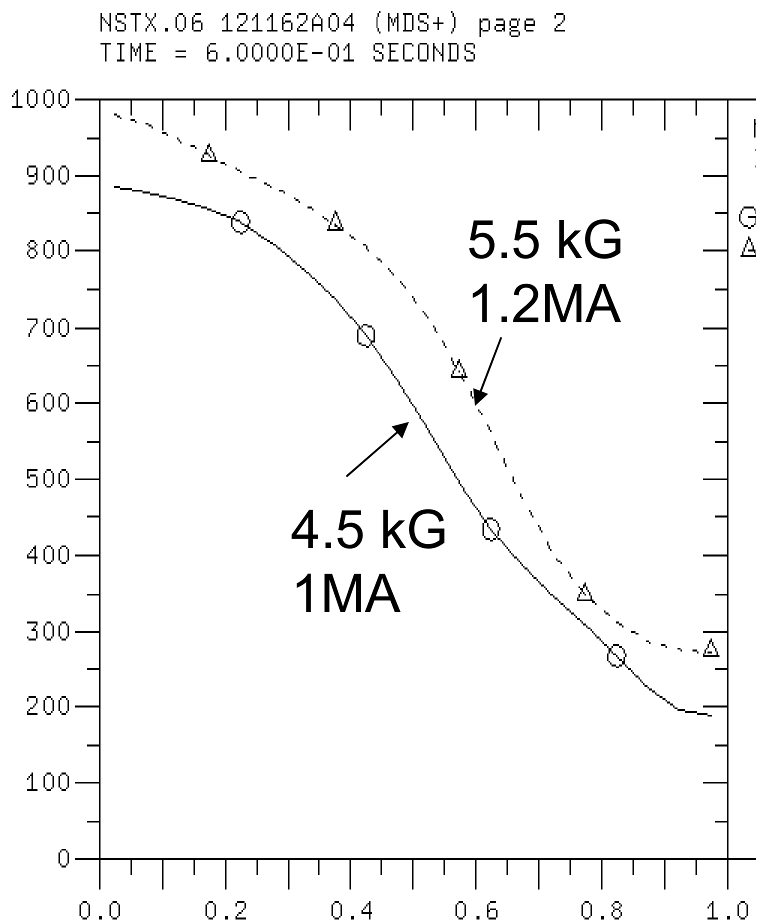
- In 4->6 case the cold pulse reaches plasma axis in ~ 2 ms
- In 4->2 case pulse strongly damped inside r/a < 0.6, faster recovery of perturbed profiles in the outer plasma
- Rapid electron transport at high P_{NB} confirmed also by ELM cold pulse (05-06 runs)

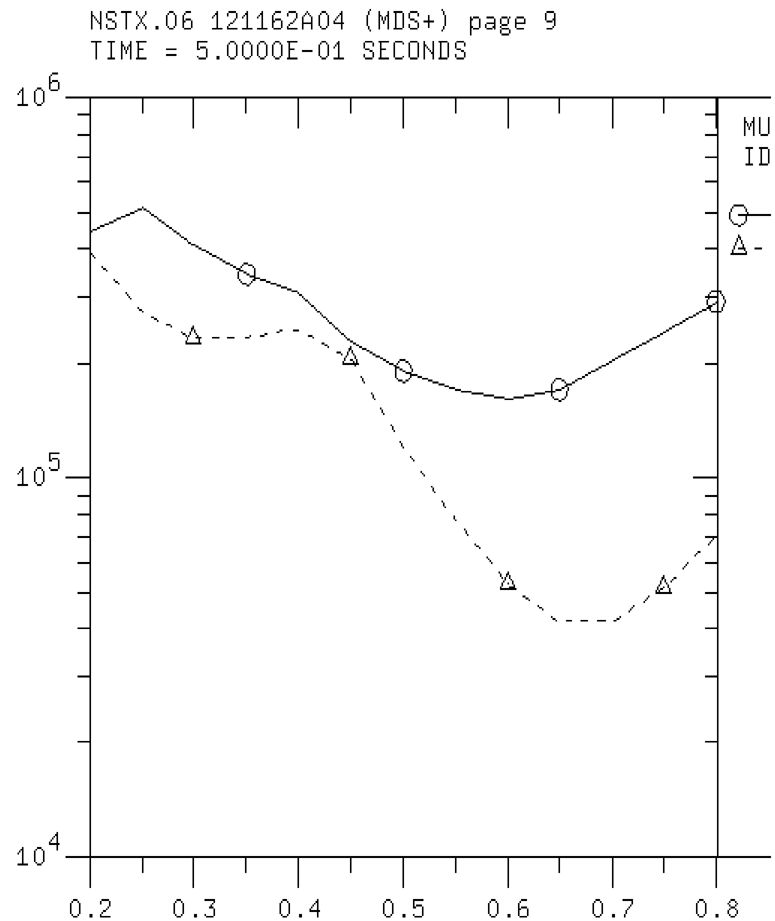
MPTS for 4->2 case confirms SXR analysis



- Consistent with cold pulse being damped in the center
- No similar data for 4->6 case

Increasing B_t improves mainly e^- transport at r/a > 0.5 (preliminary)





Consistent with previous scaling/local transport results (S. Kaye)

Is T_e flattening genuine electron transport effect ?

What other than rapid transport could cause T_e flattening in NSTX? ('TRANSP is wrong' hypothesis)

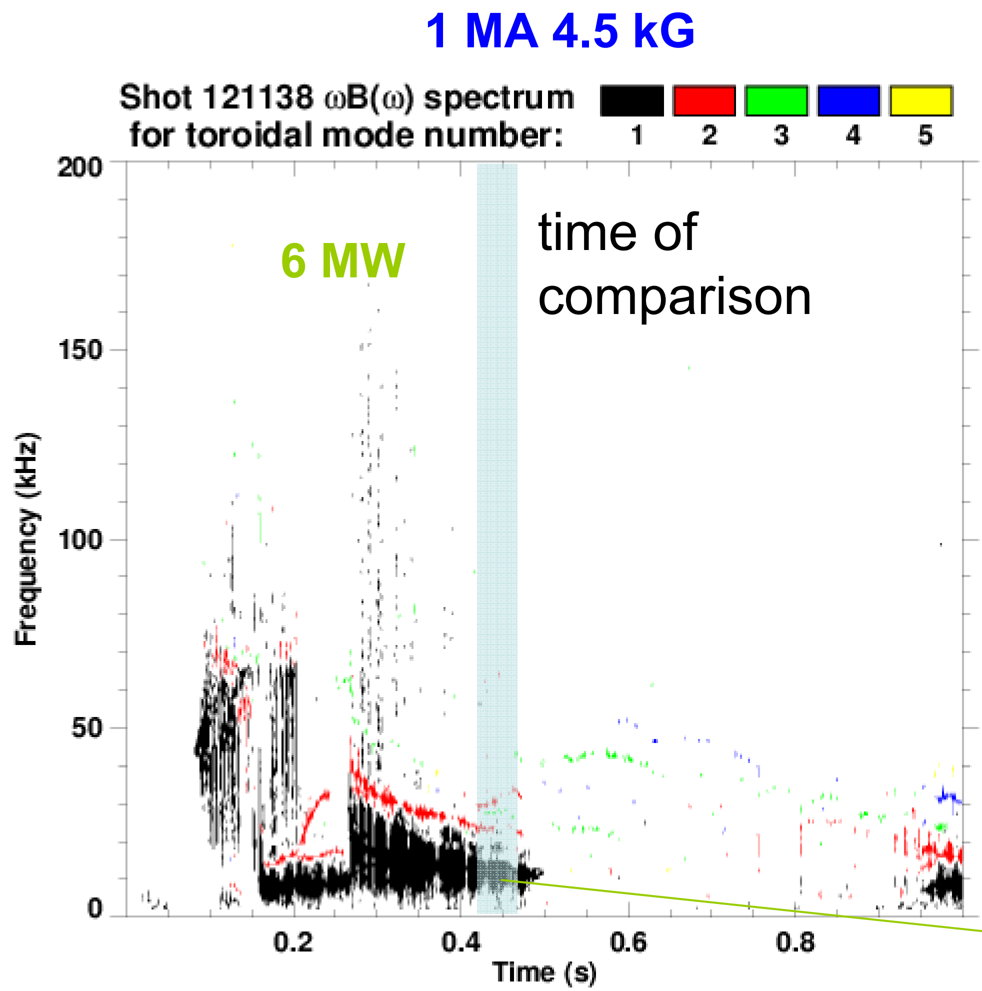
- Large islands (low-f tearing modes) in the plasma center

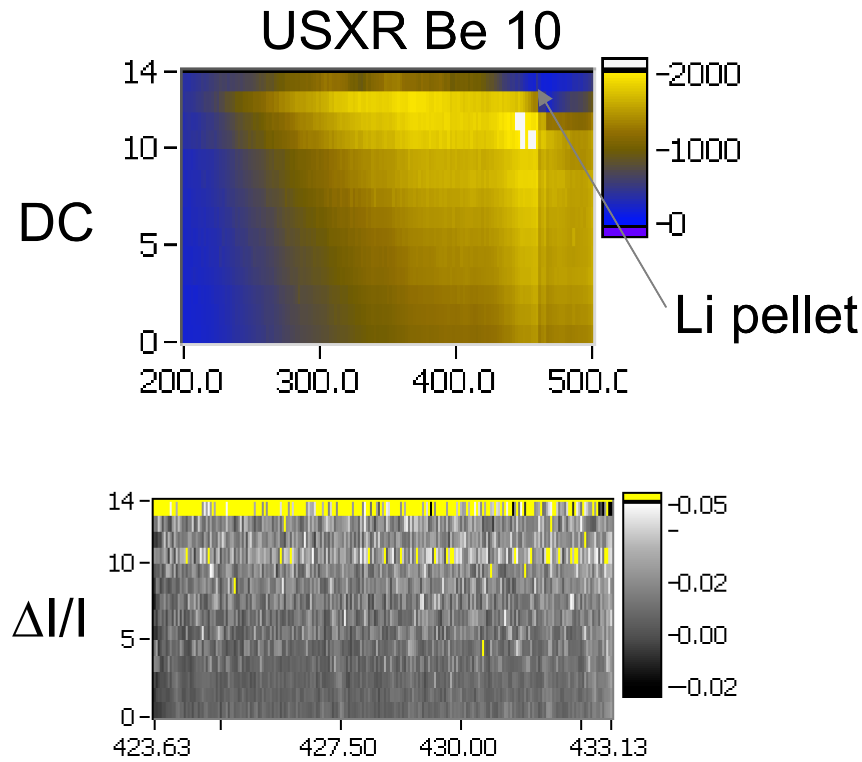
- 'Giant' ELMs propagating to the center

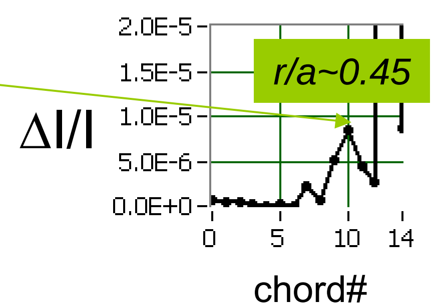
- MHD activity flattens the fast ion (FI) profile (main electron heating source) (low-f tearing modes, fast ion MHD, such as AEs, EPMs)

- Fast ion driven waves directly heat the thermal ions (e.g., CAEs, Gates '02) 'stealing' a large fraction of the beam power from the electrons

No large islands in the central plasma or giant ELMs



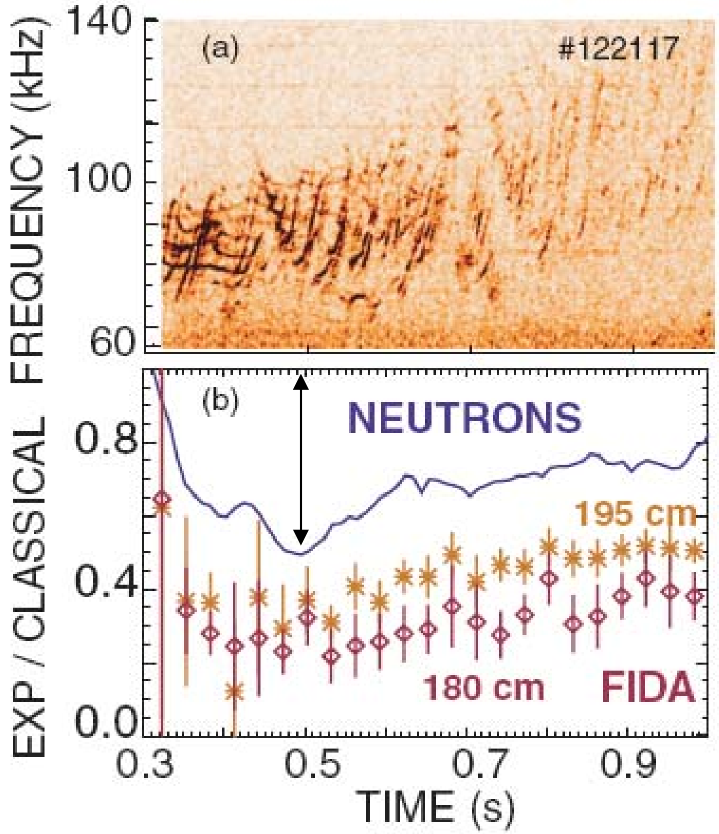




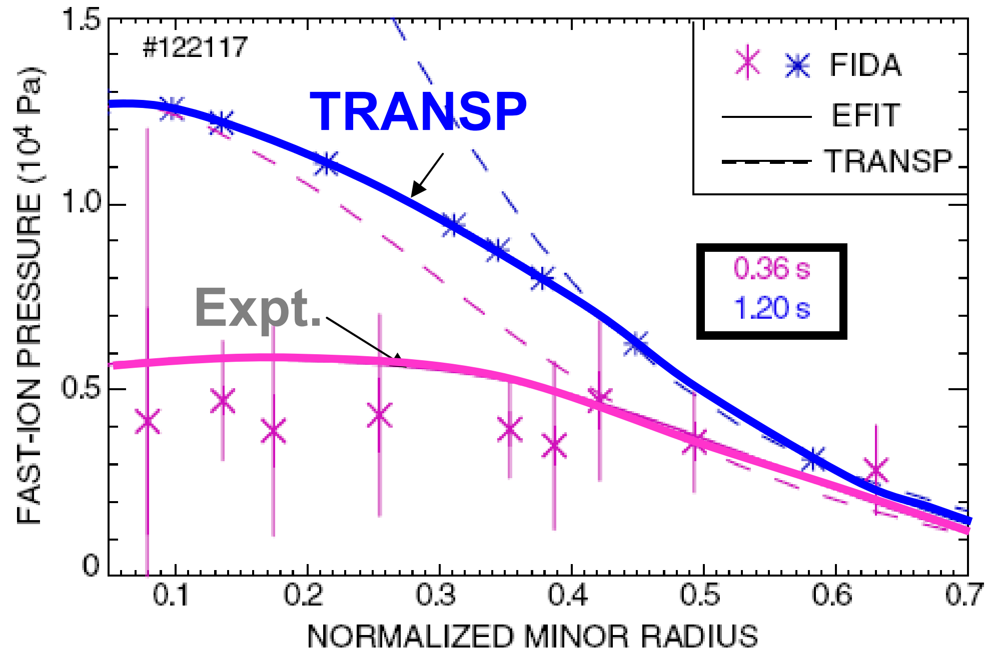
- Some early low-f MHD at 6 MW, but at r/a>0
- T_e remains flat after mode decays at t~0.45 s

Fast ion profile can indeed be flattened by AEs, EPMs

Heidbrink et al 2007

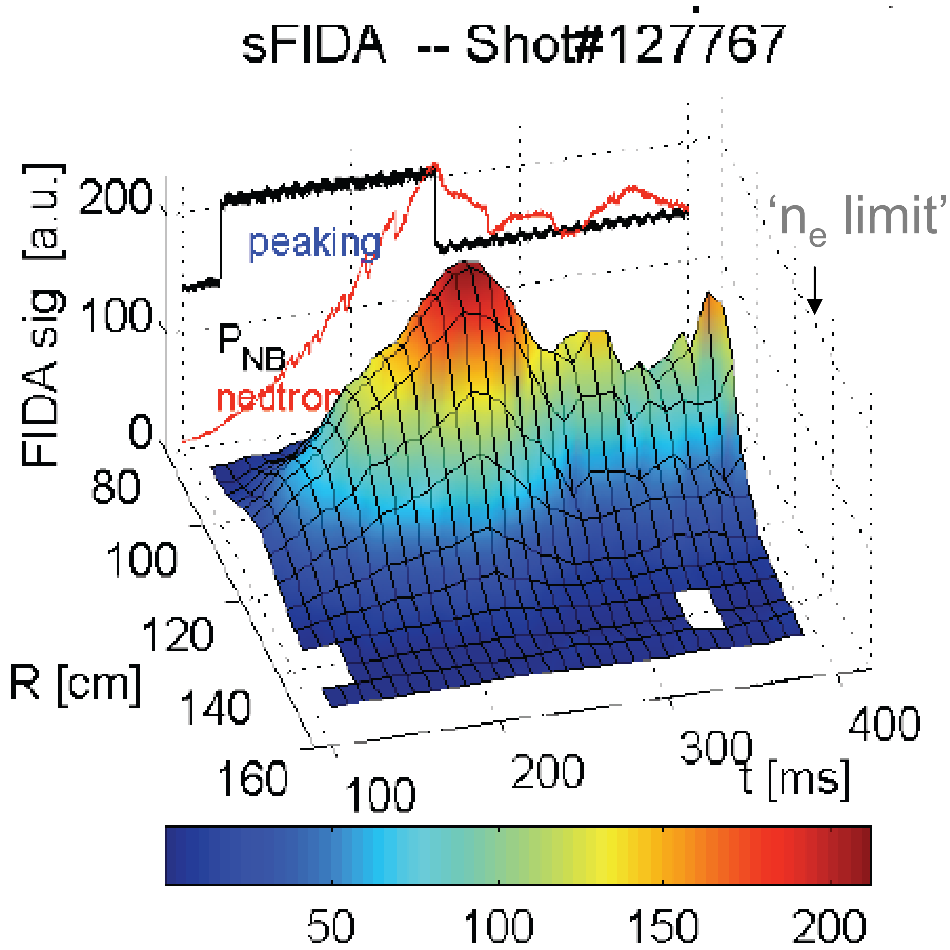


DIII-D fast ion profiles (Reversed Shear)

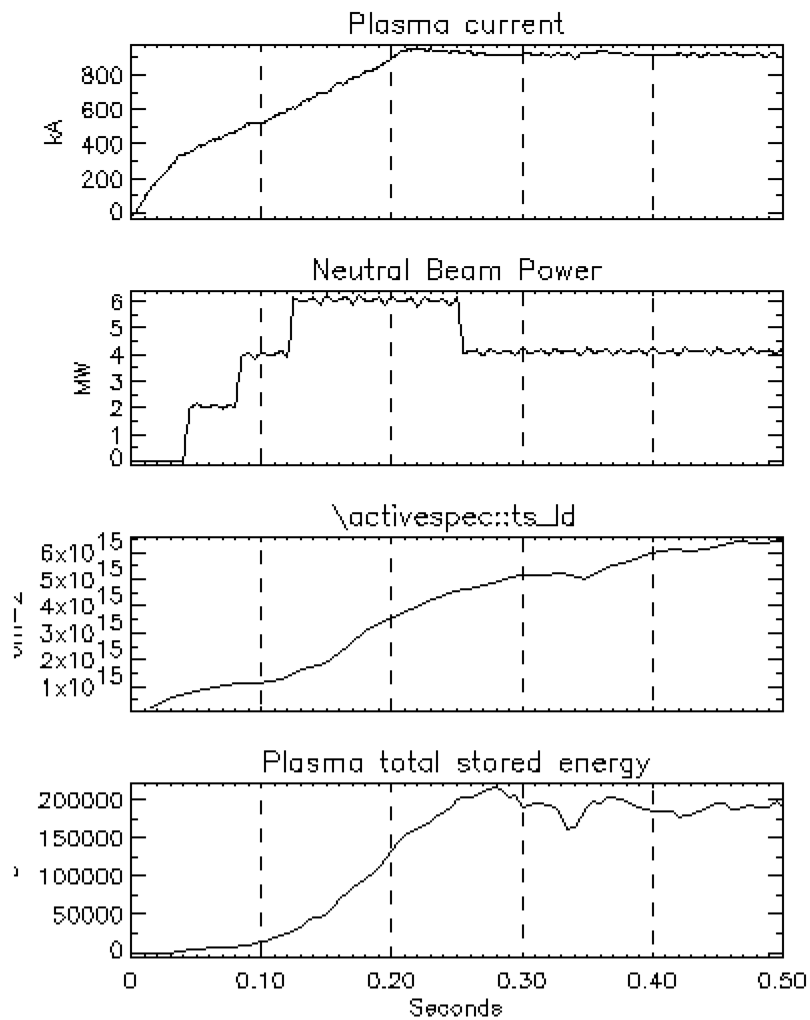


- Accompanied by large mismatch between measured and TRANSP neutrons
- Mostly TAE, EPM modes play a role (often faint in our cases)

Initial FIDA data shows peaked FI profiles, as in TRANSP

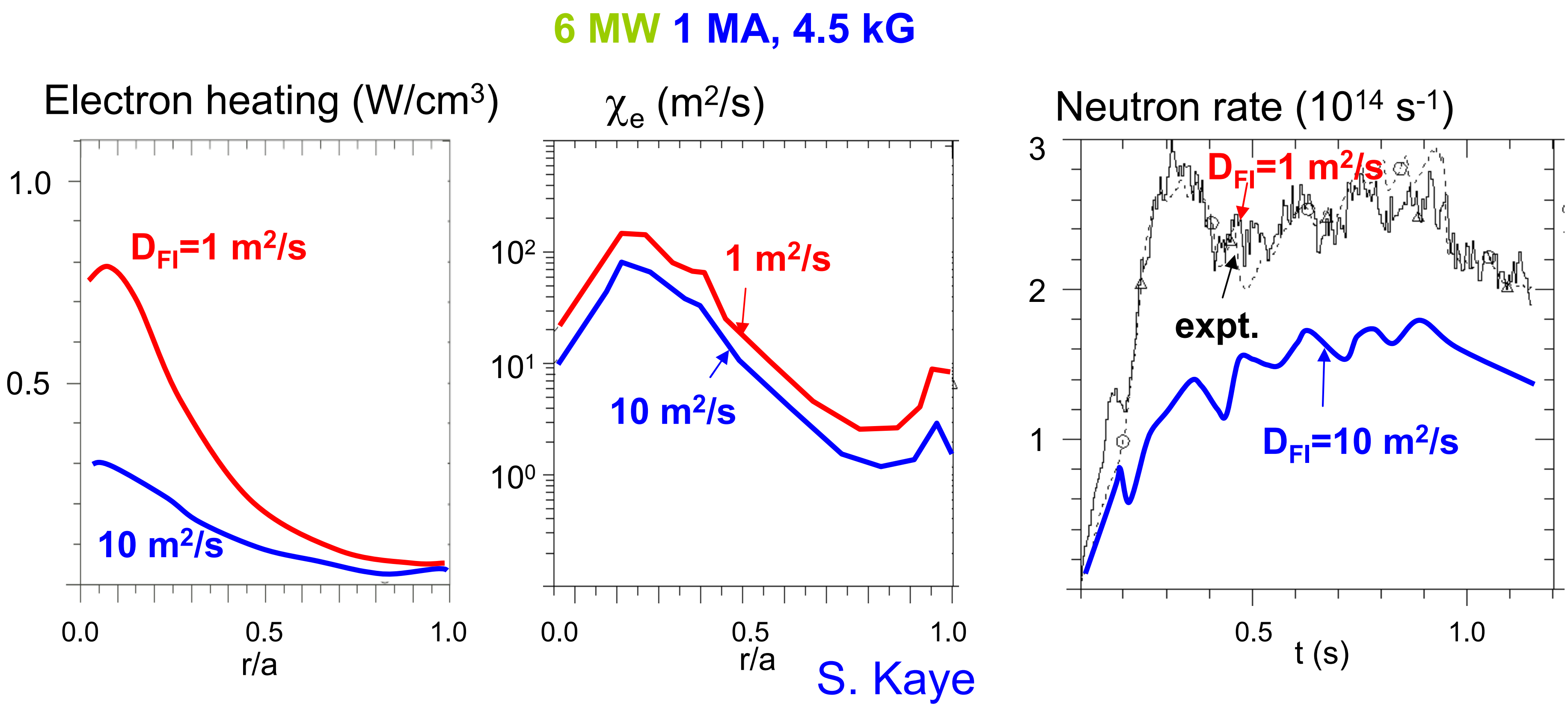


Mario Podesta



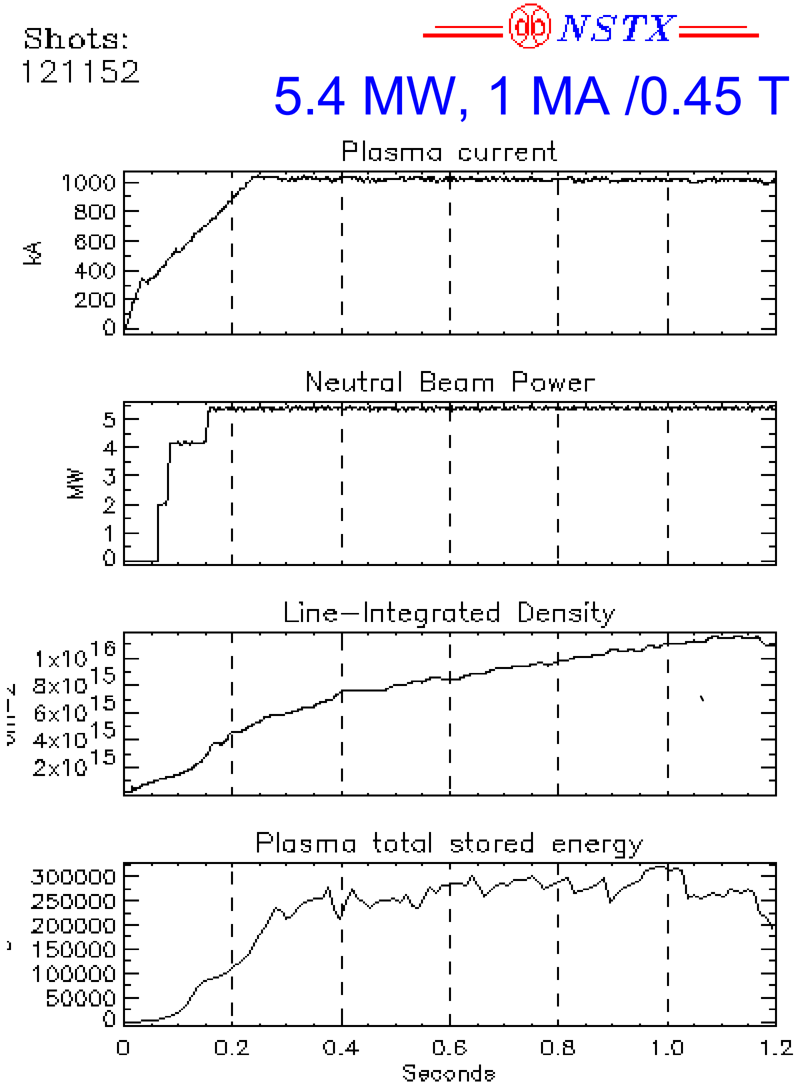
- FI profile crashes at MHD, but restores peaked character

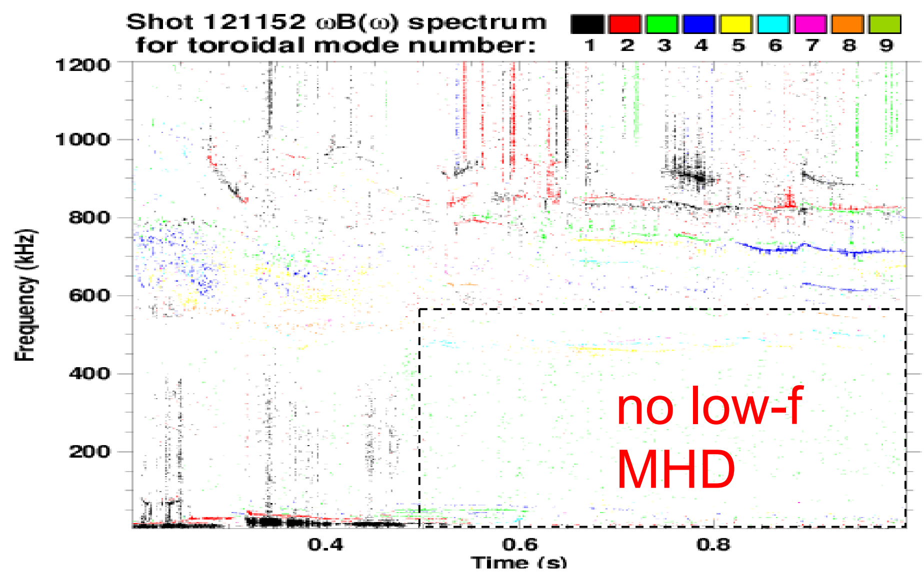
In NSTX neutrons match, χ_e little affected by flat FI profile

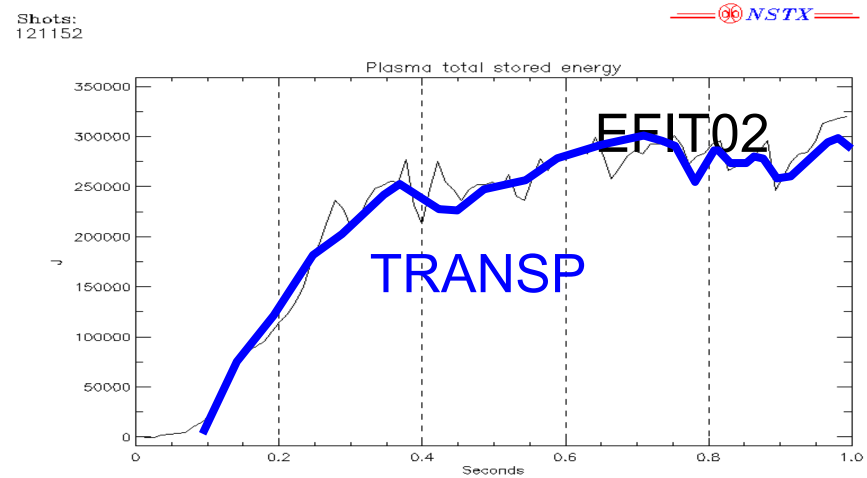


- TRANSP fast ion diffusivity artificially increased to study redistribution
- Neutron rate decreases well below experiment, while central χ_e changes little
- Same effect when D_{FI} increase limited to r/a < 0.5
- Flattening of fast ion profile does not explain T_e flattening in these plasmas

No significant heating anomaly in these high n_e, P_b H-modes

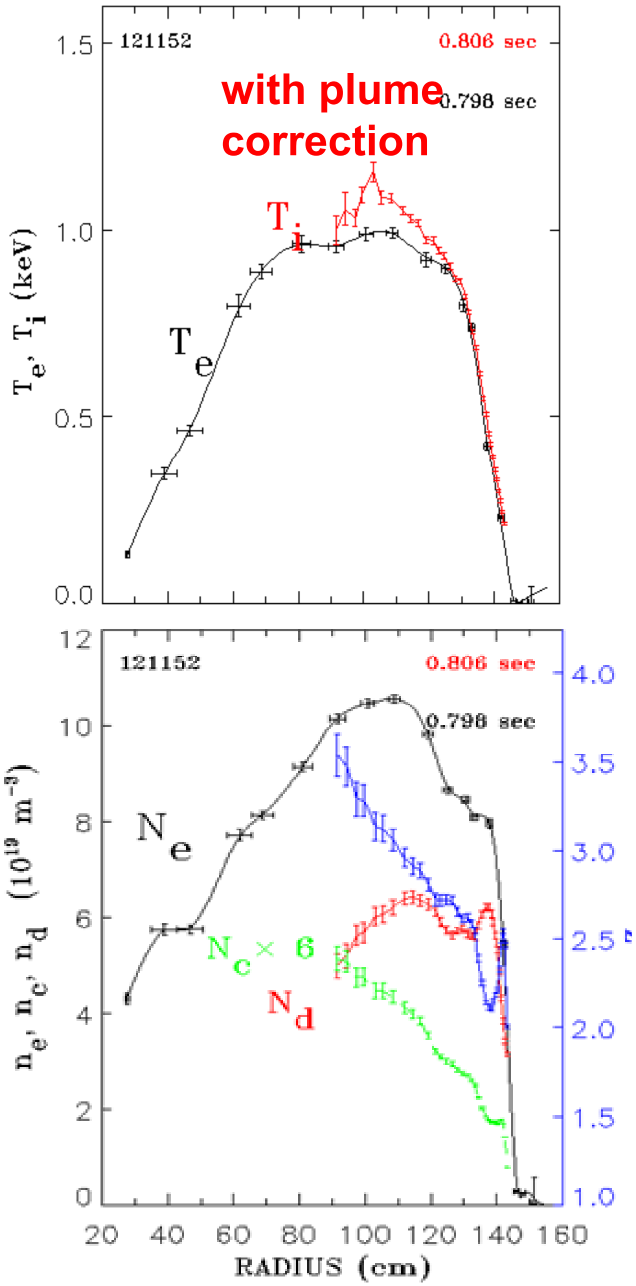


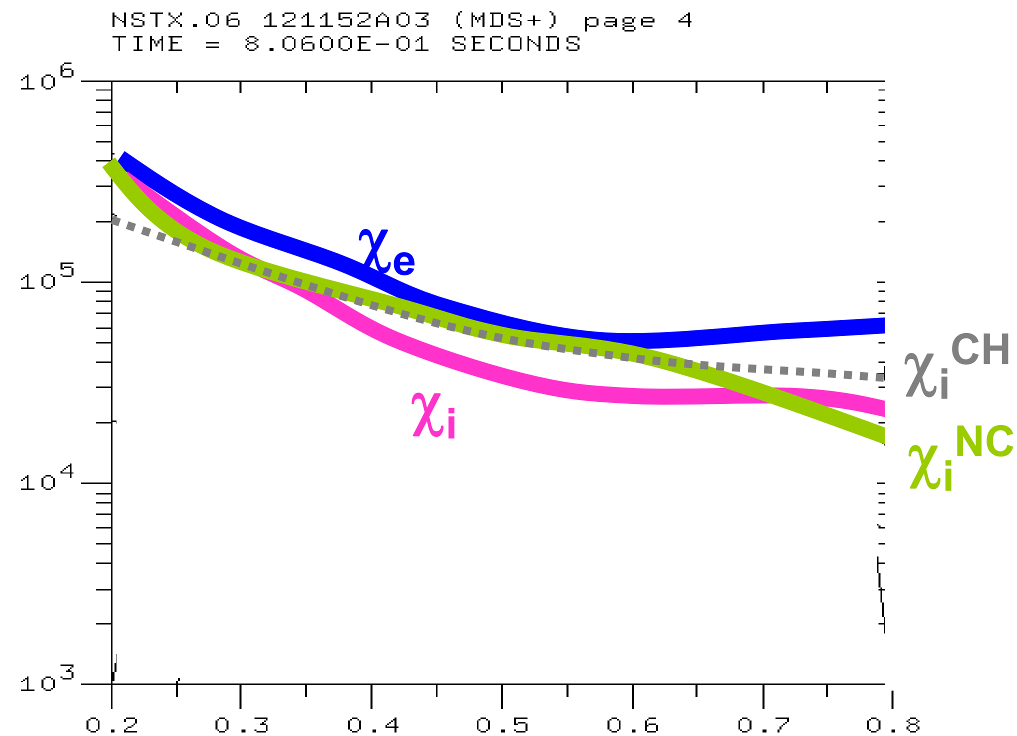




- At high n_e the anomaly in the power balance should be enhanced (Q_{ie}~P_b)
- TRANSP predicts W_t, neutrons (-12%) -> plasma profiles, FI modeling ~Ok

χ_i ~ (0.5-1)xχ^{NC} matches well the experiment

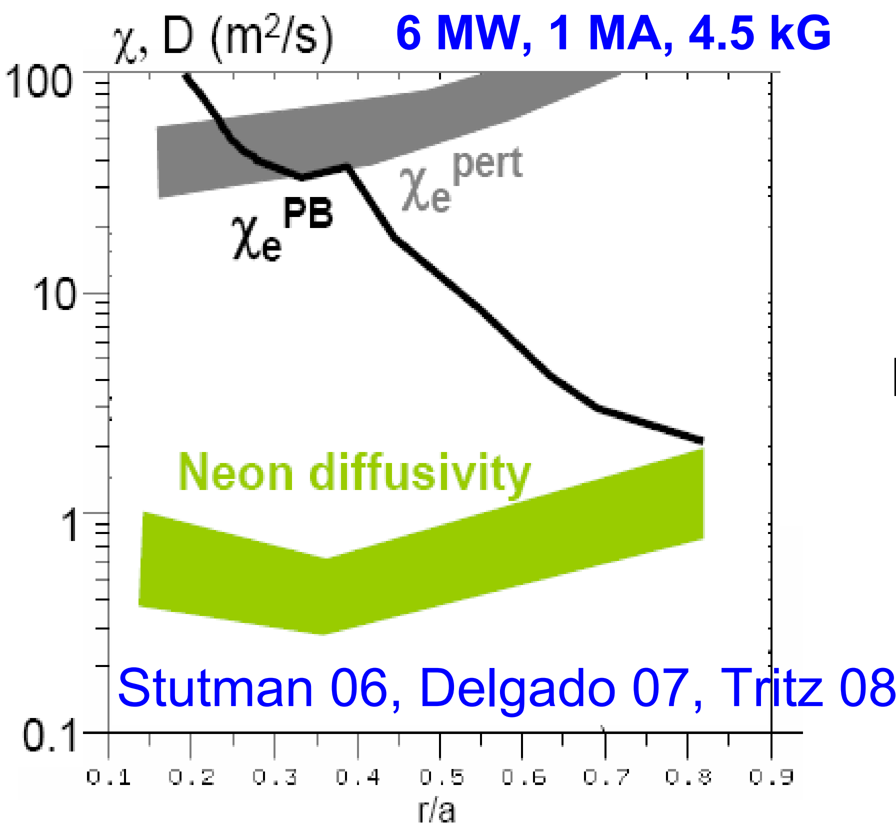


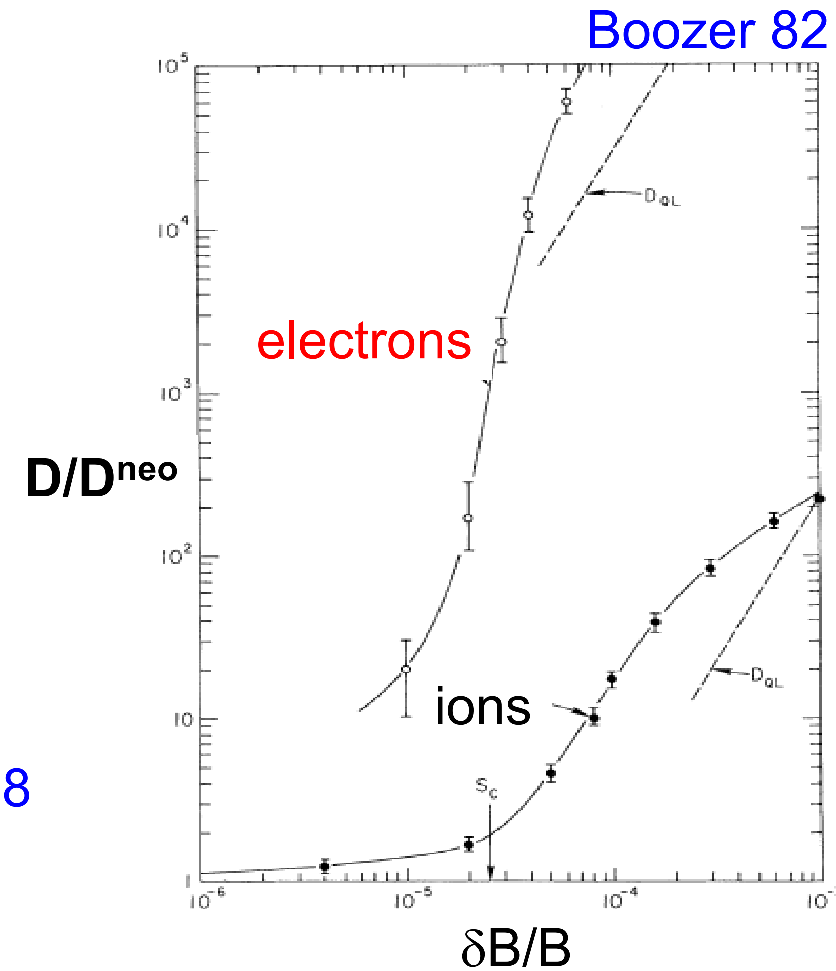


- Anomalous ion heating ≤ 0.5x χ^{NC} at high n_e
- Note also that χ_e ~ χ^{CH} at high n_e
- Rapid electron transport in central NSTX plasma not a TRANSP artifact

Hints for magnetic electron transport in NSTX

Very large gap between χ_e and D_{imp}



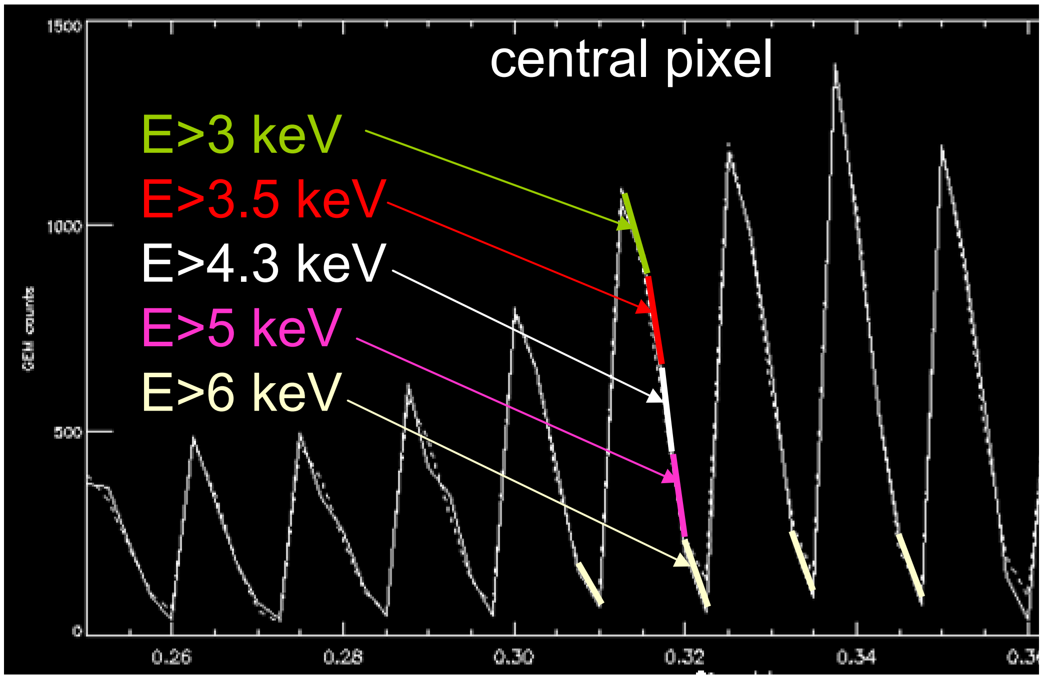


- Magnetic (stochastic) transport brings parallel thermal velocity into play ->

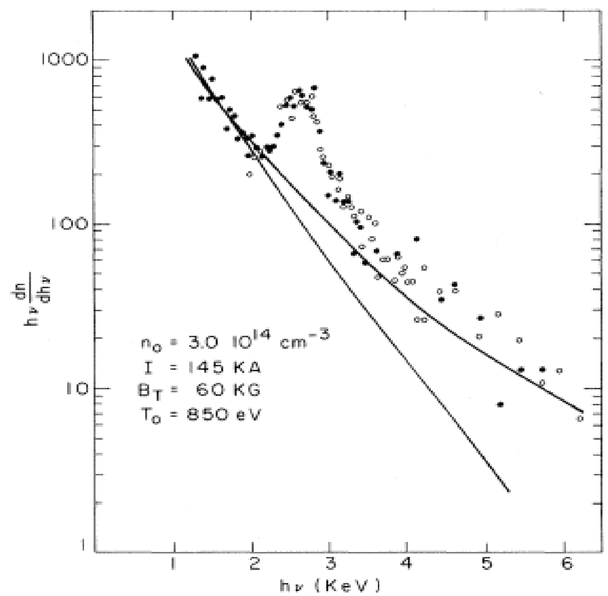
  electron thermal transport most rapid

Possibly non-maxwellian electrons in the core

Gas Electron Multiplier (GEM) hard X-ray spectrum in NSTX H-mode (Pacella 06)



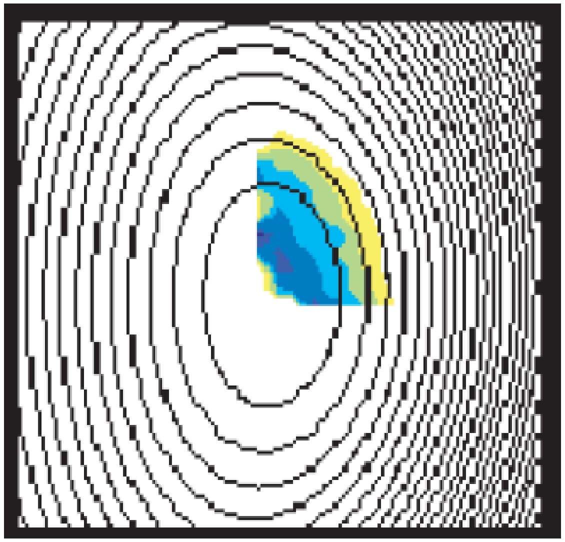
Early Alcator X-ray spectrum Molvig 78



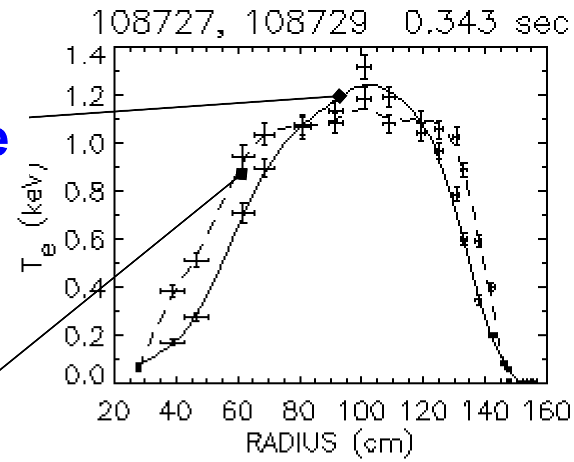
- Detector counting threshold scanned in time (10 ms)
- Tail apparent above 6 keV

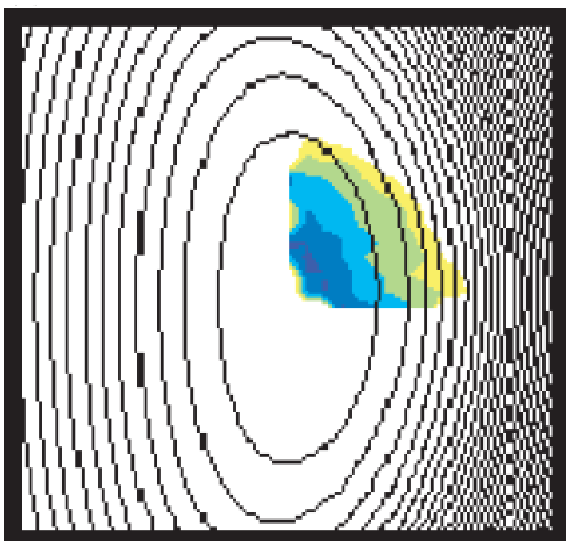
Mismatch between hard X-ray and magnetic flux surfaces

Hard X-ray images of NSTX core (Pacella 04)



2 MW L-mode



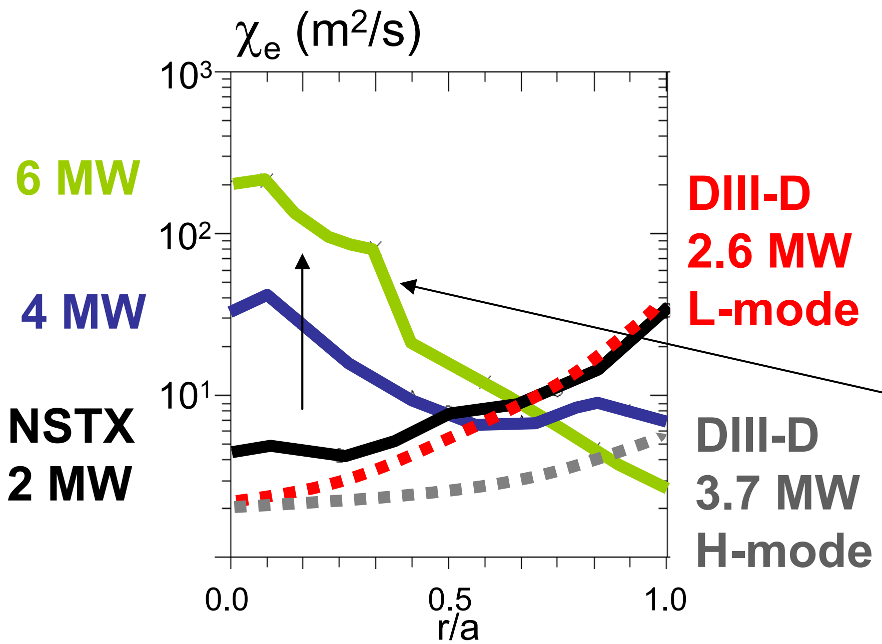


4 MW H-mode

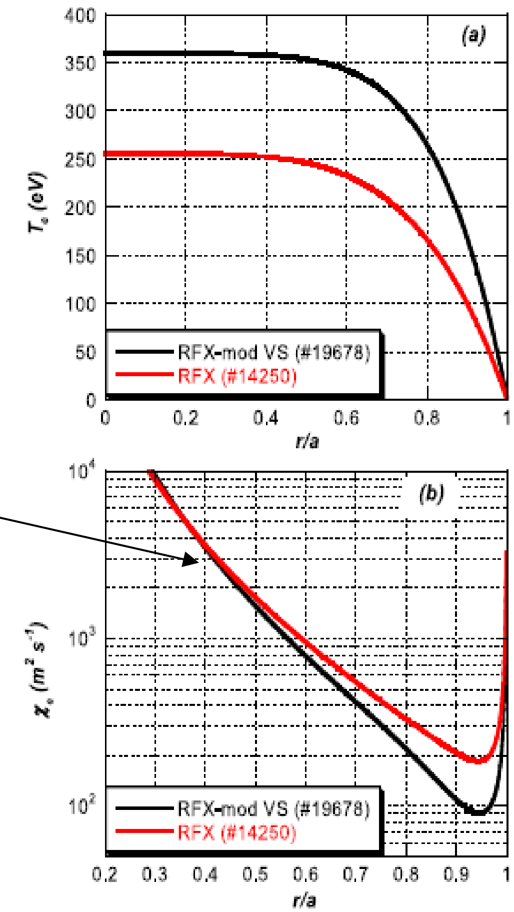
- Good agreement with EFIT at low P_b
- Mismatch when P_b increases and T_e flattens
- Consistent with 'leakage' of hot electrons

Tokamak-like χ_e, T_e profiles at low P_b, RFP-like at high P_b

χ_e in NSTX and DIII-D (Peebles 08)



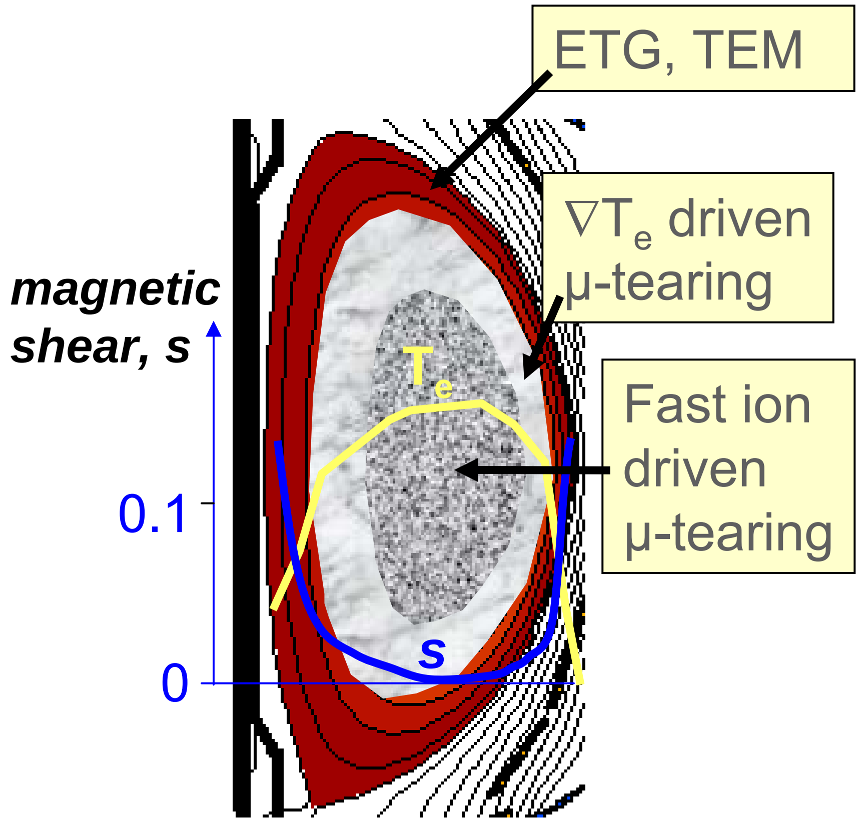
T_e and χ_e in RFX (Innocenti 07)



- Rapid magnetic transport without ∇T_e documented in RFP core (tearing)
- Large Te(r), χ_e difference between 6 and 2 MW cases consistent with

qualitative change in electron transport in NSTX : electrostatic -> magnetic

Proposed picture of electron transport in NSTX



Conditions

high P_b (FI drive)

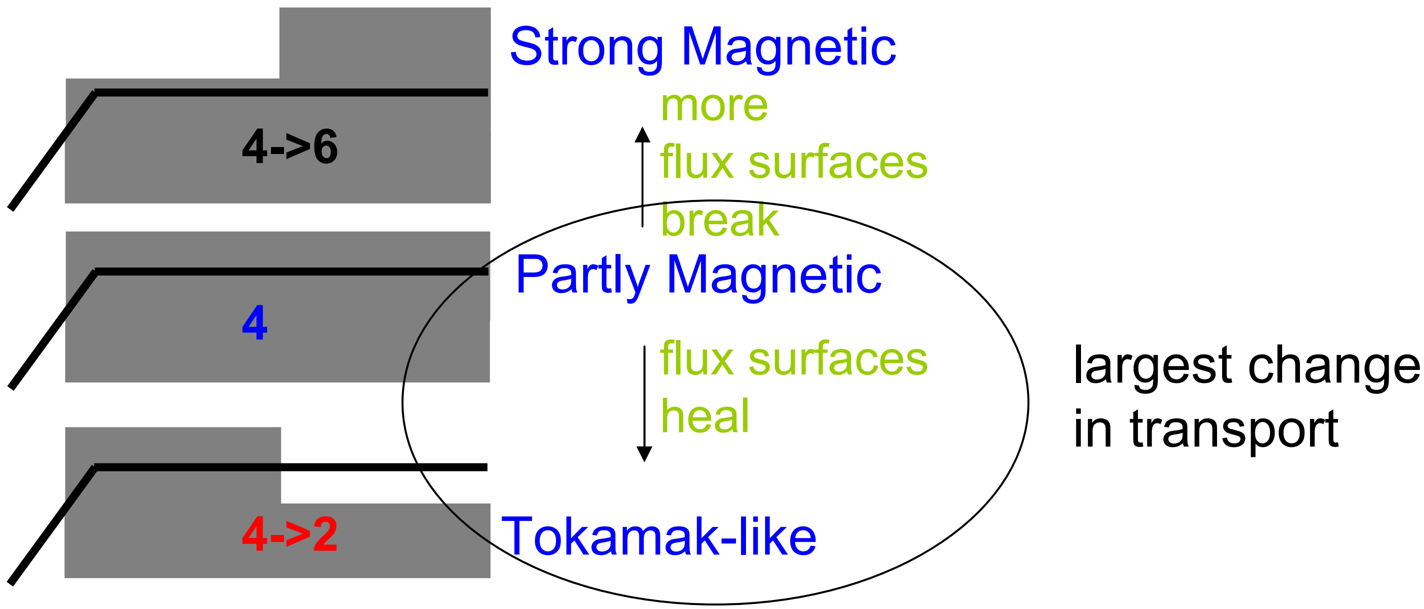
moderate to high n_e
(resistive MHD)

elevated q / low magnetic shear
(density of rational surfaces)

- ρ_i-scale islands at rational-q
- Flat T_e in region of low *s*, T_e gradient where *s* high
- 'Magnetic core', 'electrostatic edge'
- Primarily low-A effect (toroidal mode coupling)
- Some stochastic ion heating (reconnection 'sea') , non-thermal T_e, T_i likely

What else fall in place if we assume magnetic electron transport ?

Picture consistent with e^- transport changes with P_b

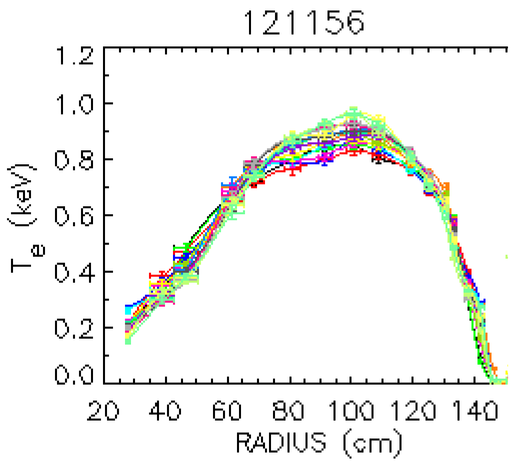


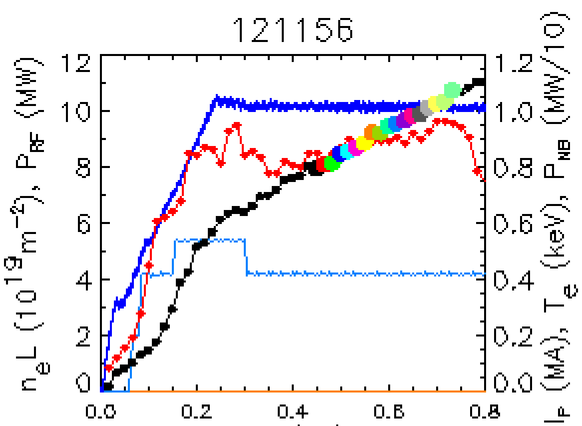
P≤ 2 MW - mostly intact flux surfaces, tokamak-like transport

4 MW - partially broken surfaces, onset of magnetic transport

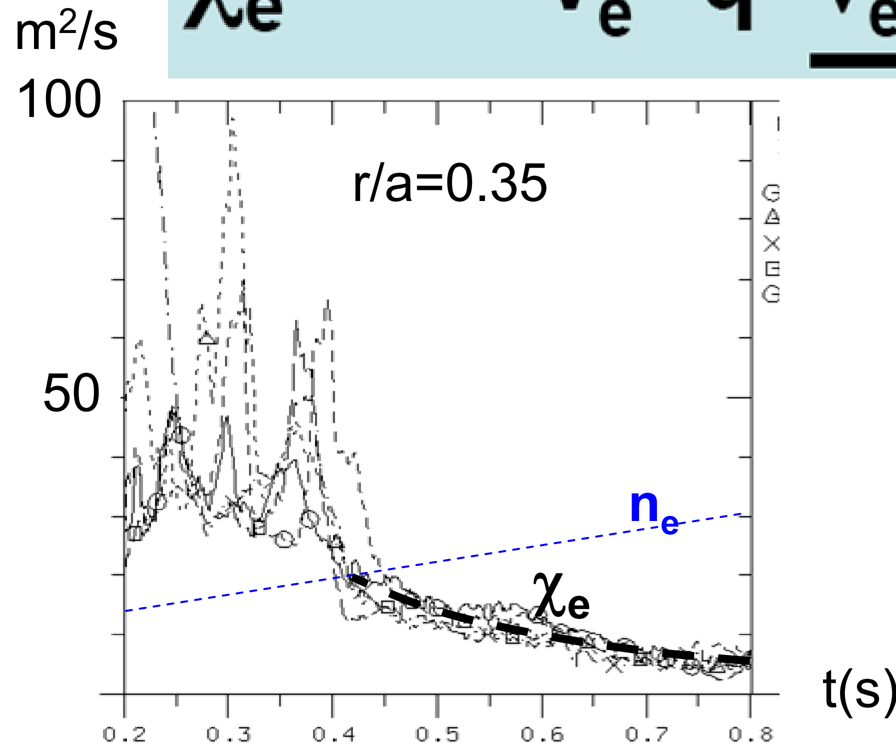
6 MW - mostly broken surfaces, strong magnetic transport

χ_e decrease in time consistent with $1/\nu_{ie}$ scaling of χ_e^{mag}





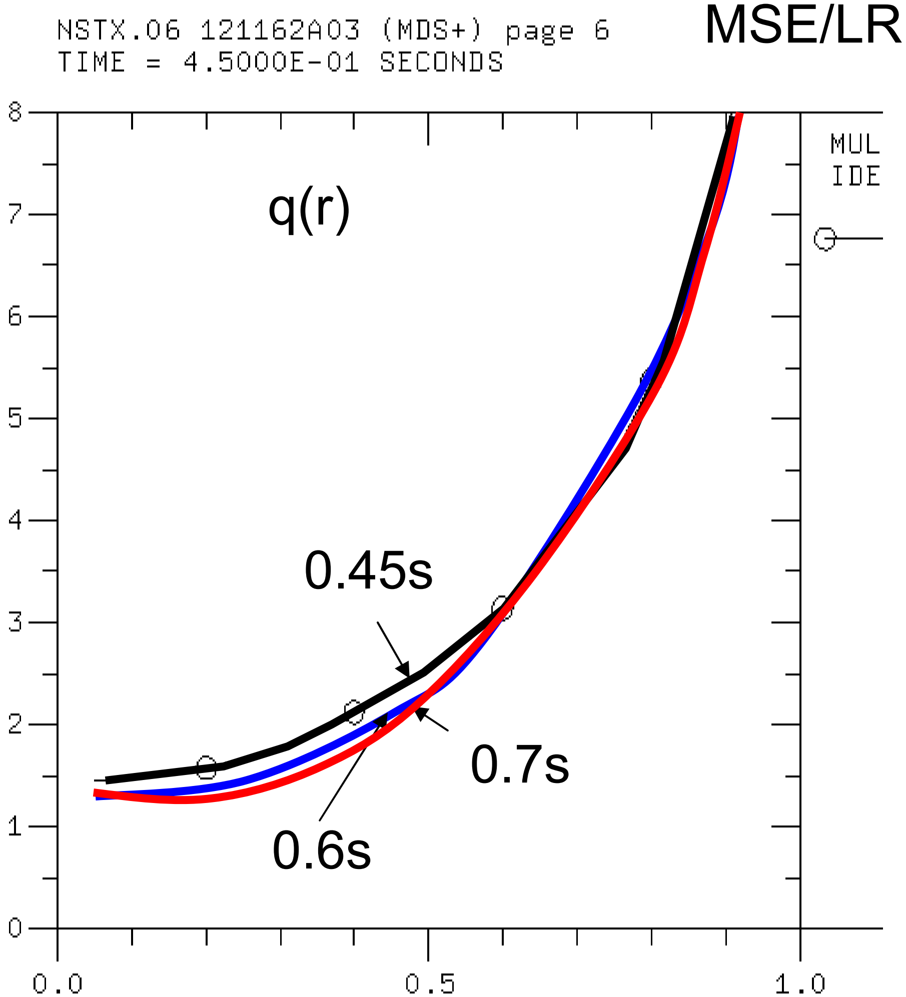
$$\chi_e^{mag} \sim v_e^2\, q^{-1} \underline{\nu_{ei}}^{-1}$$

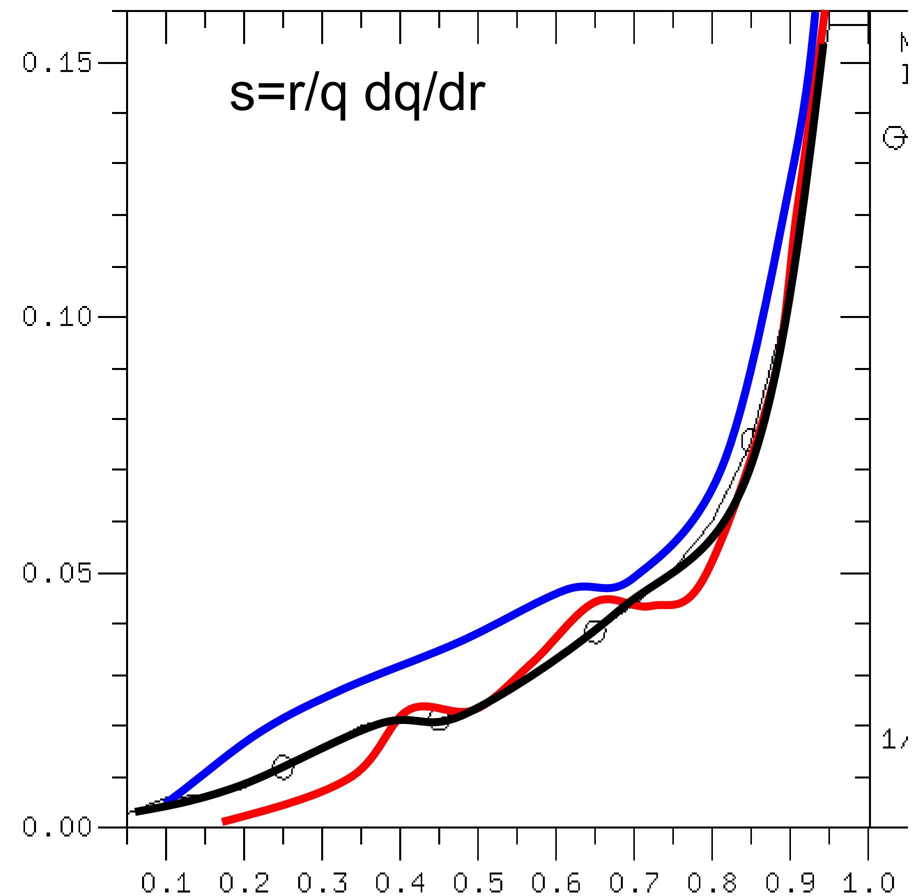


- T_e profile stays unchanged while n_e steadily increases -> $\chi_e \propto 1/n_e$
- q, *s* change little after t > 0.4 s; ν_{ei} increase only possible cause
- Strong support for magnetic transport hypothesis
- $\chi_e \sim \chi^{CH}$ at high n_e suggests ‘transport step’ becomes limited to ρ_i

q-profile, magnetic shear do not change much after t~0.4 s

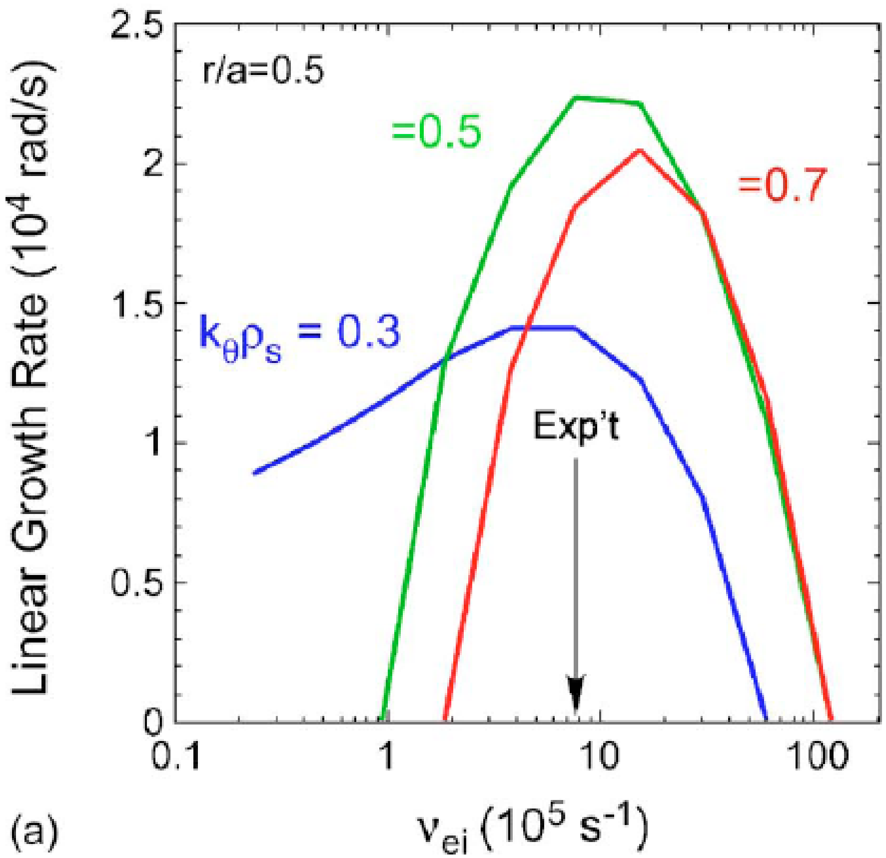
MSE/LRDFIT



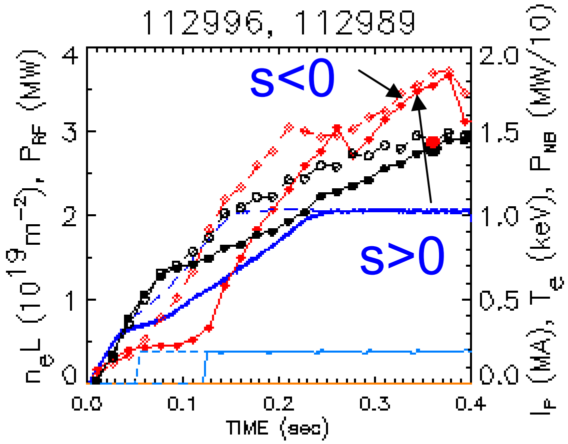


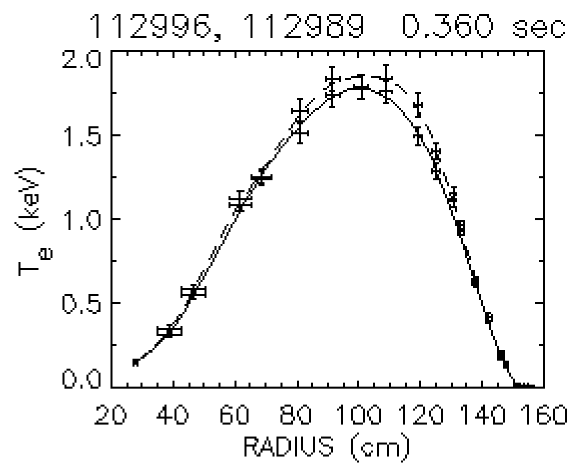
Picture also explains why high T_e only at low n_e in NSTX

Wong 08, Redi 05



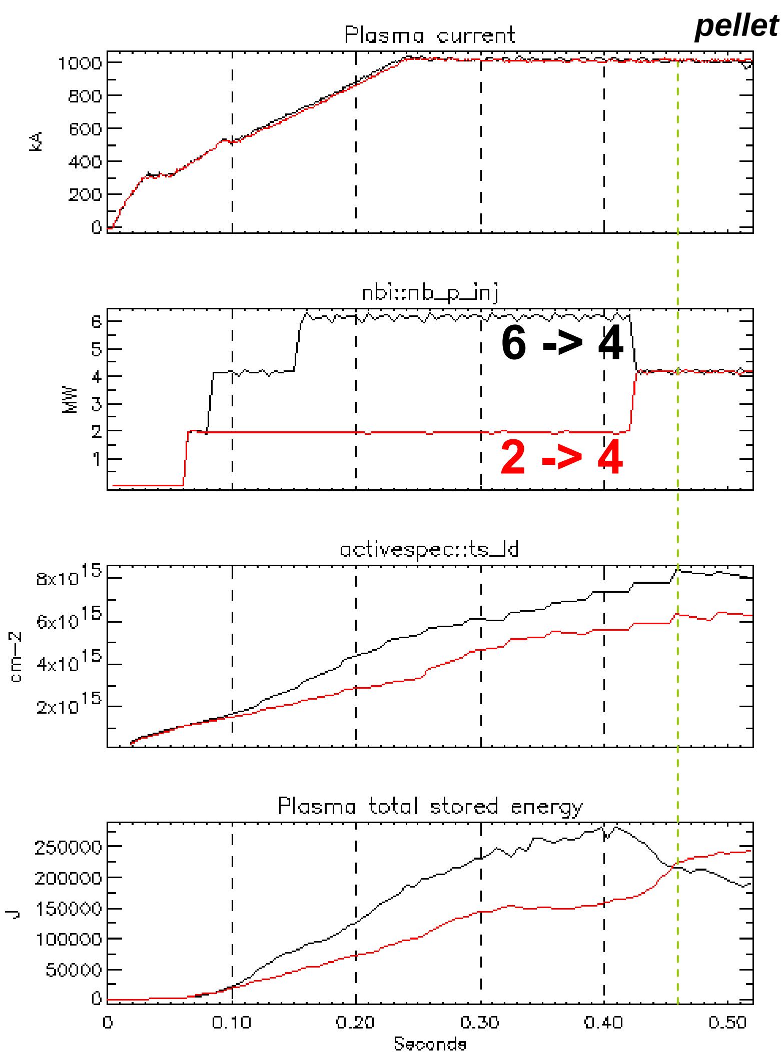
Stutman 06

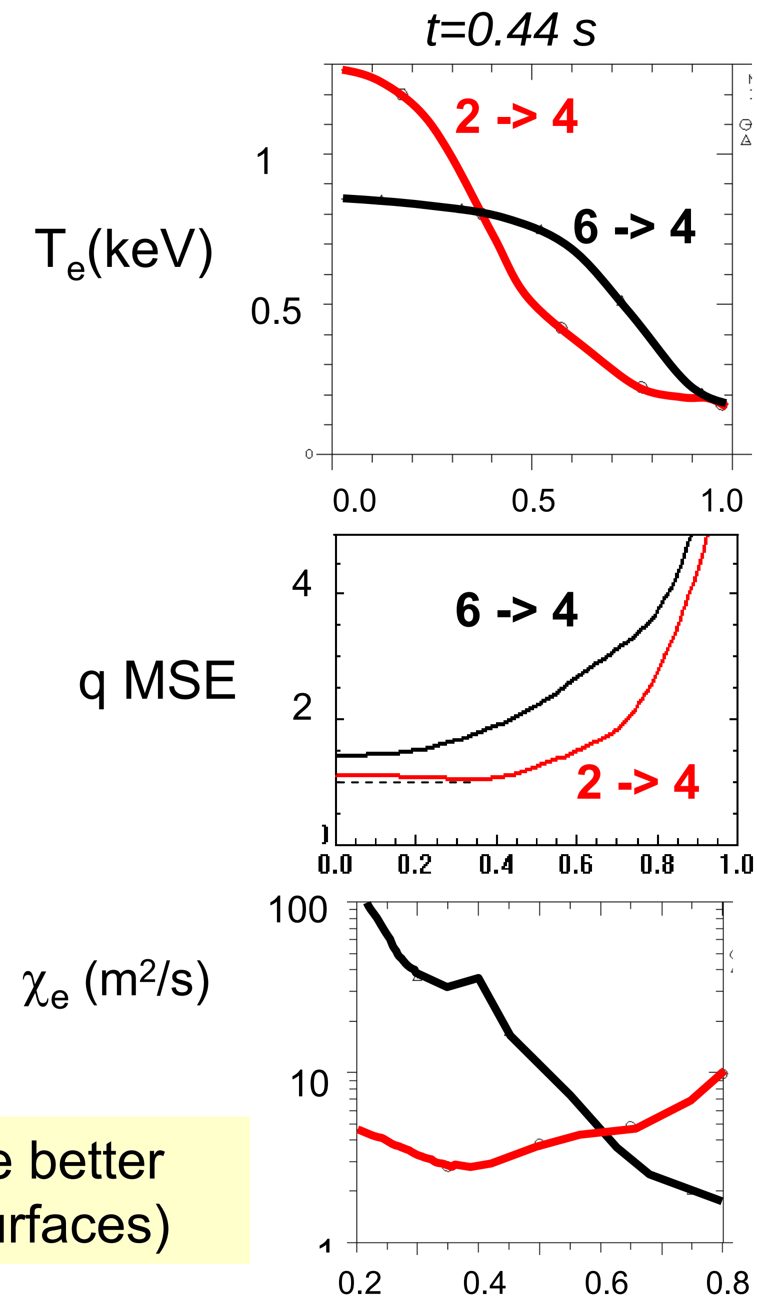




- Propensity for μ-tearing reduced at low collisionality (resistive MHD)
- High T_e at low n_e even when *s*>0

Picture also explains strong q role in NSTX electron transport

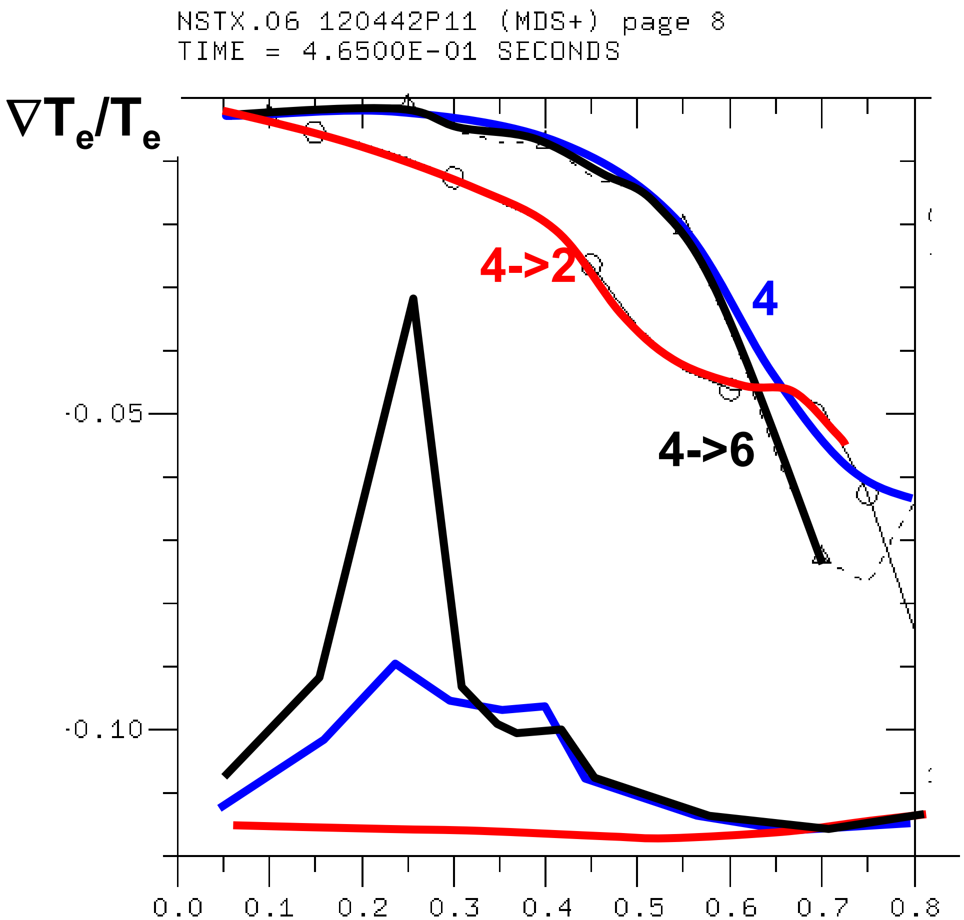


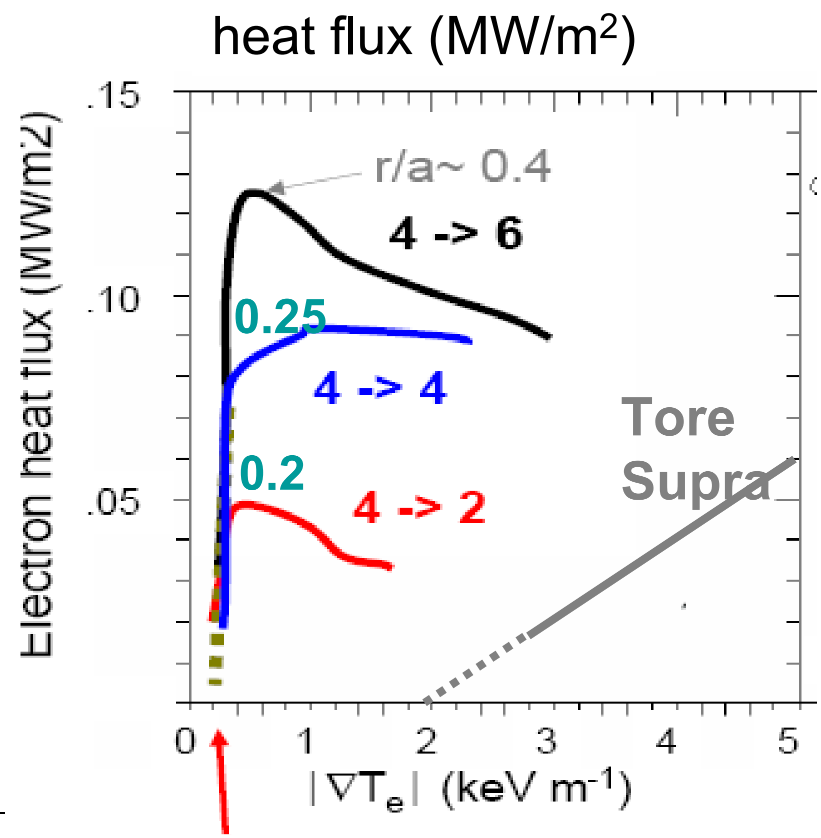


- Plasmas with same P_b but lower q have better electron transport (less dense rational surfaces)

Fast ion connection

Gradient driven transport paradigm breaks inside r/a<0.4

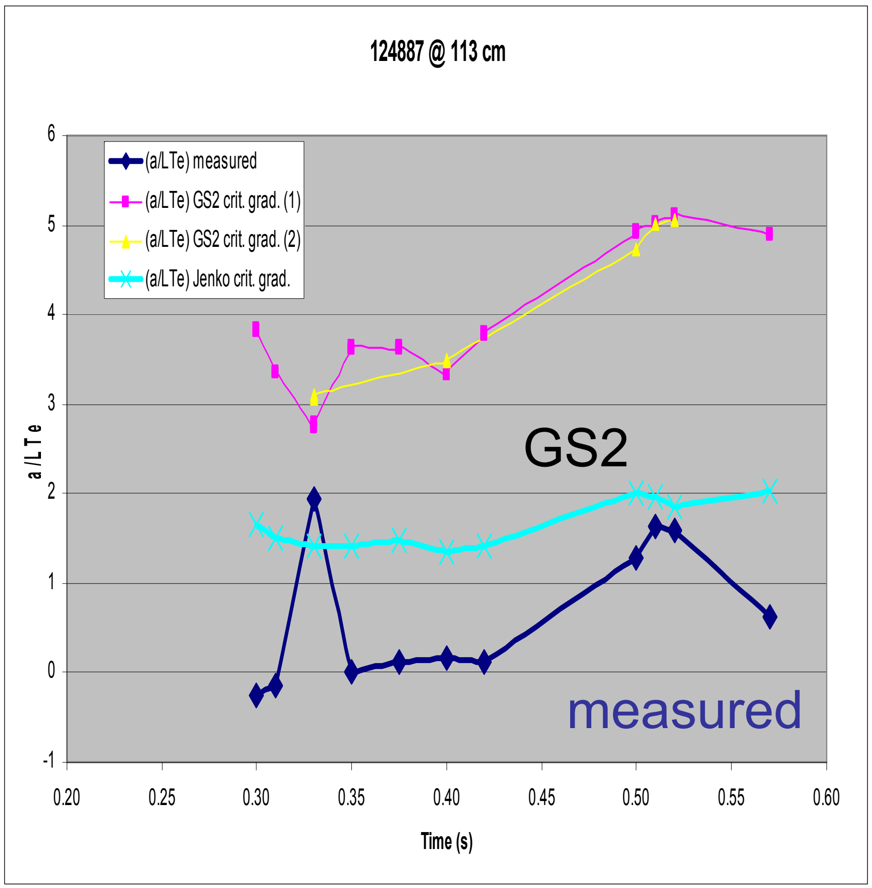




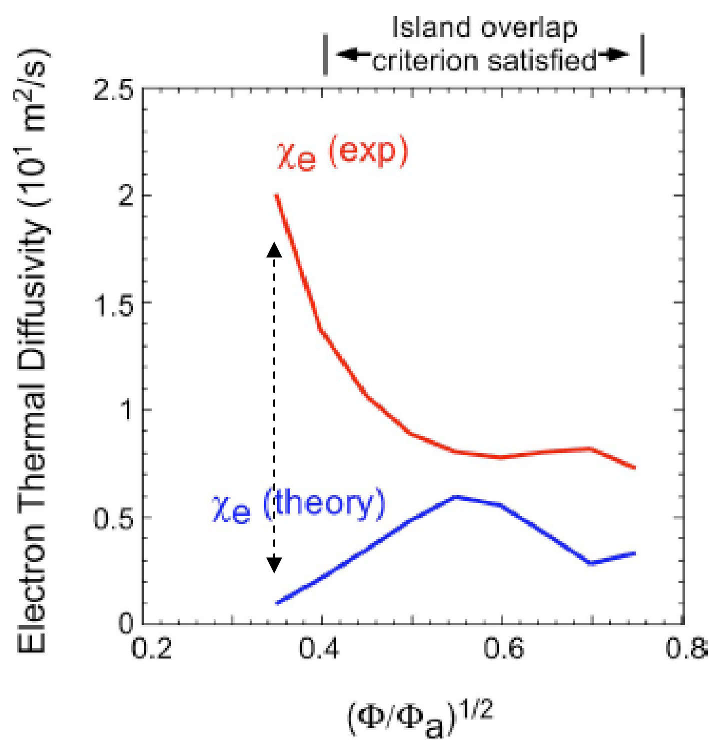
- Plasma with less gradient has worse transport
- Heat flux vs. ∇T_e shows low gradient region expanding with P_b

Central T_e gradient too low to drive any instability

∇T_e driven TEM, ETG, r/a~0.2
Smith 08

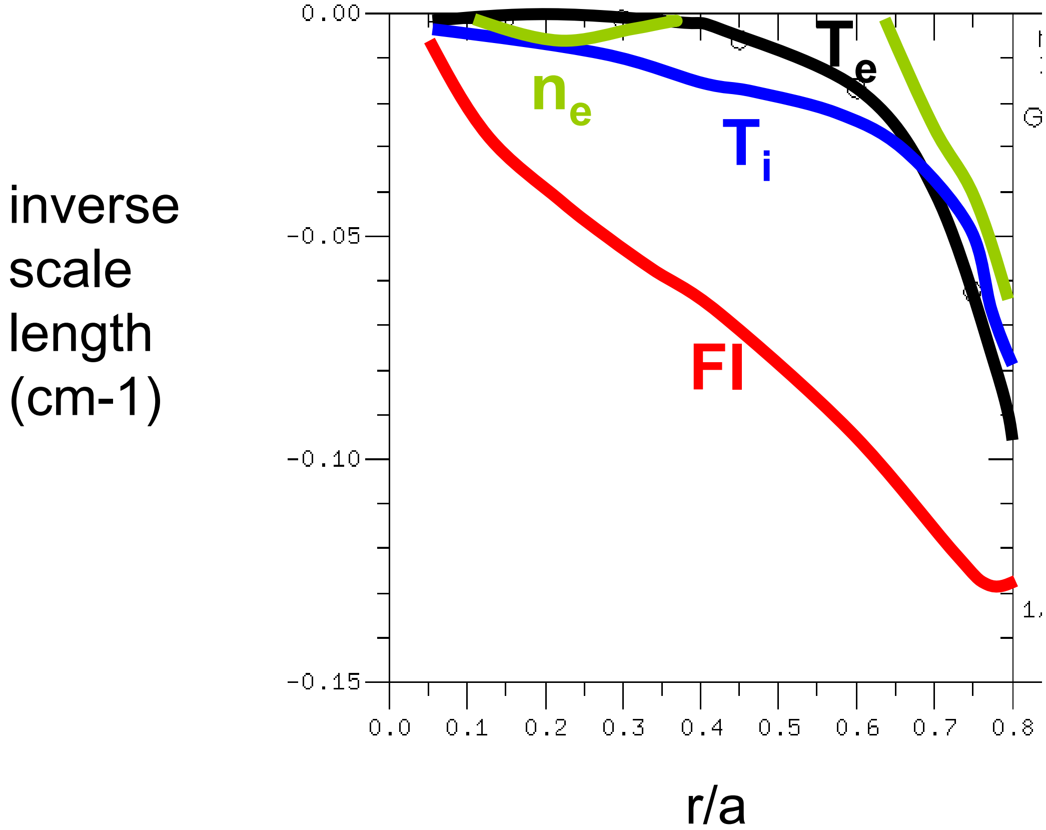


∇T_e driven micro-tearing
Wong 08



Fast ion gradients ‘the only game in town’ at r/a ≤ 0.4

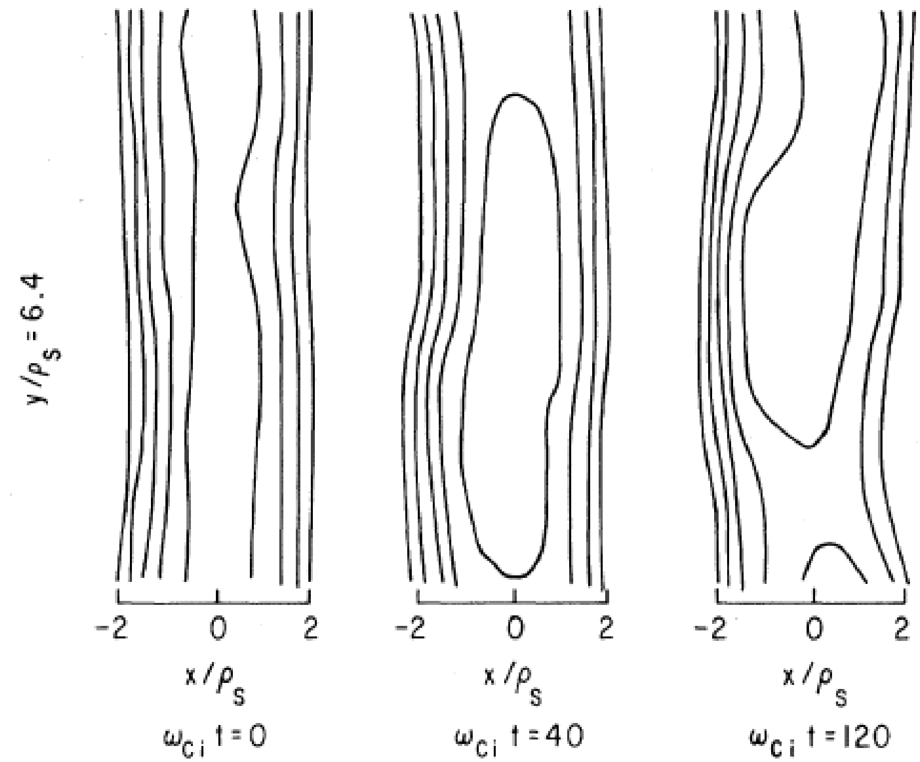
H-mode gradients 6 MW 1 MA 4.5 kG

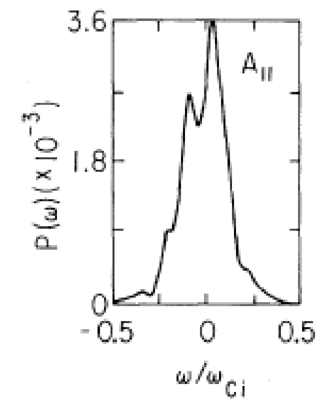


- Fast ions have also gradient in phase space

Shear Alfven modes (SAE) predicted to induce micro-tearing

Lee, Chance and Okuda, 81

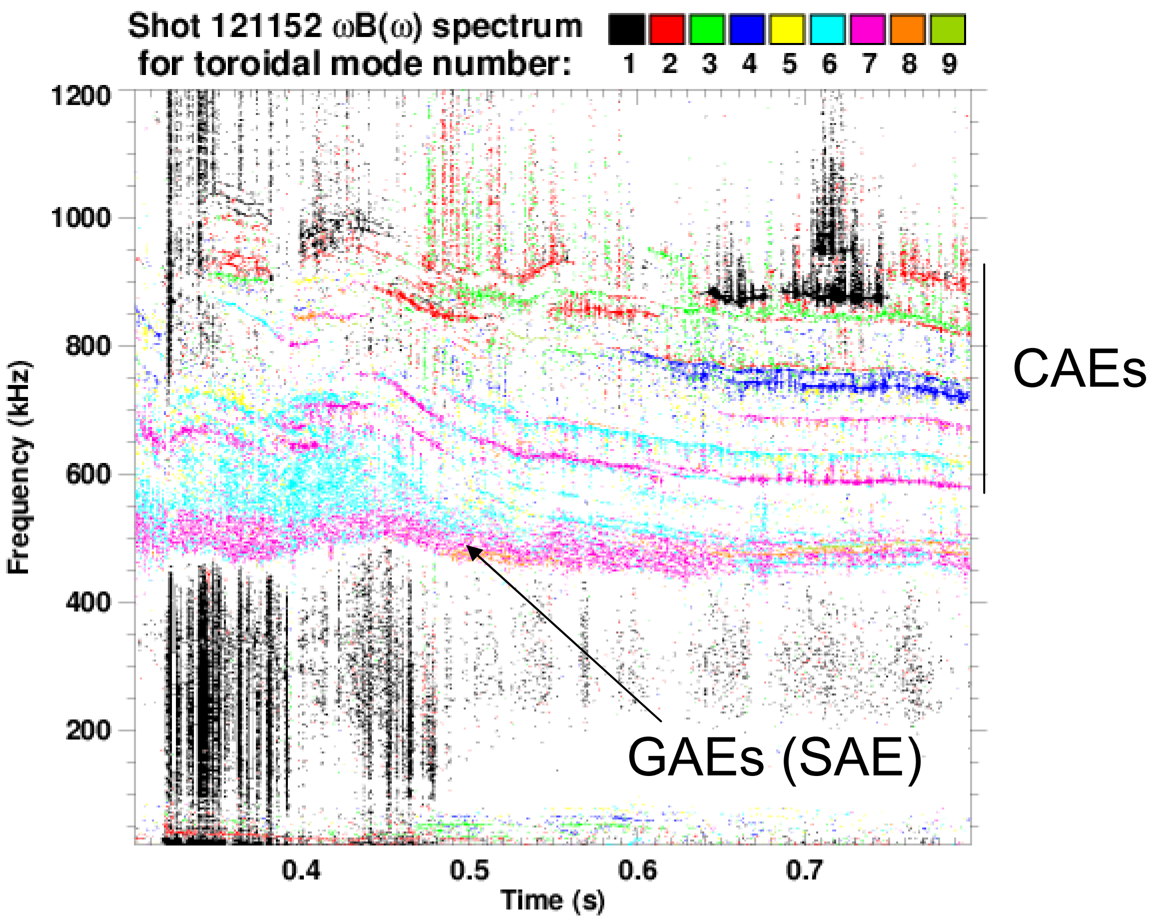




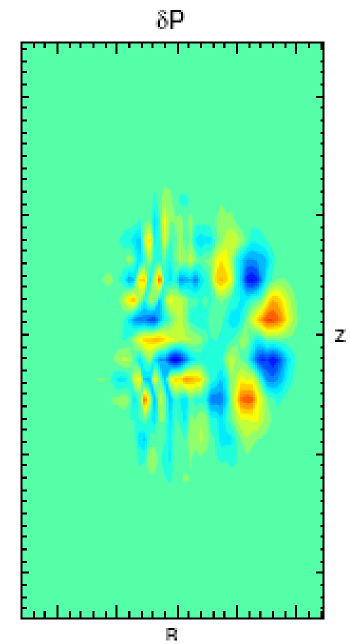
- Islands of ~ ρ_i width form at rational surfaces, due to cancelling of local magnetic shear by the mode eddy current
- Could affect large plasma volume, since rational surfaces spaced at ~ ρ_i
- Central region of low magnetic shear / flat-q most susceptible

Broad band SAEs in NSTX as component of GAE activity (Fredrickson, Gorelenkov, Belova)

6 MW
1MA
4.5 kG

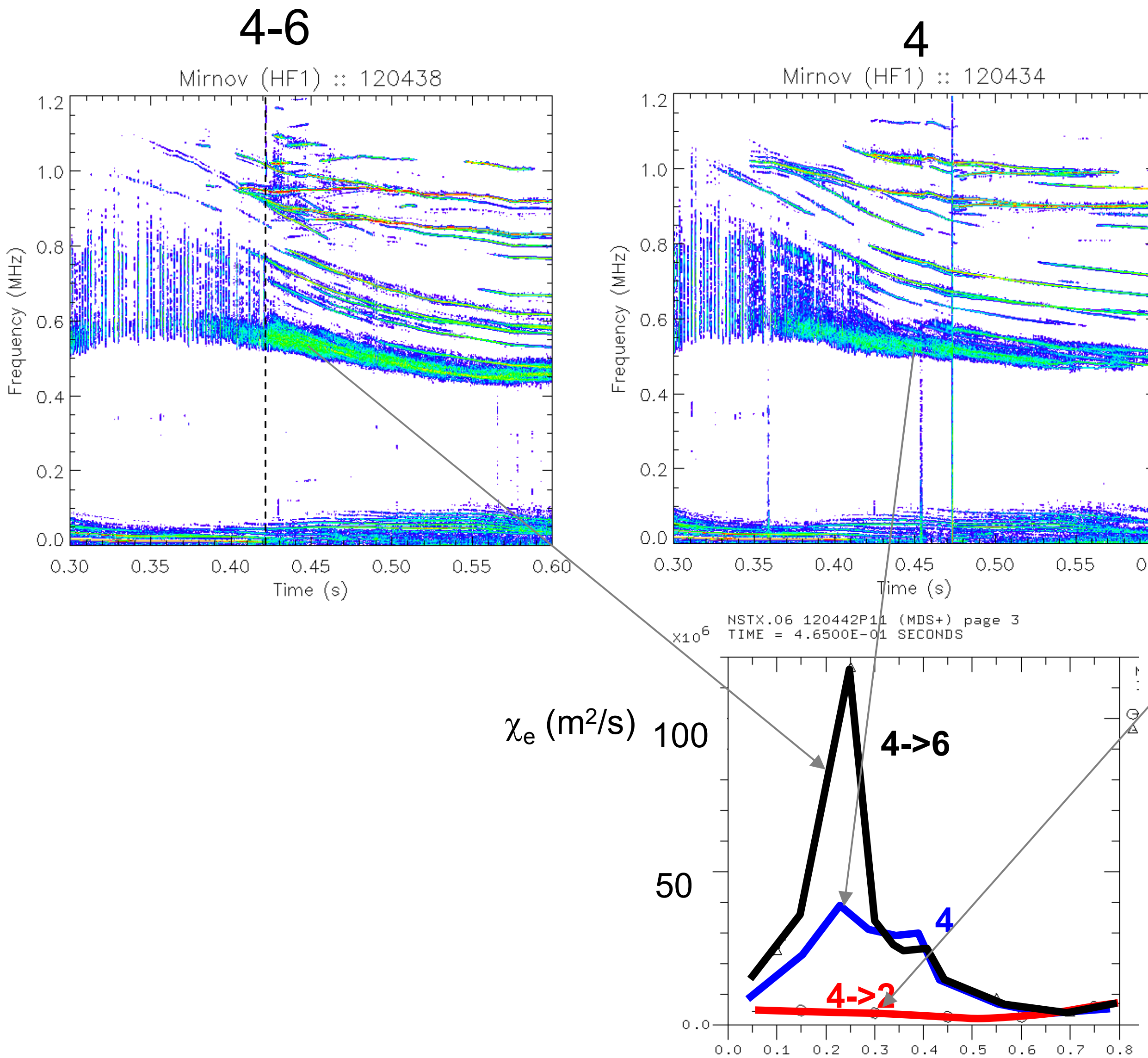


Predicted GAE structure, n=8 (Belova)



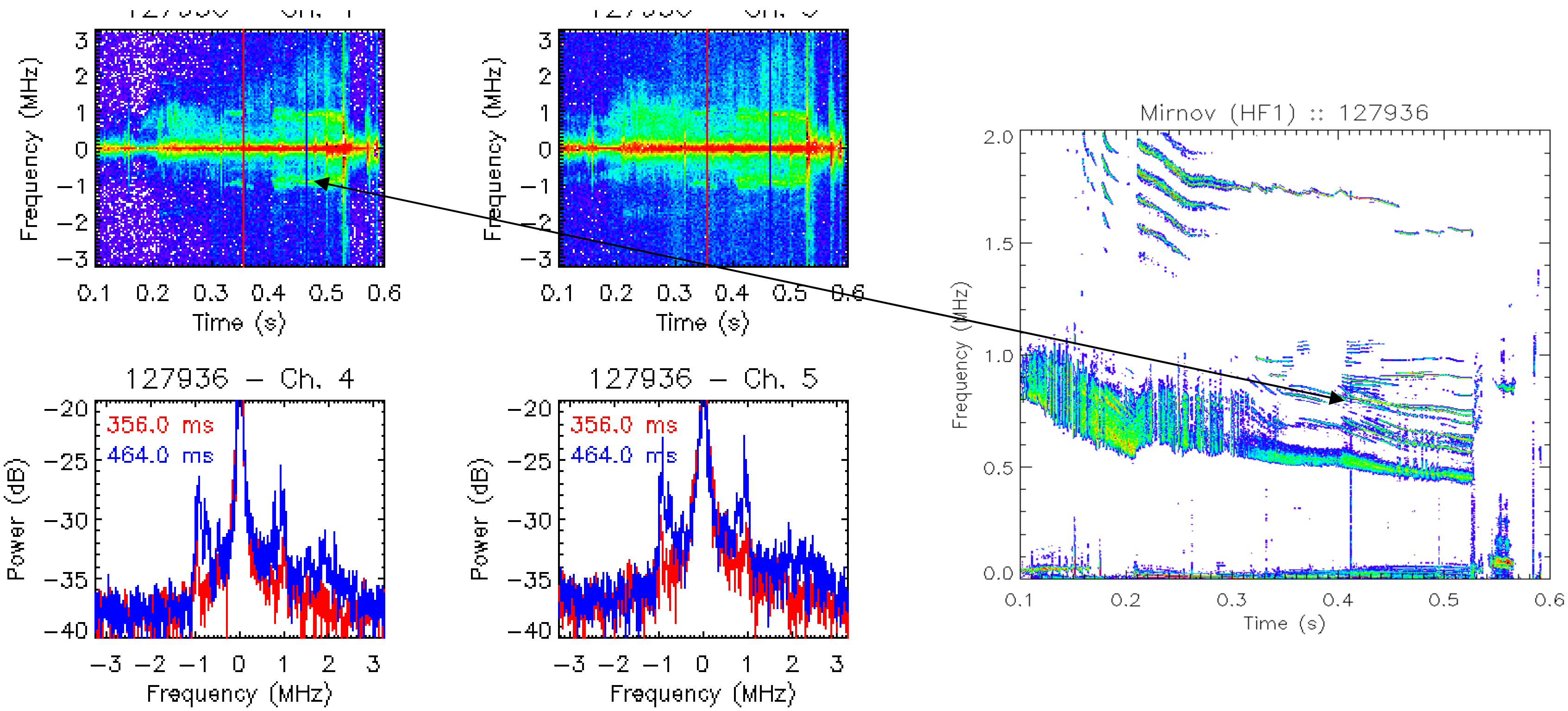
- High-n modes localized in the central plasma, $\delta B/B \leq 10^{-3}$ amplitude

Strong / weak GAE activity correlates with high / low central χ_e



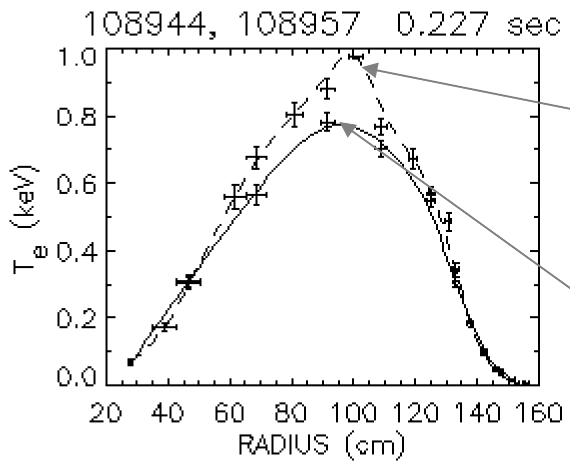
- Lower frequency TAEs, RSAEs might also play a role (Gorelenkov)
- T_e flattening in RS L-modes? (Stutman06)

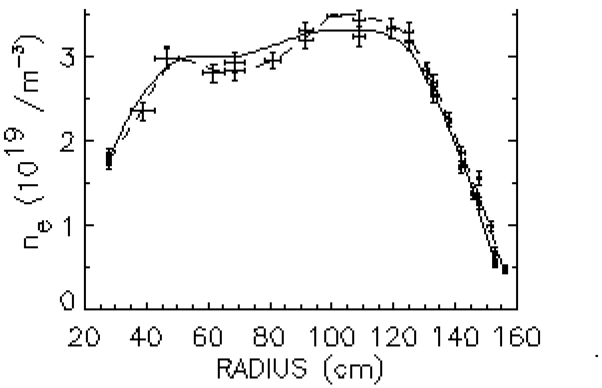
High-k scattering shows GAEs but no sub-ρ_i scale fluctuations (preliminary)

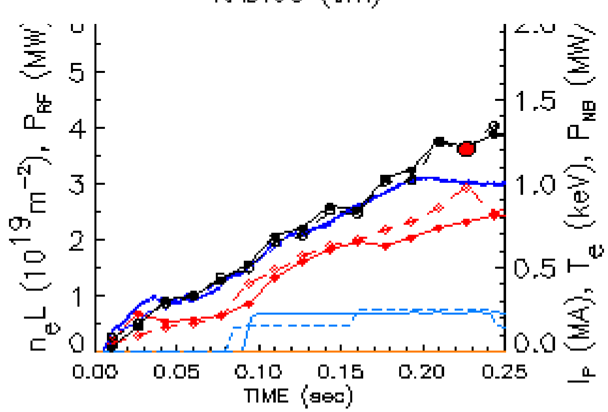


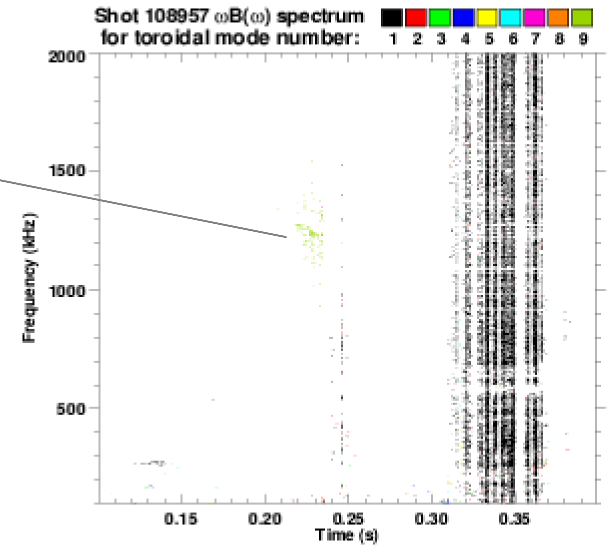
• Possible indication for electron transport mechanism being at $\geq \rho_i$ scale

Very similar plasmas without GAEs have higher central T_e

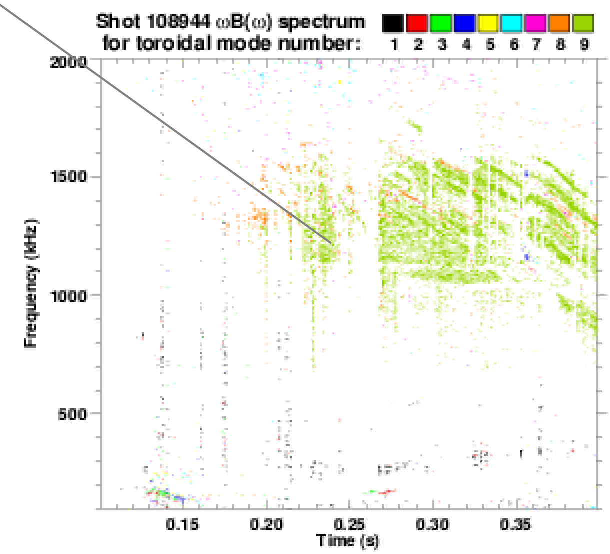








2.4 MW
A+B+C
60 kV



2.2 MW
A, 100 kV

Possible implications and further work