Analysis of pellet and ELM induced perturbations in NSTX

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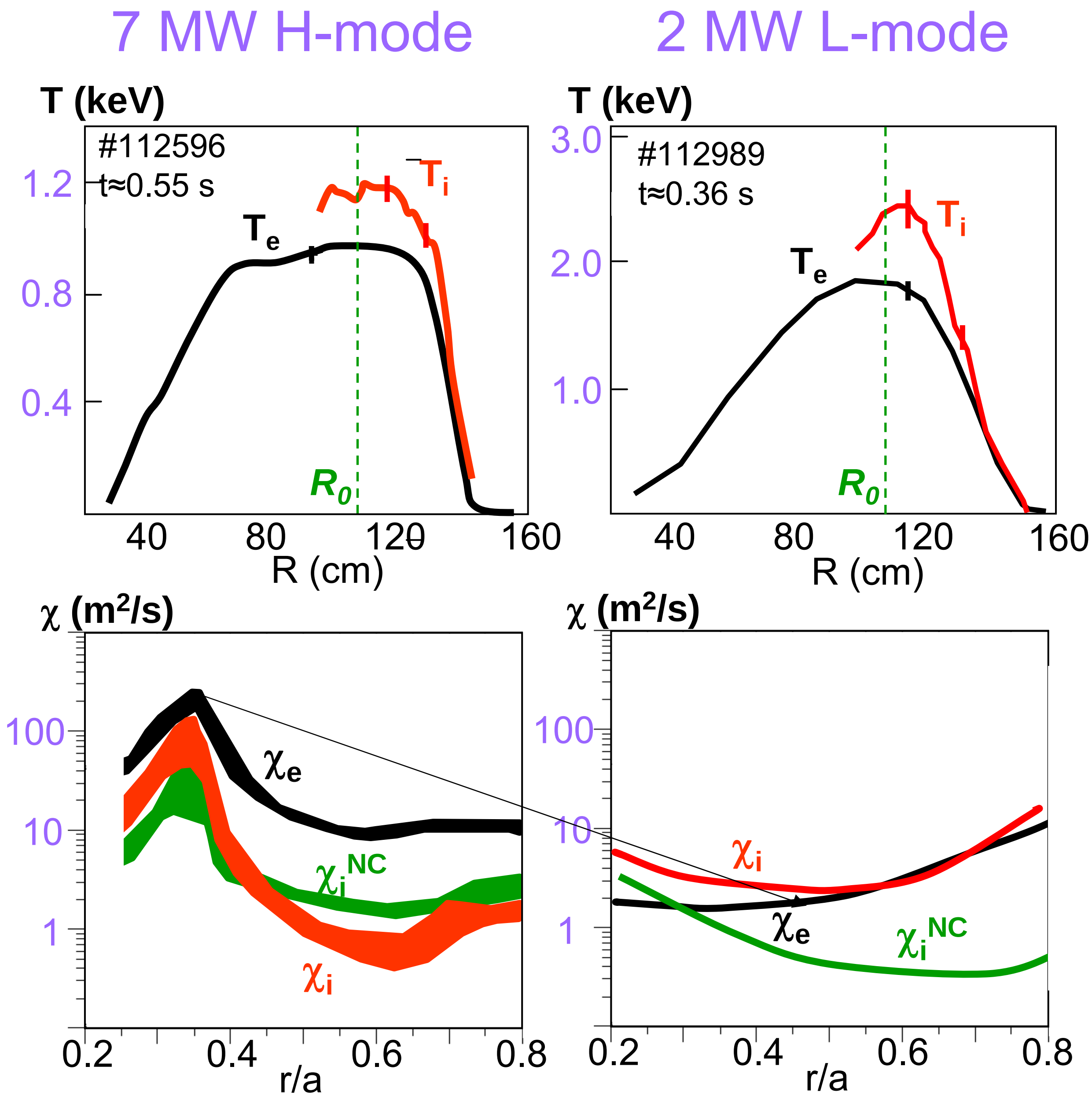
Electron transport in NSTX presents interesting puzzles. In high density H-modes $\chi_e >> \chi_i \approx \chi_i^{NC}$ although the beams preferentially heat the electrons. In contrast, $\chi_e \approx \chi_i > \chi_i^{NC}$ in low n_e L-modes. In an attempt to understand these effects, perturbative transport studies are planned in parallel with the power balance measurements. Since ECE is not applicable in NSTX, a 'multi-color' soft X-ray technique is being developed for the diagnostic of fast T_e perturbations (see also posters by L. Delgado and K. Tritz). The plasma is simultaneously viewed by soft X-ray arrays in different energy bands and modeling of the emission profiles used to propagate on fast time scale (<0.1 ms) the T_e profile measured by laser scattering. The technique is capable of good accuracy over tens of ms. Both ELMS and pellets are investigated as perturbation sources. After Type-I ELMs, the perturbed T_e profile shows fast 'cold pulse' propagation in the outer plasma, with a marked slow down towards the axis, in contrast with the radial dependence of χ_e^{PB}. The first results from Li pellet injection demonstrate this is a good tool for the planned transport studies. The preliminary analysis indicates fast cold pulse propagation to the plasma center in H-mode, similar to the ELM case. This suggests that most of the Type-I ELM effects reflect in fact electron transport. In contrast, in low n_e/shear reversed L-modes, strong damping of the cold pulse and possibly polarity reversal occurs around mid-radius.

Work supported by US DoE grant DE-FG02-99ER5452 at JHU

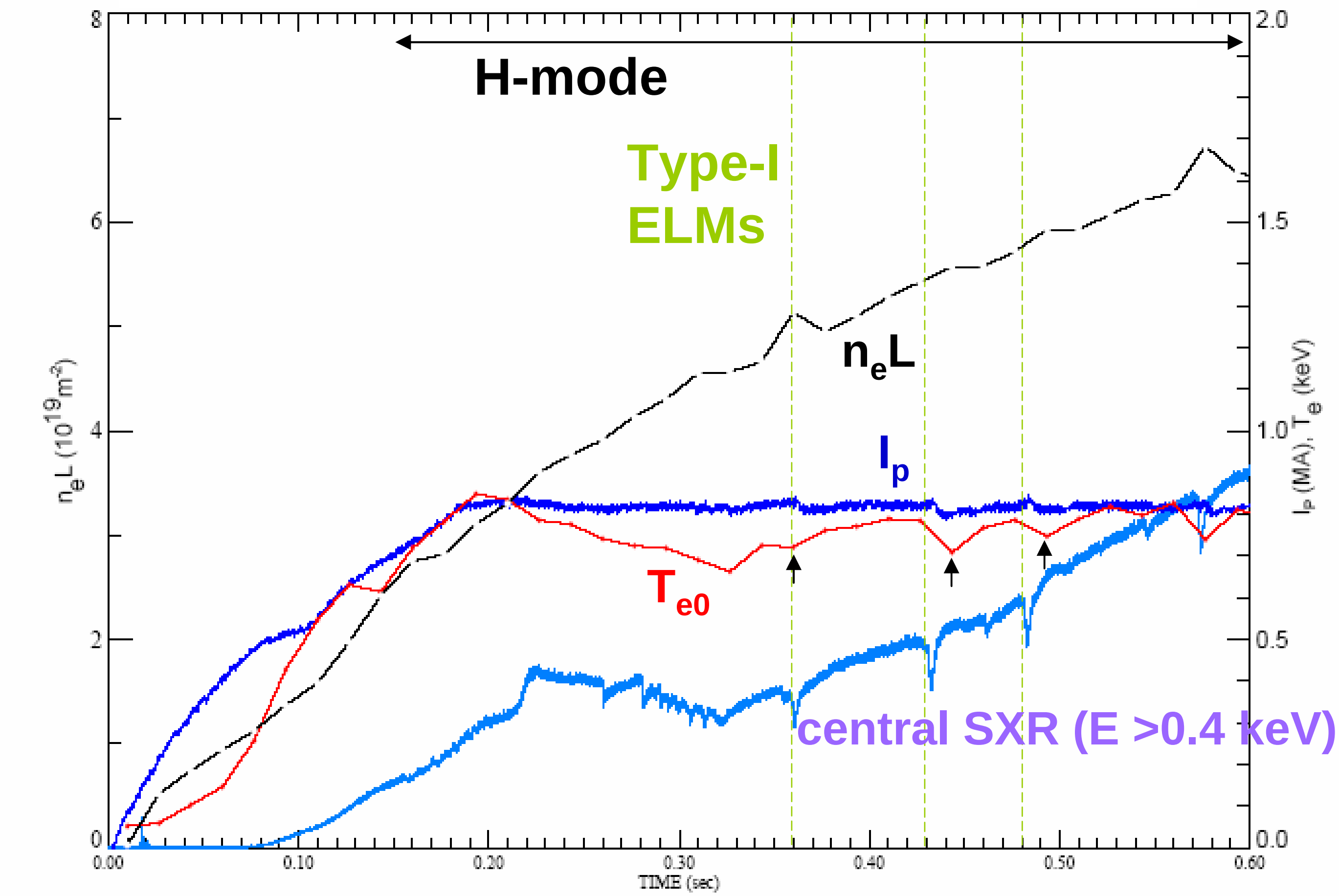
Puzzles in NSTX electron transport



- T_i exceeds T_e although electrons primarily heated
- Flat T_e in H-mode
  <-> very large central χ_e
- Ions close to neoclassical
- Much reduced χ_e in low n_e /high T_e 'L-mode
- Perturbative studies and correlation with high & low-k fluctuations may help understand these puzzles
- This work: A first assessment of pellet and ELM induced T_e perturbations
- Fast T_e diagnostic based on 'multi-color' USXR

T_e perturbation at Type-I ELM

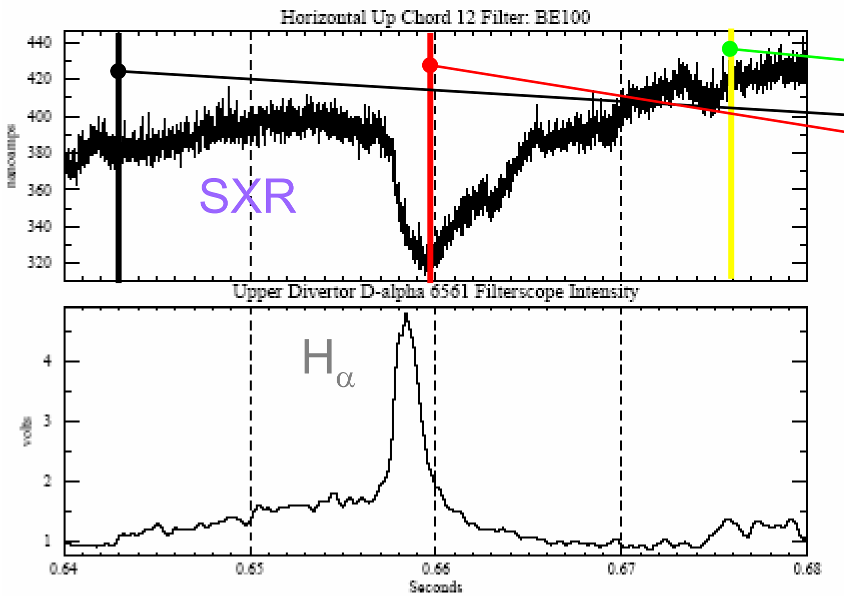
#112550 (7 MW NBI, 0.8 MA, 4.5 kG)

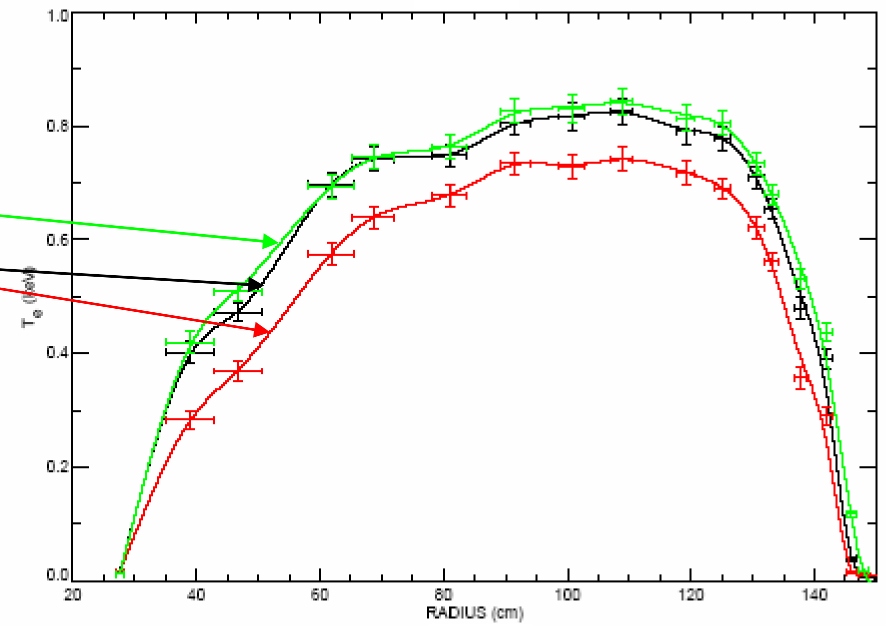


- 10-15% core δT_e at Type-I ELM from Multi-point Thomson Scattering (MPTS)
- δn_eL most often small

ELM causes mostly T_e perturbation

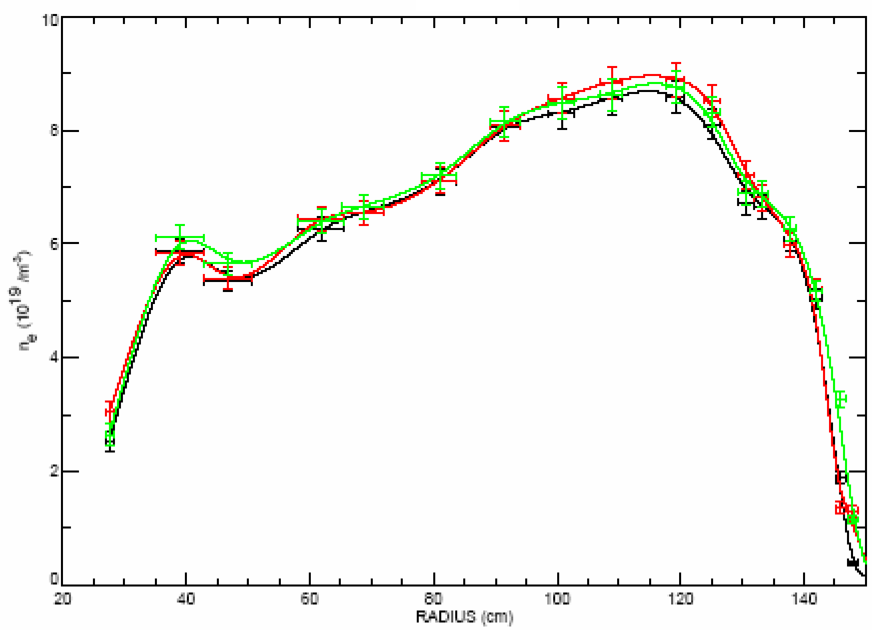
#112581 (7 MW NBI, 1 MA, 4.5 kG)





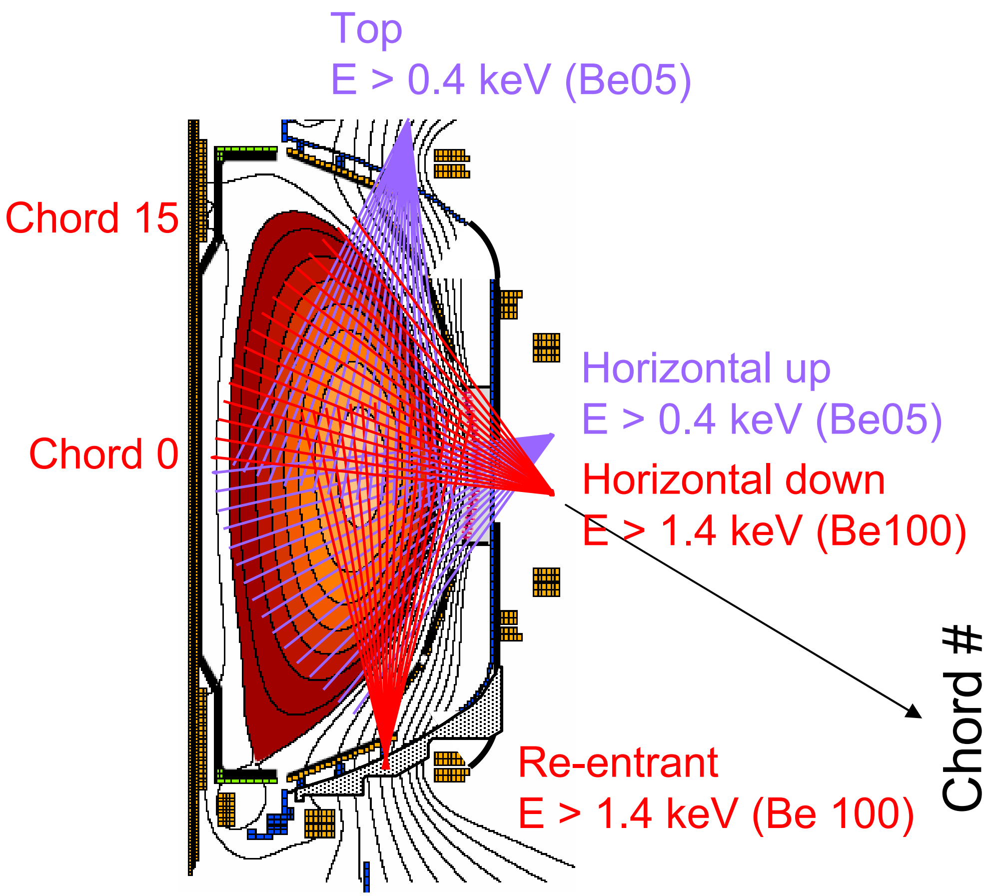
- Thomson T_e profile drops after ELM and recovers ~ 17 ms later
- Note ∇T_e does not change at drop
- Density profile little perturbed

(Note that the density 'ears' have been dissipated by earlier ELMS)

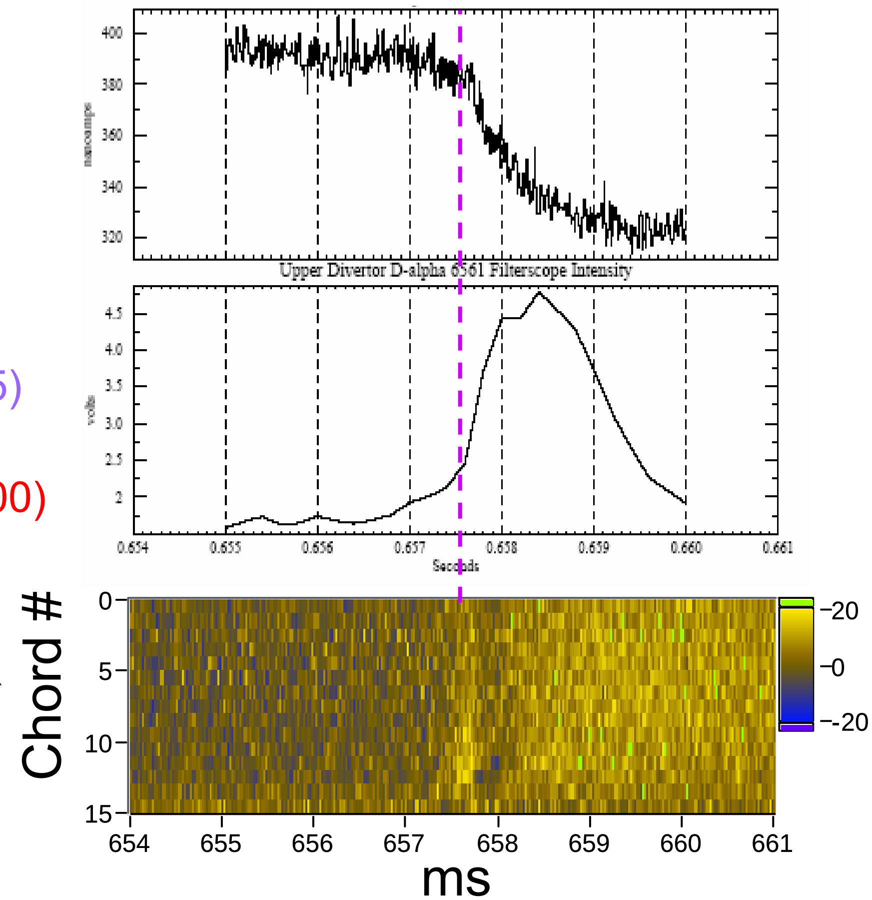


Core T_e drop not caused by internal MHD

NSTX SXR diode system



Core SXR perturbation, #112581
(Horizontal down, E > 1.4 keV)

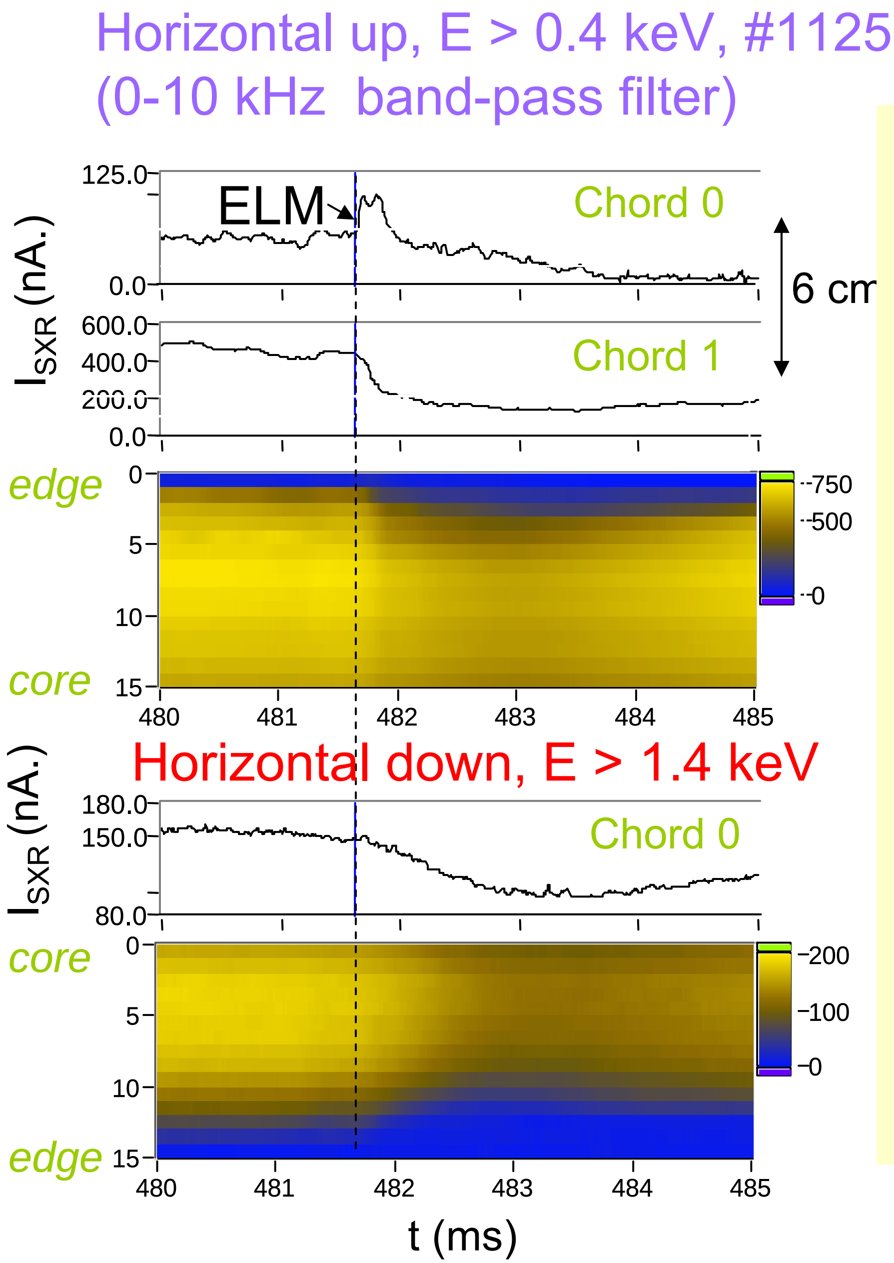


- Selectable cutoff energies:
  - core/edge MHD imaging
  - 'two-color' T_e profiles

- No core coherent modes or reconnections prior to drop

(See also posters by K. Tritz and P. Riddha)

Global SXR drop triggered by the ELM



- ELM manifest as peripheral 'reconnection-like' event occurring on the MHD time scale

- No indication the mode extends more than $\rho \gtrsim 0.9$ into the plasma

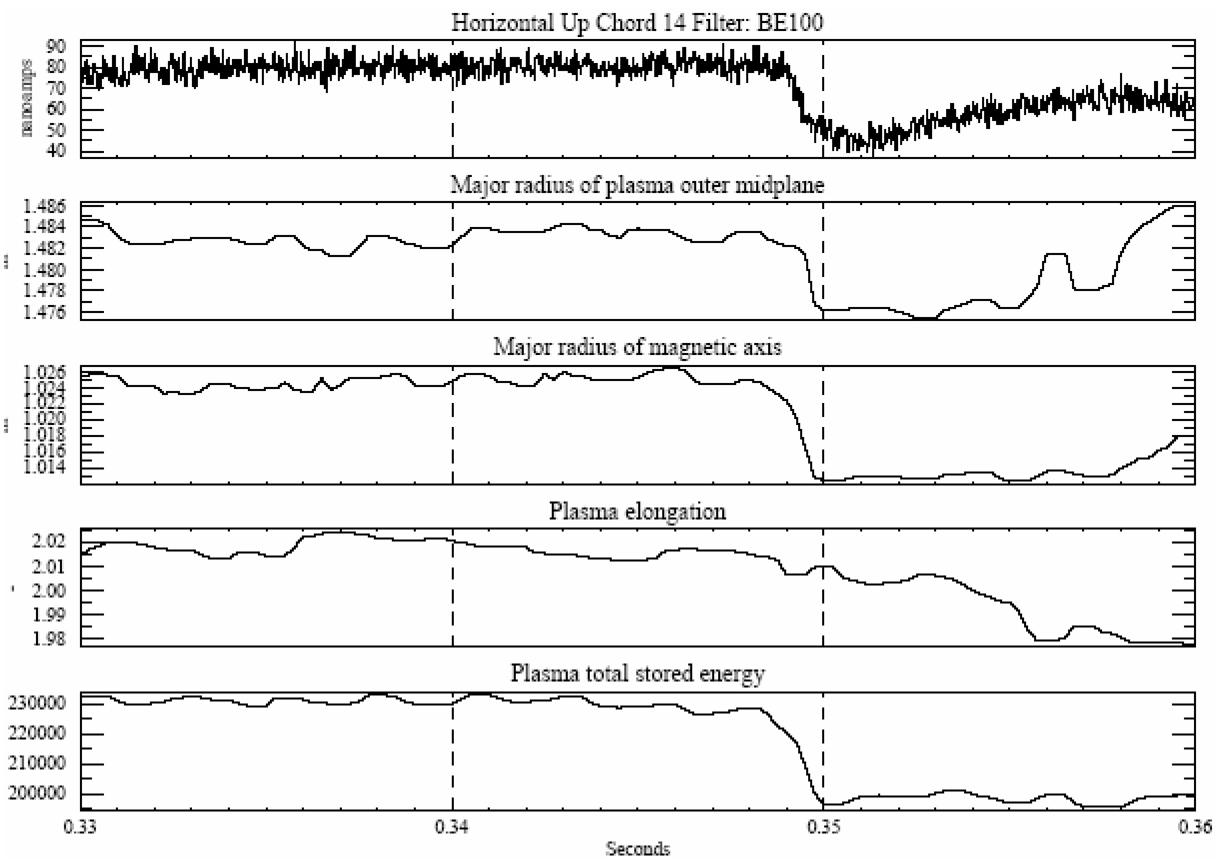
- Following the peripheral event, the E>1.4 keV SXR emission drops 50% on ~ 1.5 ms time scale

- 'Erosion' of the SXR profiles prior to the ELM (see poster by K. Tritz)

Small change in plasma equilibrium during ELM

Equilibrium changes computed by fast (0.1 ms) EFIT during large Type-I ELM

(S. Sabbagh, U. Columbia)



(113415
7 MW NBI,
0.8 MA, 4.5 kG)

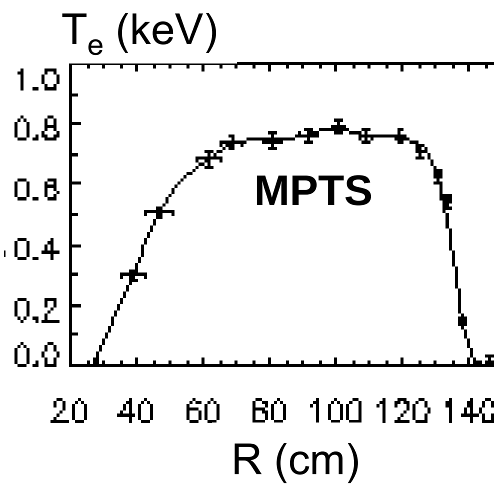
- In spite 12.5% δW_{tot}, only 0.4% δR_{out}, 0.9% δR_0 and 0.5% $\delta\kappa$
- SXR drop must reflect rapid electron heat loss following perturbation of peripheral T_e profile

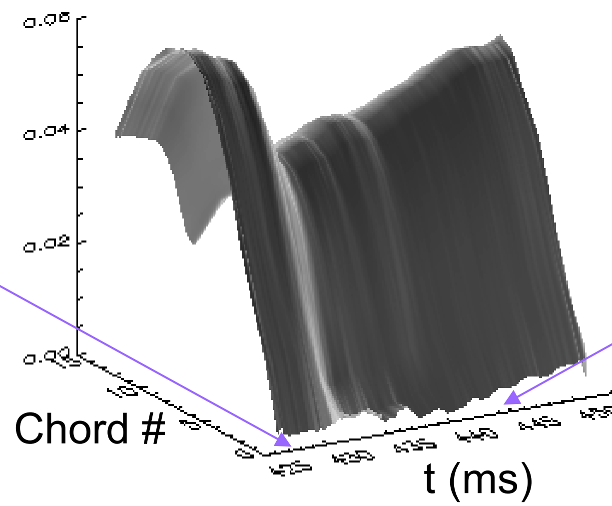
‘Two-color’ T_e profile after ELM agrees with MPTS

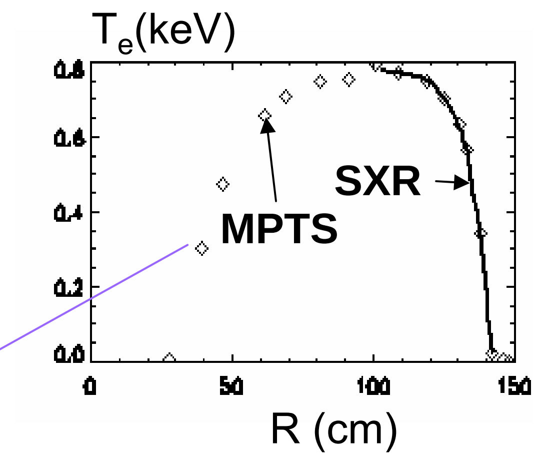
MPTS T_e profile
at t_1=0.427s

E > 1.4 keV / E > 0.4 keV
(Horiz. Up / Re-entrant)

SXR and MPTS
T_e profile at t_2=0.443s

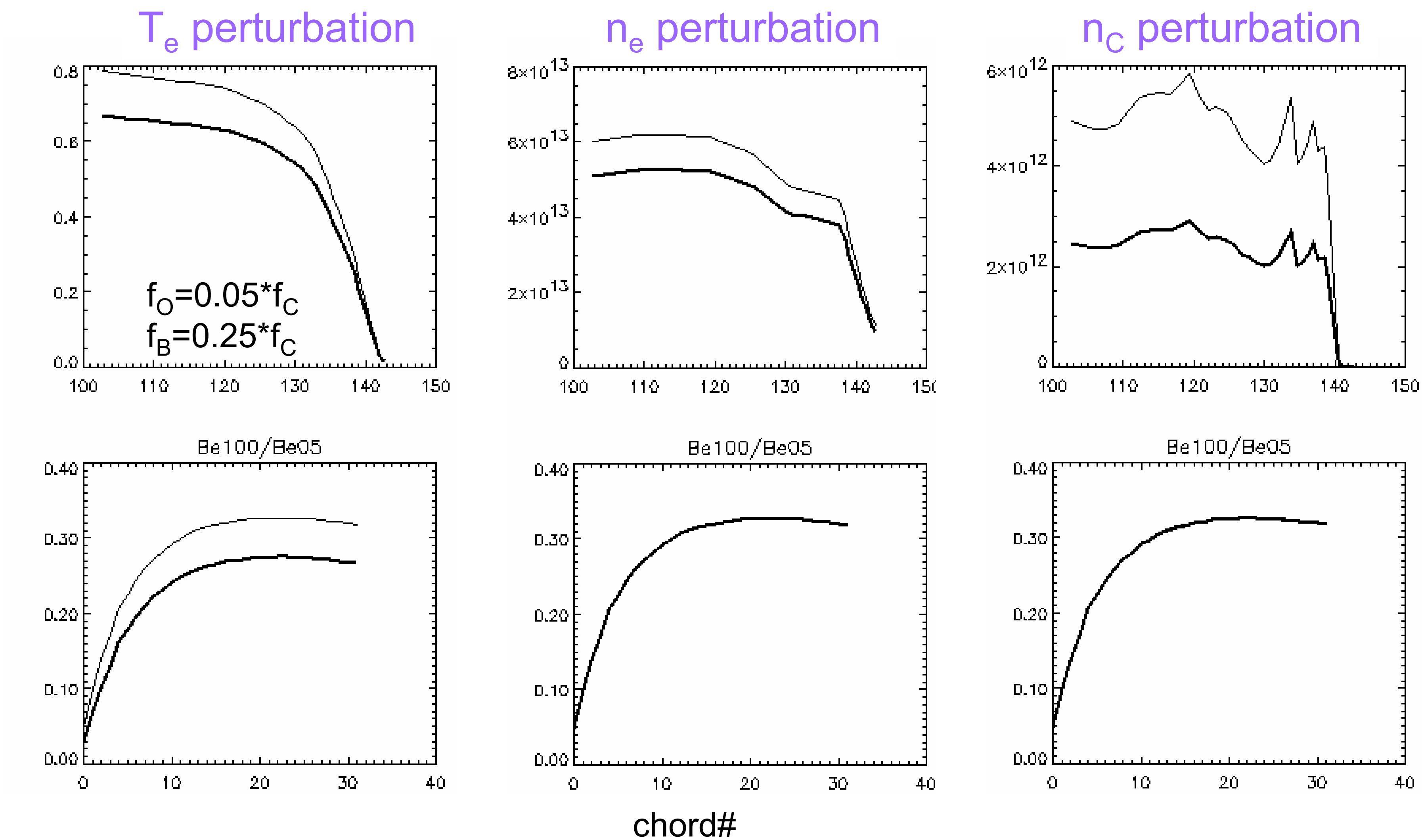






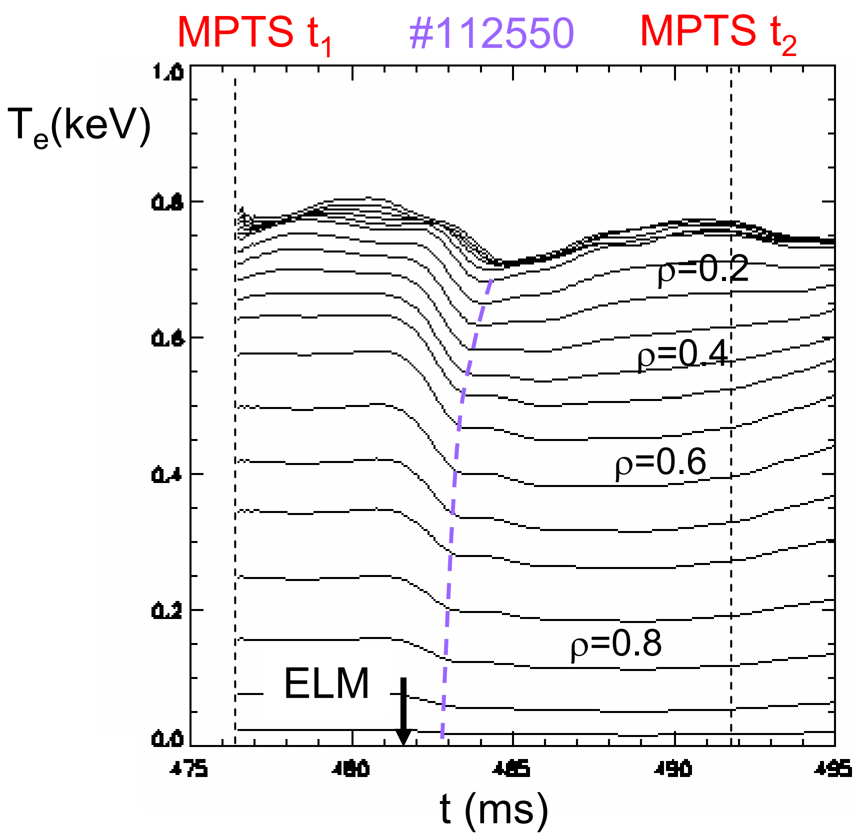
- MPTS profile at t_1 propagated in time using SXR intensity ratio:
  - SXR profiles fitted for n_Z profile (CE radiative coefficients + EFIT mapping)
  - profile ratios then fitted with $\mathbf{T_e(r,t_1)^{MPTS}+\delta T_e(r,t)}$
- n_e, n_z perturbation neglected in the first approximation

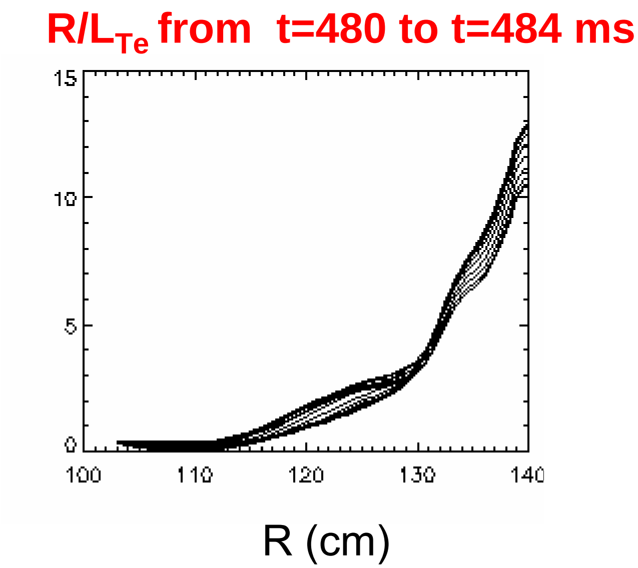
‘Two-color’ ratio insensitive to n_e, n_z perturbations



- Intensity ratio reflects mainly $T_e(r)$ changes (at constant C:O:B fractions)
- In spite line integration, ratio insensitive to large changes in $n_e(r)$, $n_Z(r)$

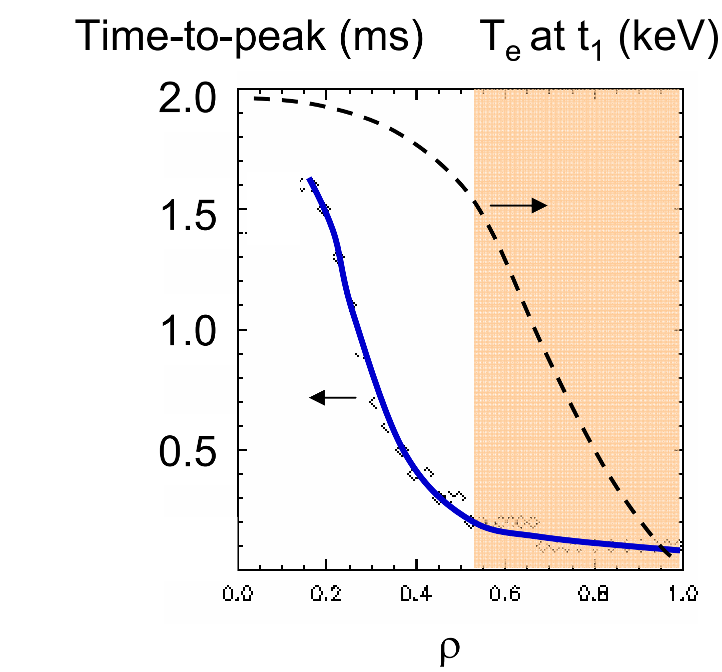
‘Two-color’ modeling shows fast T_e drop at ELM

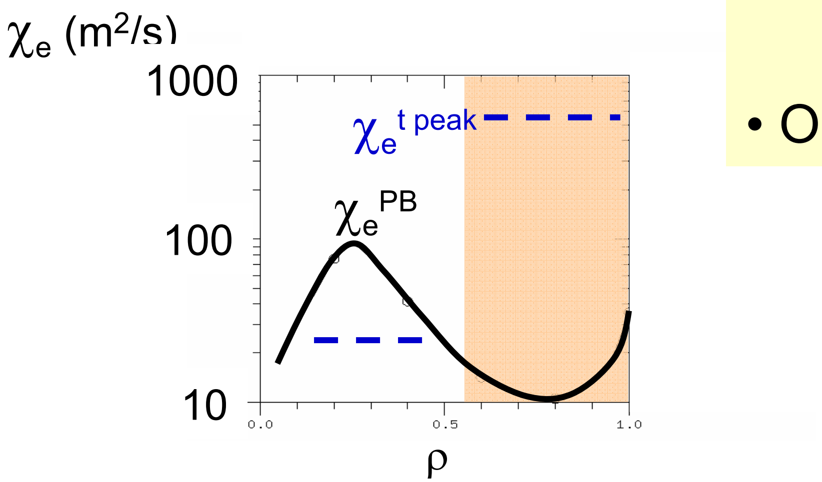




- Edge perturbation reaches central plasma in a few ms
- Almost no delay in perturbation peak in the outer plasma
- T_e profile evolves with little change in gradient (‘stiffness’)

Two regions of cold pulse propagation





- Very fast propagation in the region of strong T_e gradient ($\rho > 0.5$)
- Markedly slower propagation inside
- $\chi_e^{t\ peak} = 1/8\ \Delta r^2/\Delta t_{peak}$ (sawtooth model)
  - -> hundreds m^2/s outside $\rho > 0.5$
  - -> tens of m^2/s inside
- Opposite trend to χ_e^{PB}

Local χ_e estimate using LHD cold pulse model

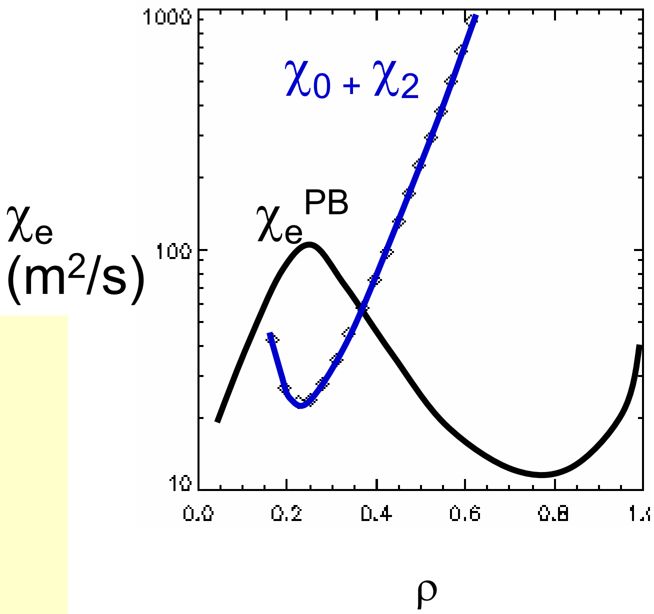
Inagaki *et al*, PPCF 04, neglects ion damping (e-i coupling)

$$\frac{3}{2} n_e \frac{\partial \delta T_e}{\partial t} = \nabla \cdot \left(n_e (\chi_0 + \chi_2) \nabla \delta T_e - n_e \chi_1 \frac{-\nabla T_e}{T_e} \delta T_e \right)$$

$$\chi_0(r) = -q_e/(n_e \nabla T_e)$$

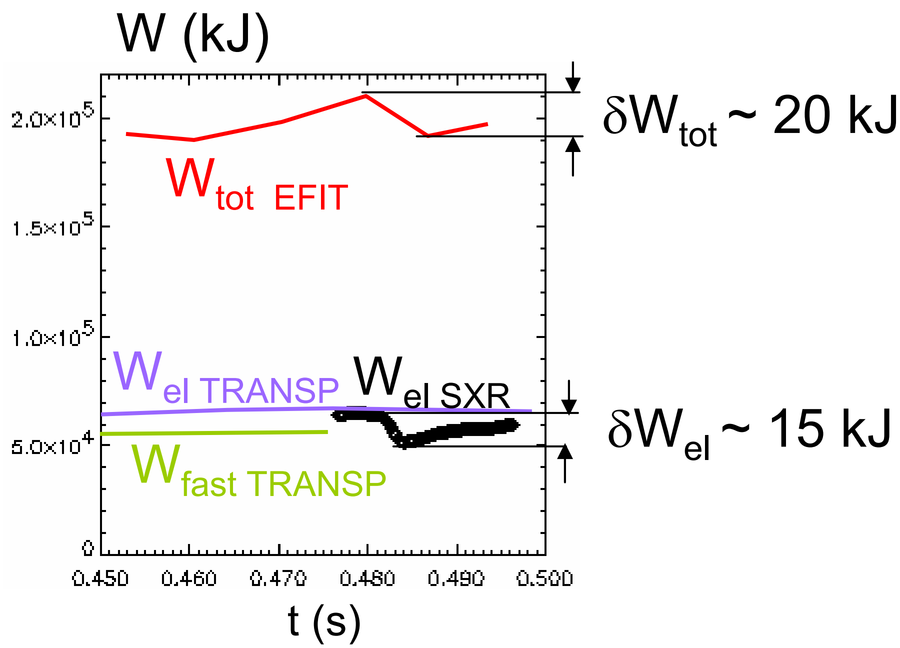
$$\chi_1(r) = \frac{\partial \chi_0}{\partial T_e} T_e,$$

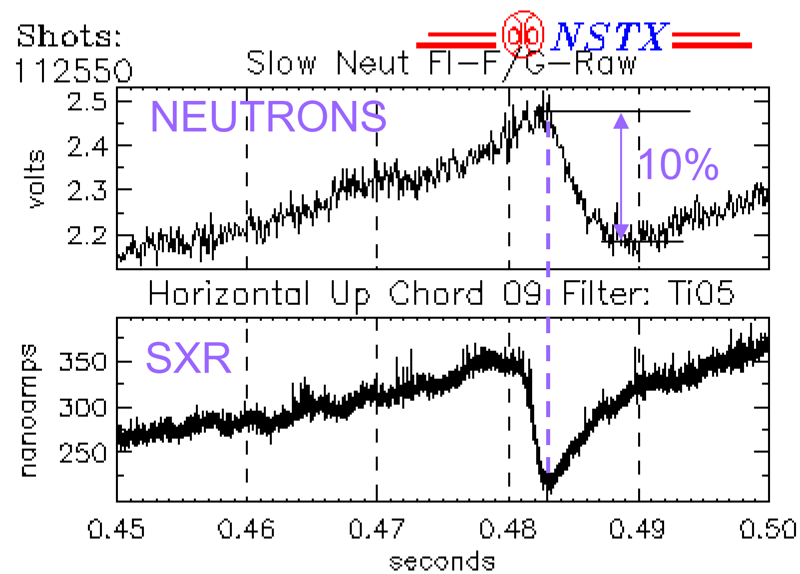
$$\chi_2(r) = \frac{\partial \chi_0}{\partial \nabla T_e} \nabla T_e \quad (\sim \chi_e^{inc})$$



- Very rapid perturbed transport in the T_e gradient region, rapidly decreasing inside
- Electron transport strongly driven above critical in the ∇T_e region, but nearer to threshold where T_e flattens ?

What about the ions ?

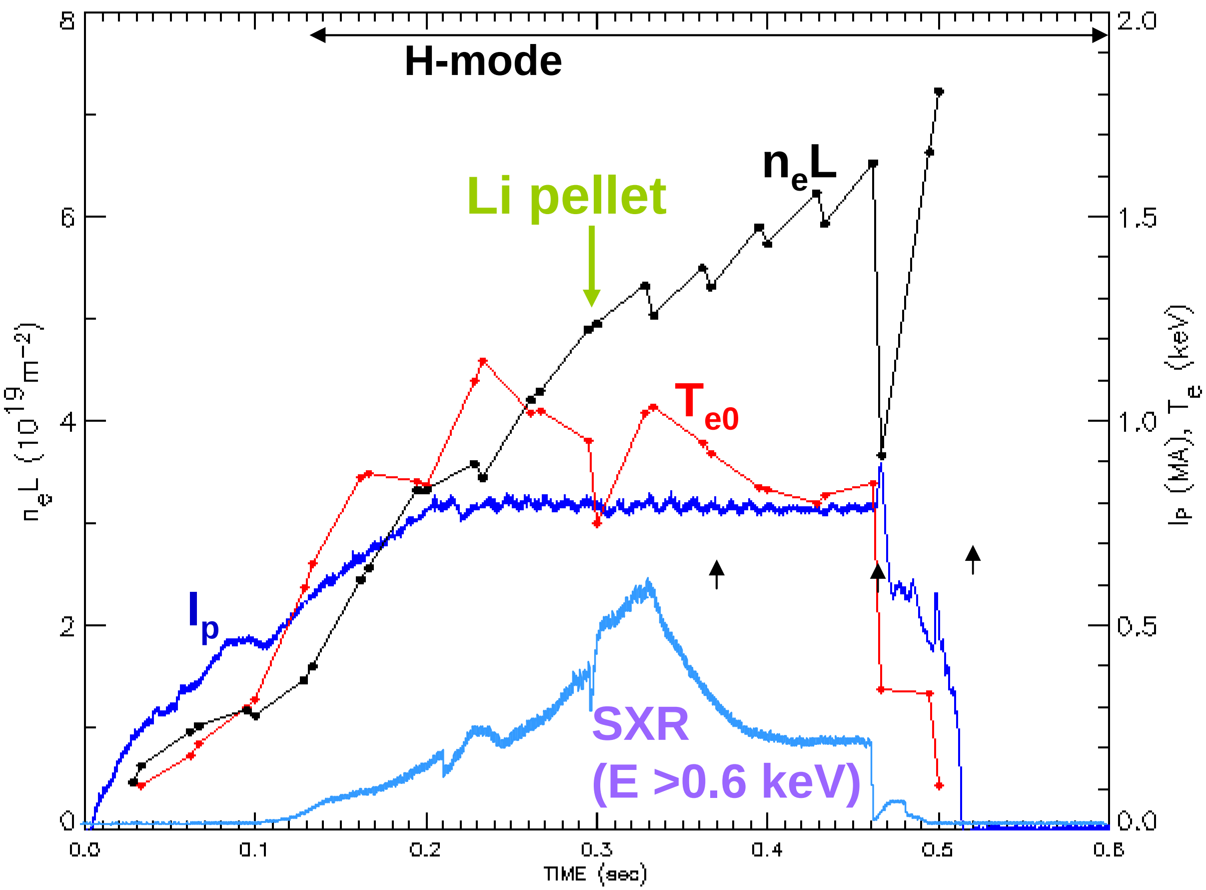




- At most ~ 5 kJ thermal ion heat loss -> $\delta T_i/T_i$ mostly from i-e coupling -> perturbed ion transport also much slower than electron one ?
- Delayed neutron drop reflects changed fast ion population due to changed T_e profile

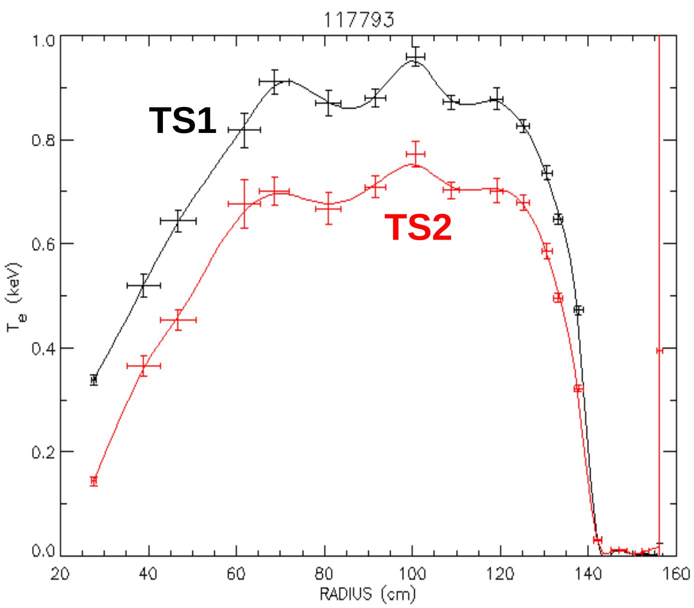
First results from Li pellet injection: H-mode

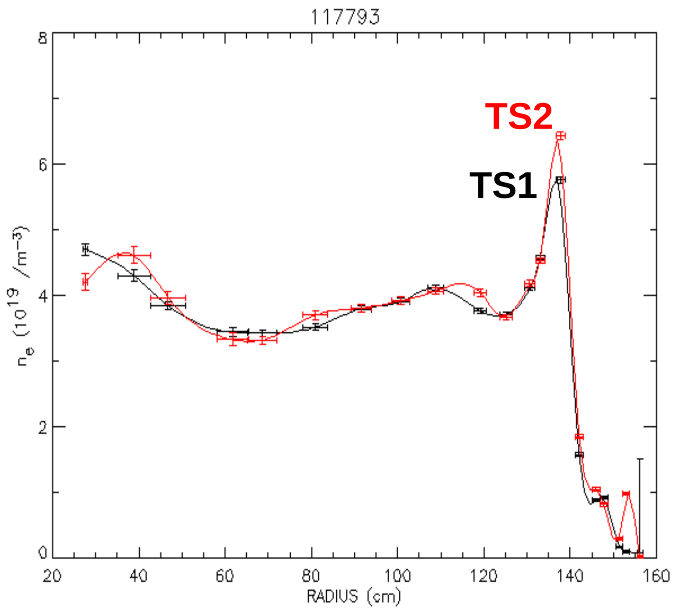
#117793 (7 MW NBI, 0.8 MA, 4.5 kG)



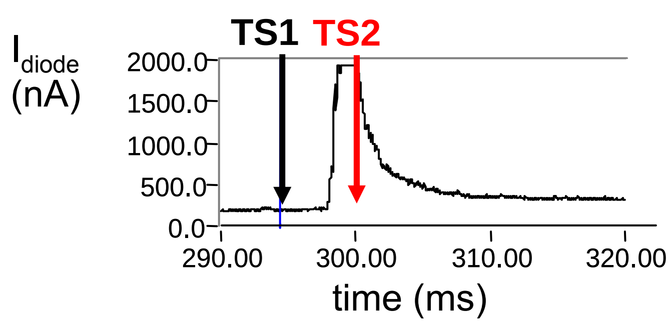
- 0.43 mg Li pellet injected at ≈ 150 m/s velocity
- 20% δT_{e0}, with only small $\delta n_e L$
- Rapid SXR drop resembling that observed at Type-I ELM

MPTS profiles before and after injection

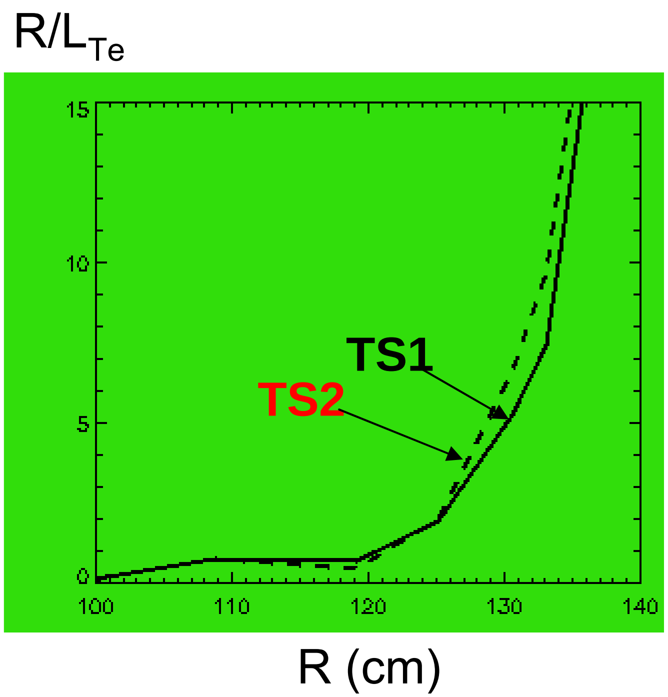




Li III Ly$_{\alpha}$ JHU Telescope

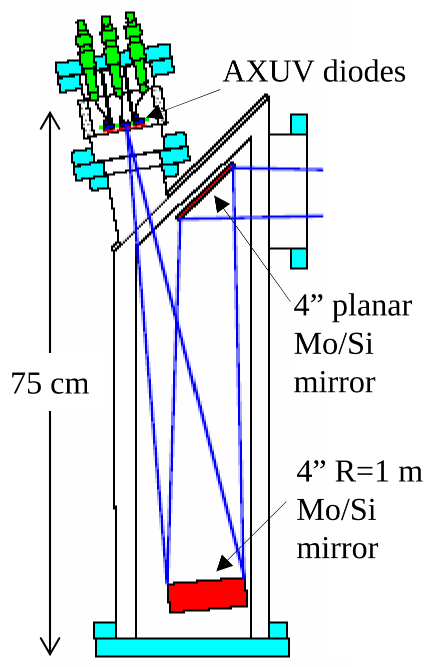


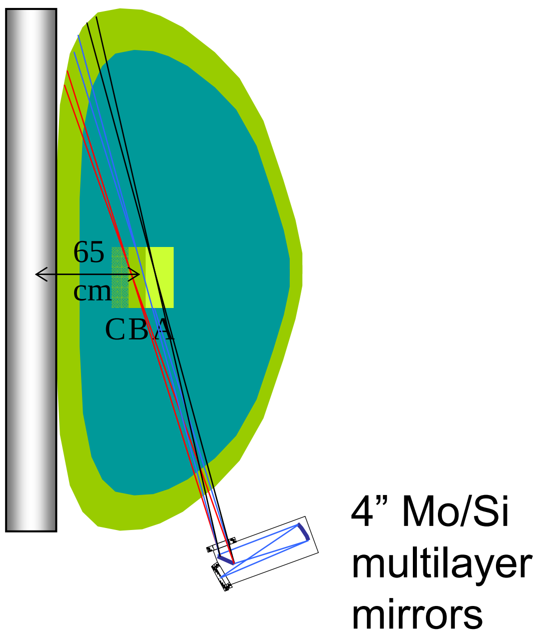
- Li III 135 Å Ly$_{\alpha}$ emission monitored by JHU multilayer Telescope
- Successive MPTS profiles show global T_e drop resembling that at ELM
- Only small n_e increase, localized inside pedestal

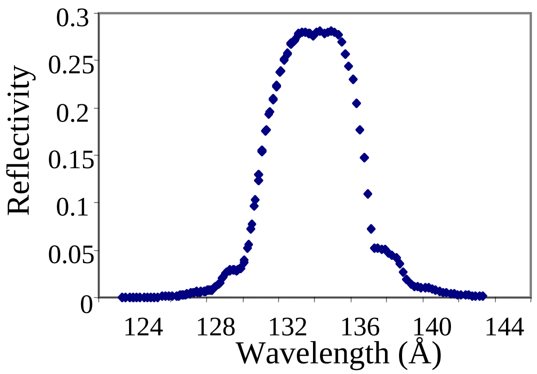


• Pellet perturbed T_e profile at TS2 has same normalized gradient as at TS1 ('stiff' behavior as in the case of ELM perturbation)

135 Å Multilayer Mirror Telescope on NSTX

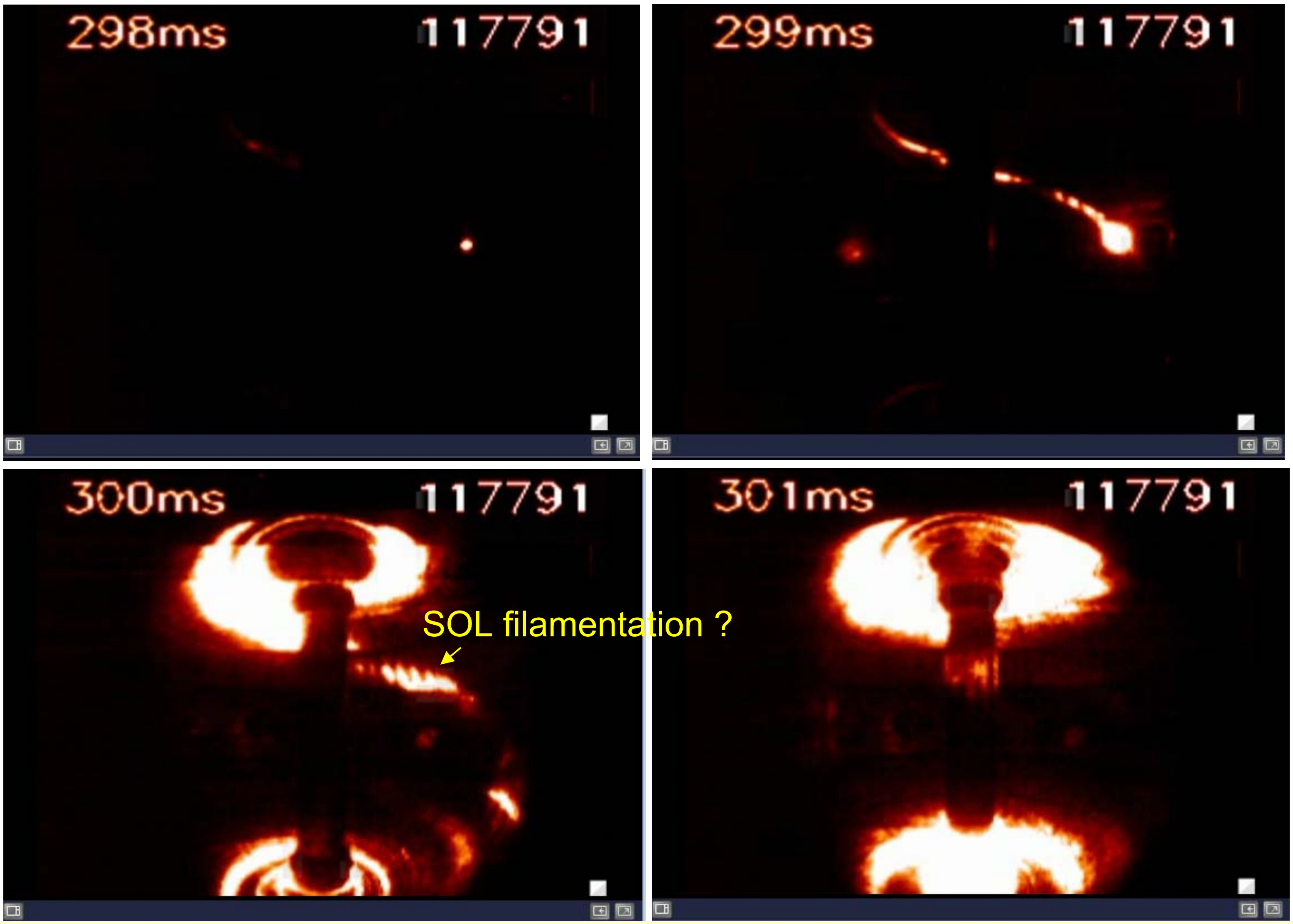






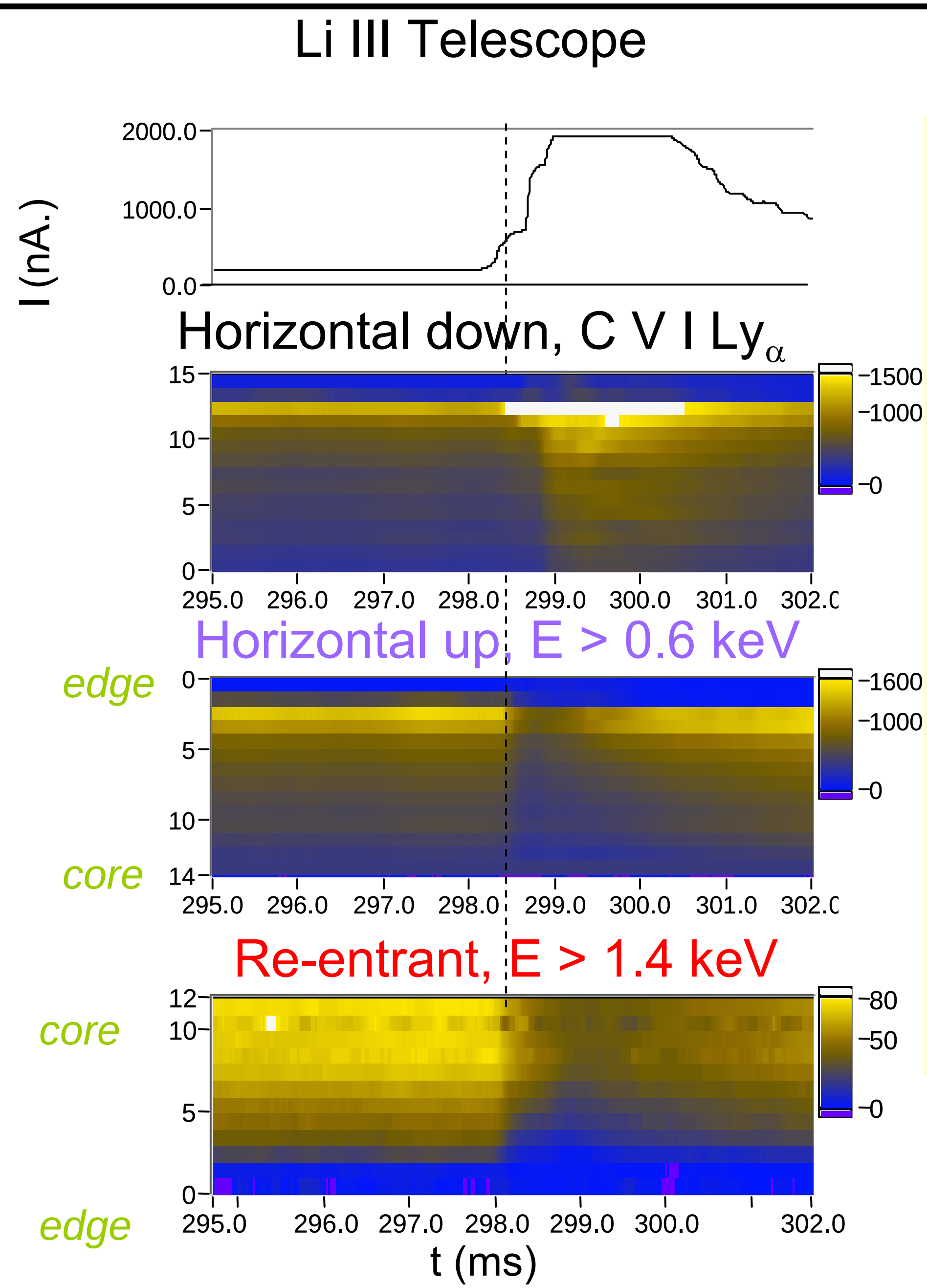
- f = 0.5 m turbulence imaging instrument under development
- Served as Li III Ly_{α} monitor using a 1 cm^2 AXUV diode for detection

Fast camera shows pellet ablating in the edge



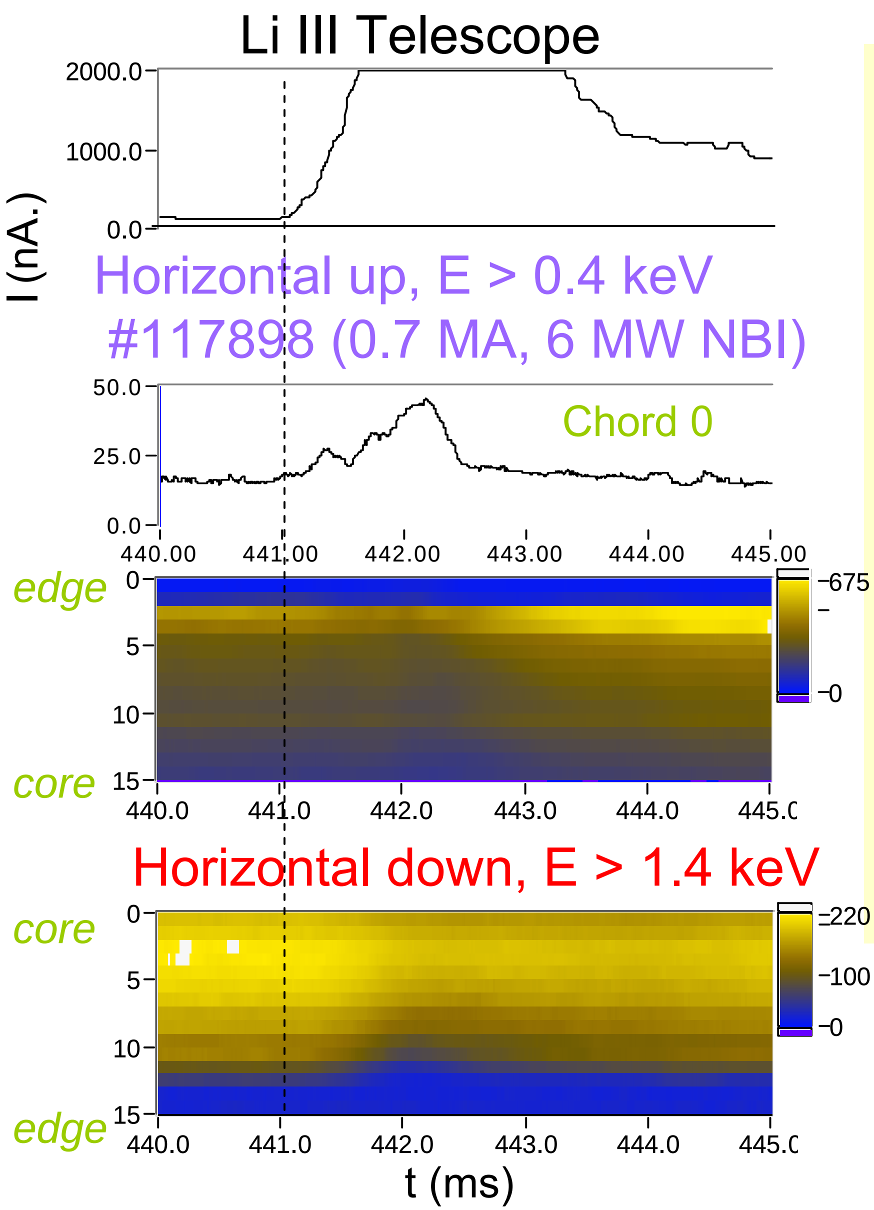
- Low energy (C VI Ly$_a$) SXR imaging also indicates pellet stops in the pedestal

Rapid SXR drop induced by the pellet



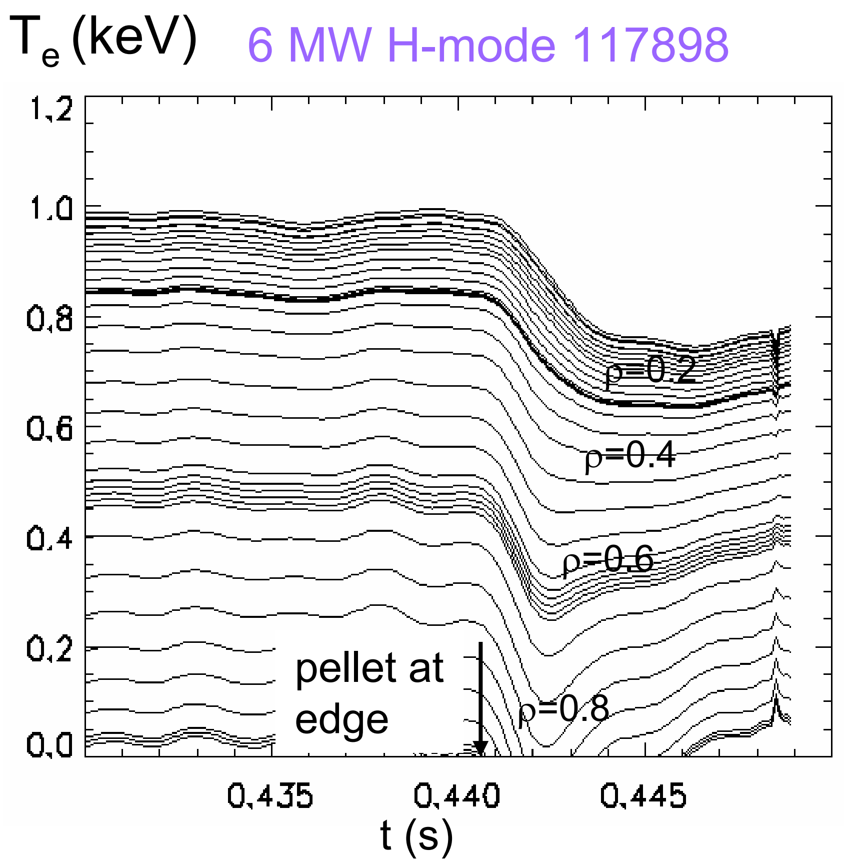
- Pedestal emission (E > 0.6 keV) drops then increases (δn_{Li})
- Rapid drop in E > 1.4 keV core emission
- Perturbation reached the core $\approx$ 1 ms after the pellet 'touches' the pedestal
- The pellet might have triggered an ELM ?

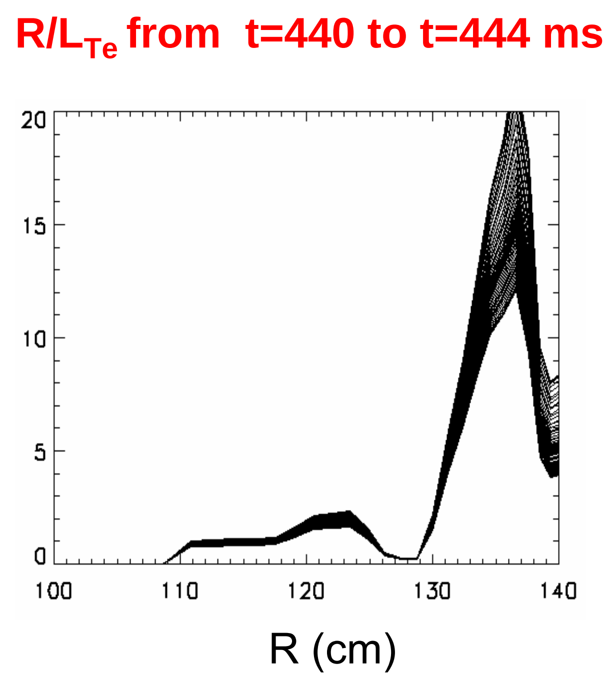
Perturbation is rapid also when no ELM suspected



- Slightly different picture seen in ‘small Type-I ELM’ discharge (see poster by K. Tritz)
- Pedestal emission only increases (likely δn_{Li})
- Clearly no ELM triggered in this case
- Still rapid drop in core emission

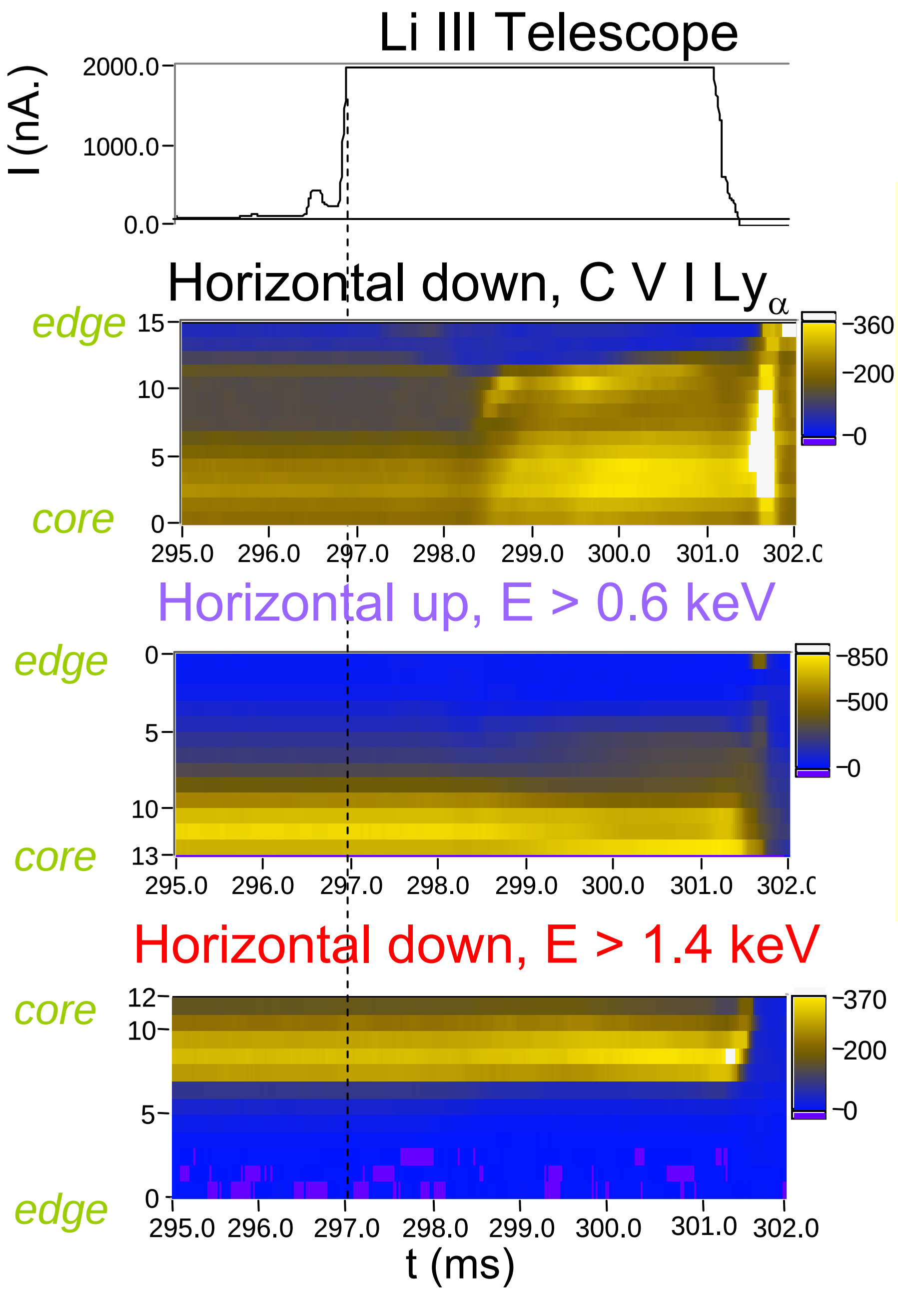
Preliminary analysis of perturbed T_e profiles





- SXR analysis less accurate due to high-Z contamination
- Perturbation picture nevertheless similar to that from Type-I ELM

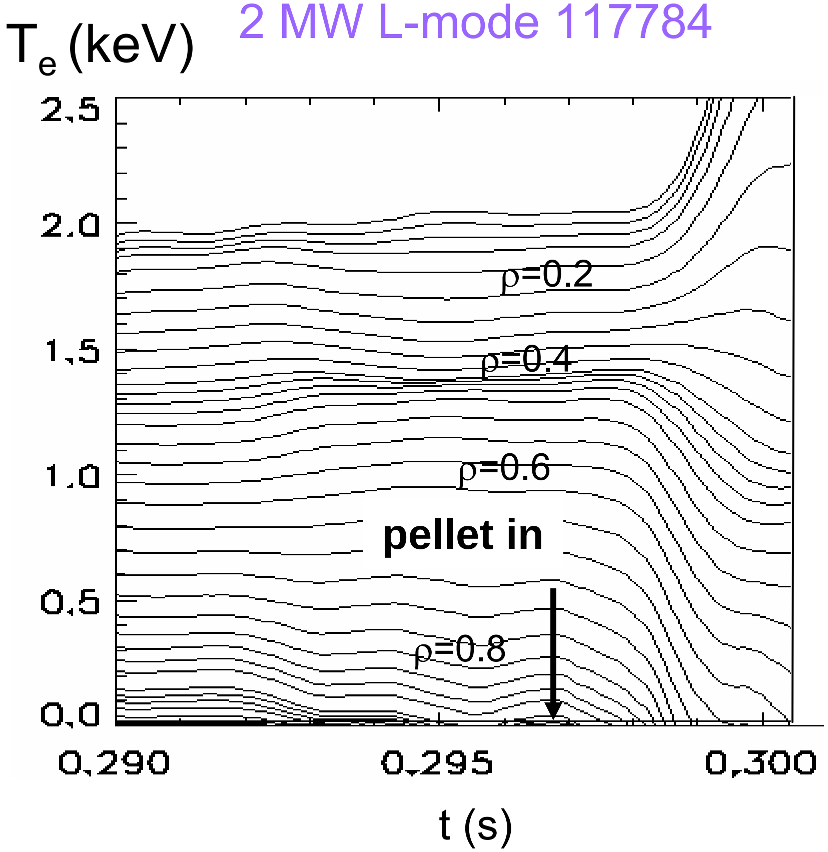
Strikingly different picture in low n_e 'L-mode'

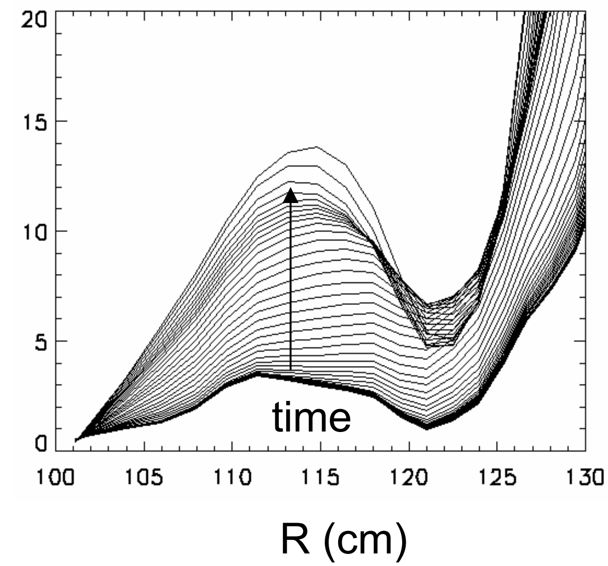


- C VI Lya image suggests deeper pellet penetration than in H-mode
- E>1.4 keV central emission lasts unperturbed several ms after pellet penetration
- Plasma collapse due rather to MHD than core cooling

Preliminary analysis shows large change in ∇T_e

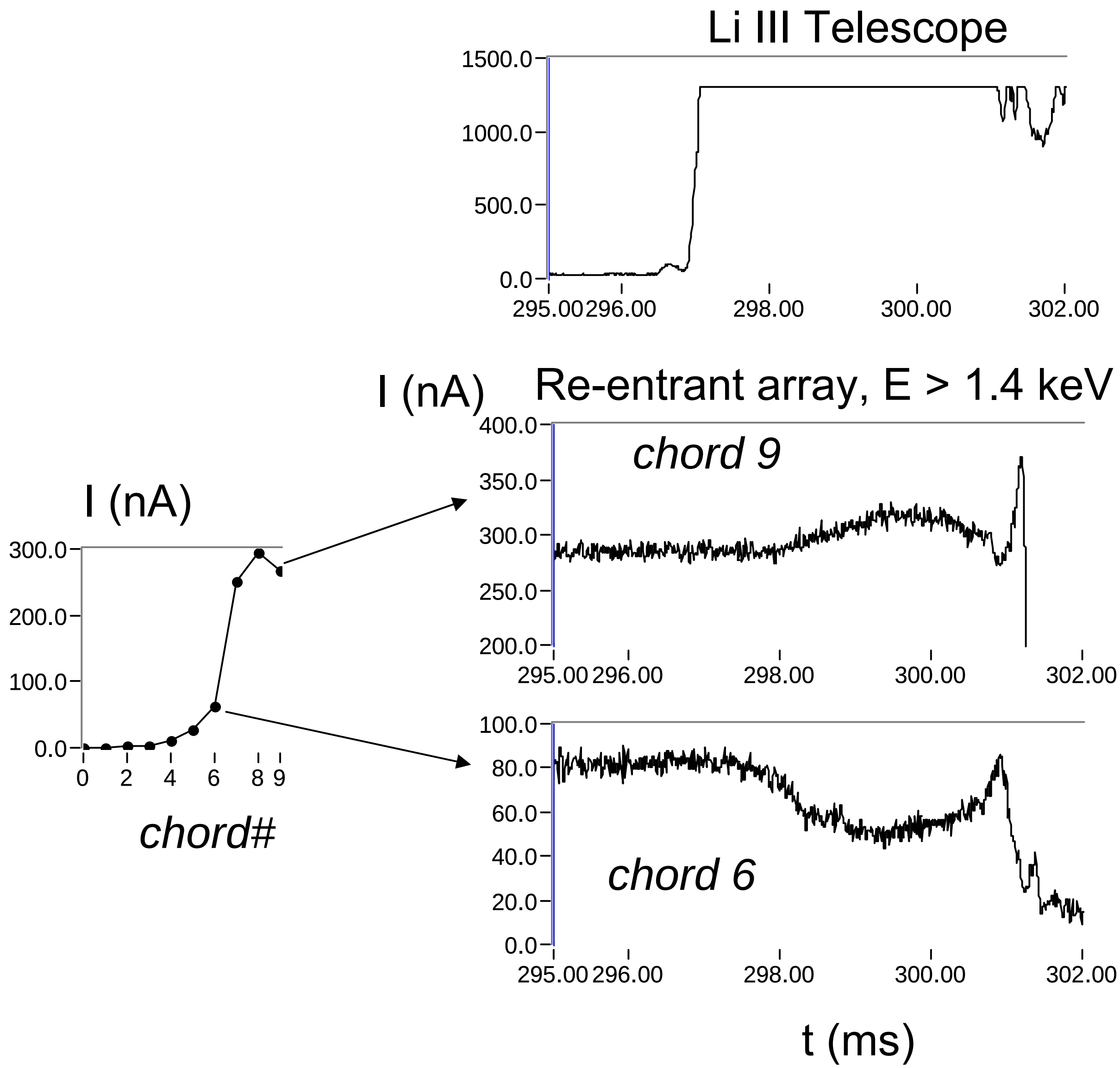
2 MW L-mode 117784



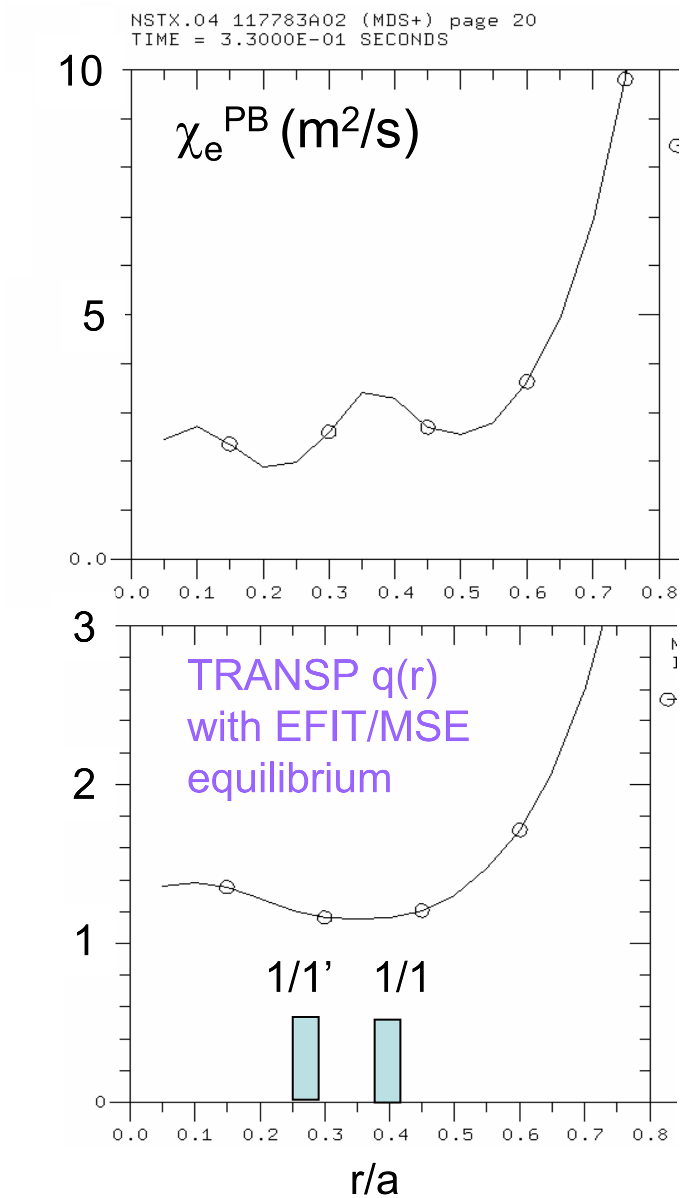


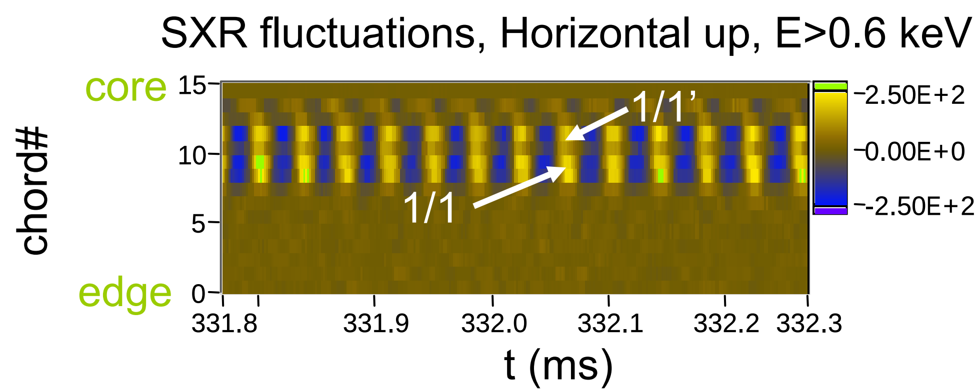
- T_e perturbation appears to change polarity inside r/a≈0.4 (q≈1) (reproducibility not yet verified)
- Large change in normalized T_e gradient ('non-stiff' profile)
- 'Cold pulse' polarity reversal often seen in tokamaks

T_e peaking evident in high energy SXR data



Low χ_e^{PB}, reversed q-profile in low n_e ‘L-modes’

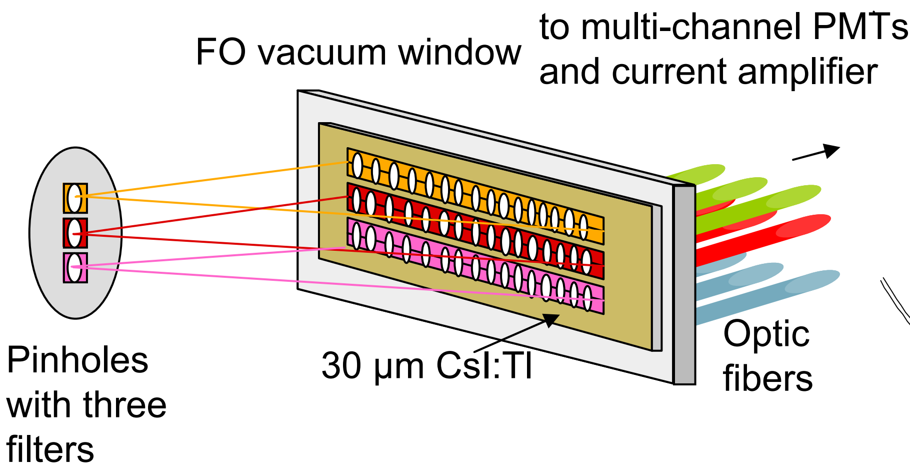


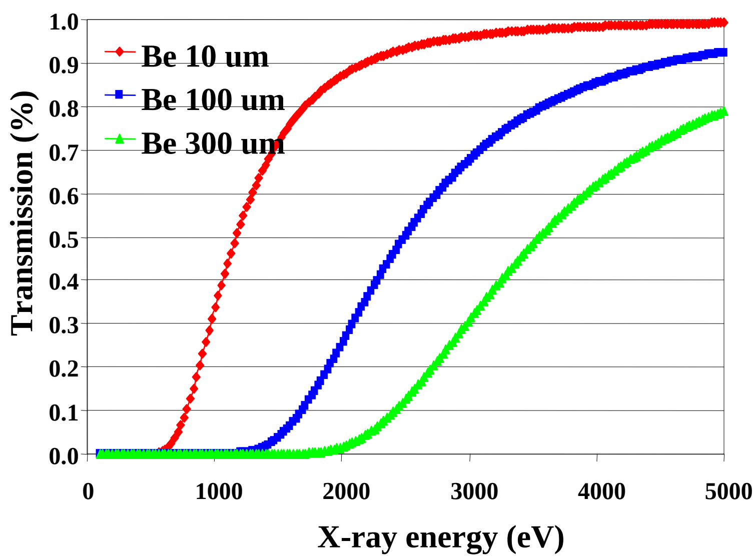


- SXR data also indicates shear reversal (two m=1/n=1 modes)

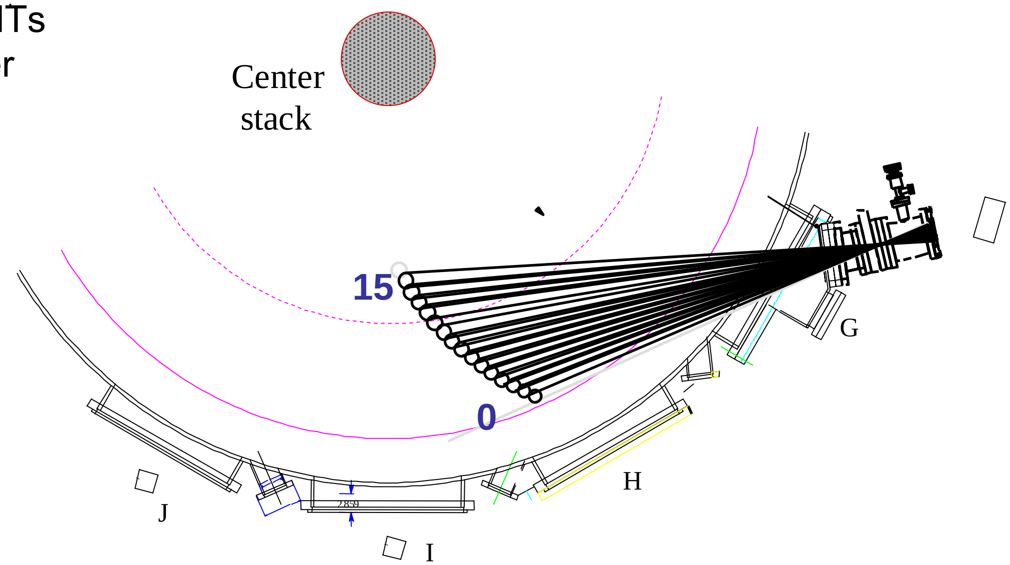
New fast $T_e(r)$ diagnostic prototyped this run (poster by L. Delgado)

Three-color optical SXR (OSXR) array

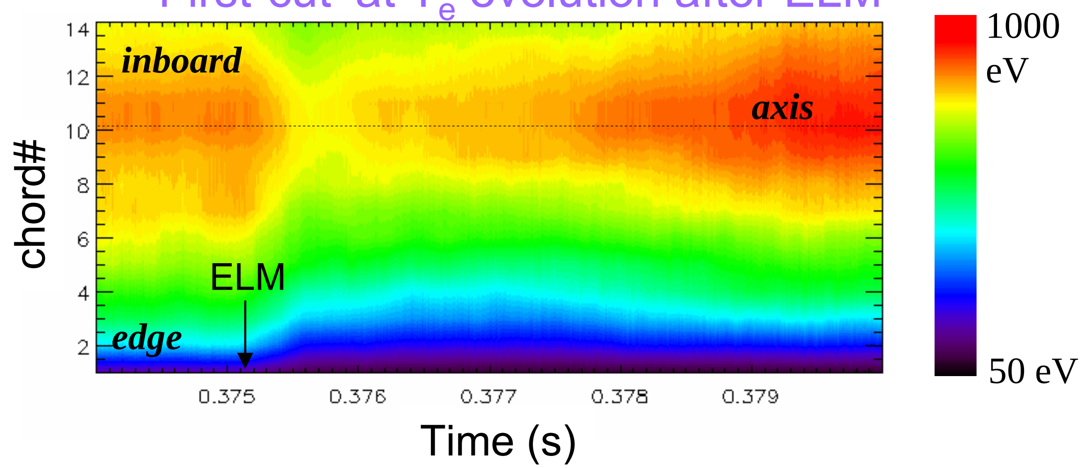




Prototype NSTX tangential system



'First-cut' at T_e evolution after ELM



Conclusions

• The ‘multi-color’ SXR technique can provide fast T_e measurements in the ST

• Low velocity Li pellets are good tools for perturbative transport in NSTX

• The comparison between the ELM and pellet perturbation strongly suggests the T_e crash seen at ELMs is an electron transport rather than a MHD effect; *is the Type-I ELM more of an electron transport phenomenon than believed* ?

• Very fast cold pulse propagation in the high n_e NSTX H-mode; *are electromagnetic instabilities (e.g., micro-tearing) at play ?*

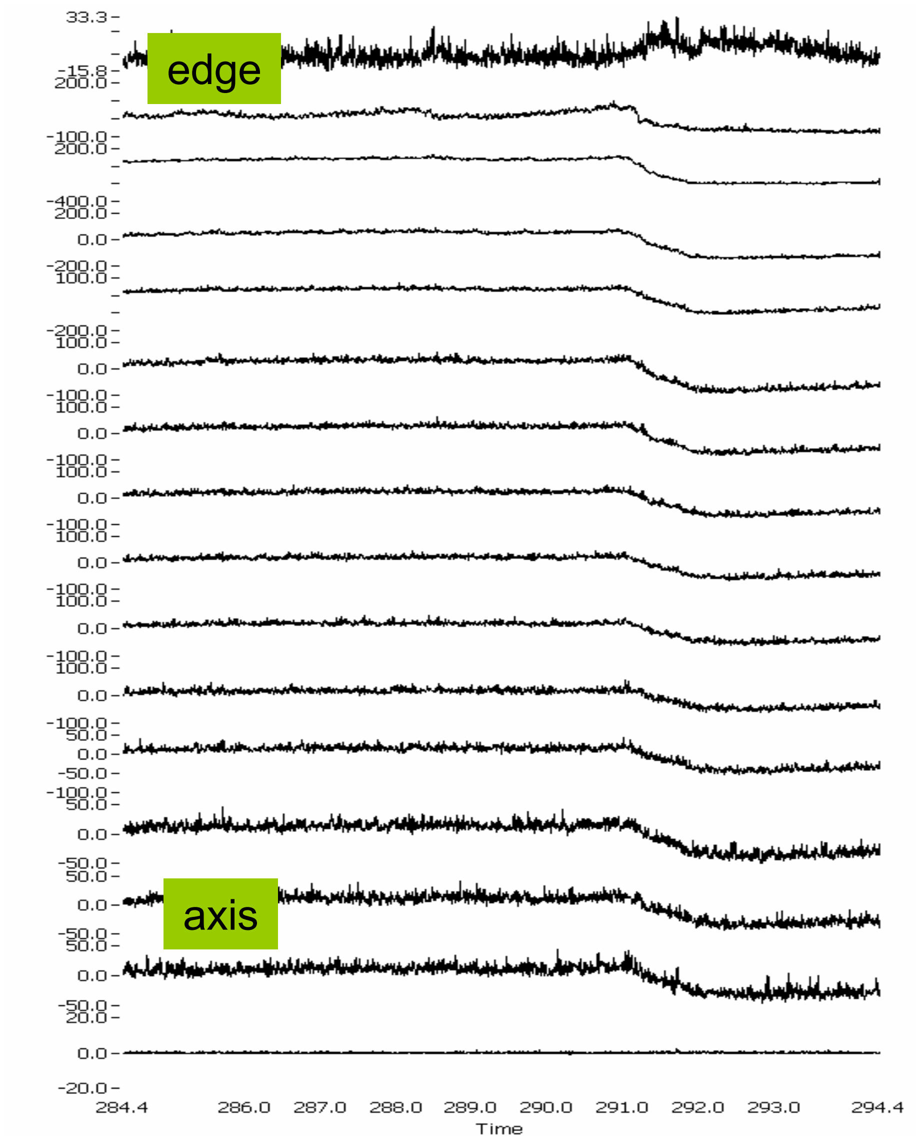
• The large difference between core electron transport in the high n_e H-mode and the low n_e L-mode appears to carry over also in the perturbed transport

• Correlations between perturbative electron transport and high-k fluctuations possible at NSTX might provide interesting clues

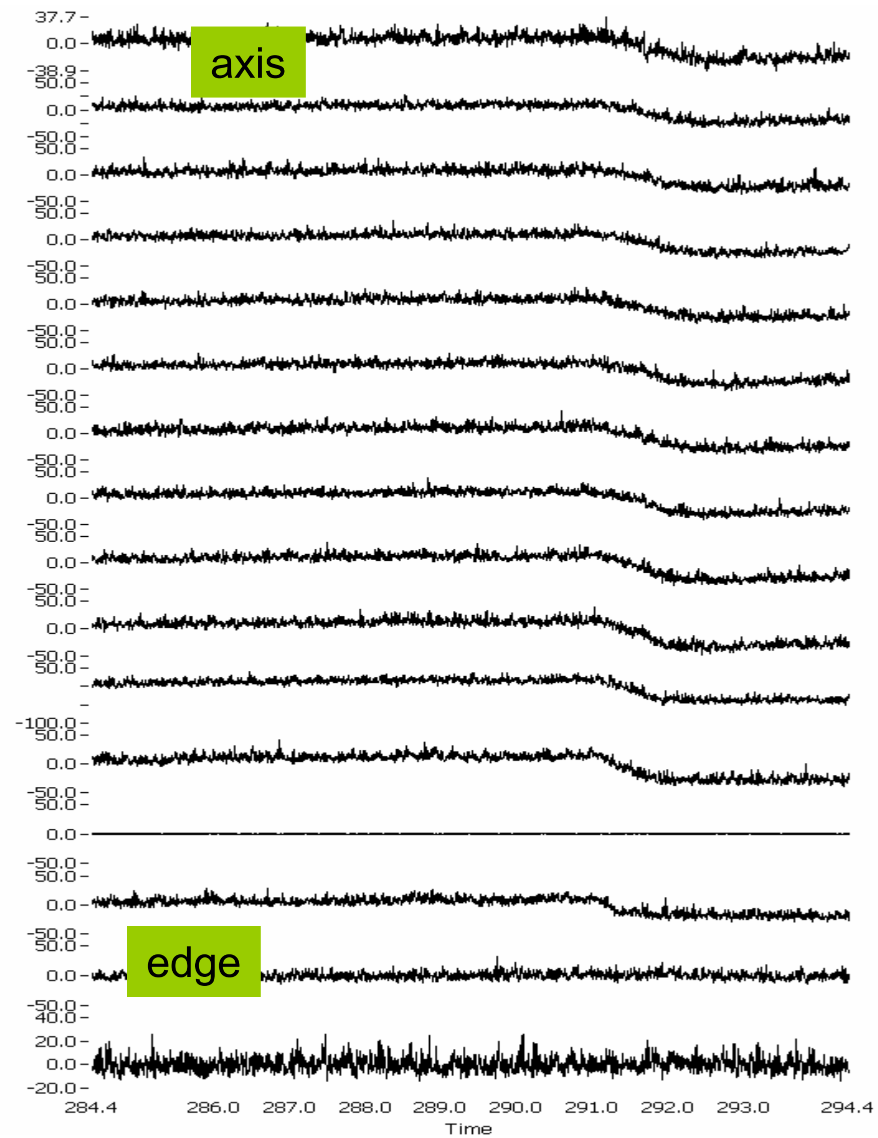
Sign-up sheet

Raw SXR data during Type-I ELM

Hor. Up E > 0.6 keV



Hor. Down E > 1.4 keV



- ELM MHD signature limited to edge -> SXR crash is transport effect