Investigation of the relationship between ELM energy loss and perturbed electron transport on NSTX

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Motivation

NSTX has observed a high-power H-mode regime in which large Type I ELMs result in a fast moving cold-pulse perturbation causing a global decrease in the electron temperature profile and a loss of total plasma stored energy of ~15-30%.

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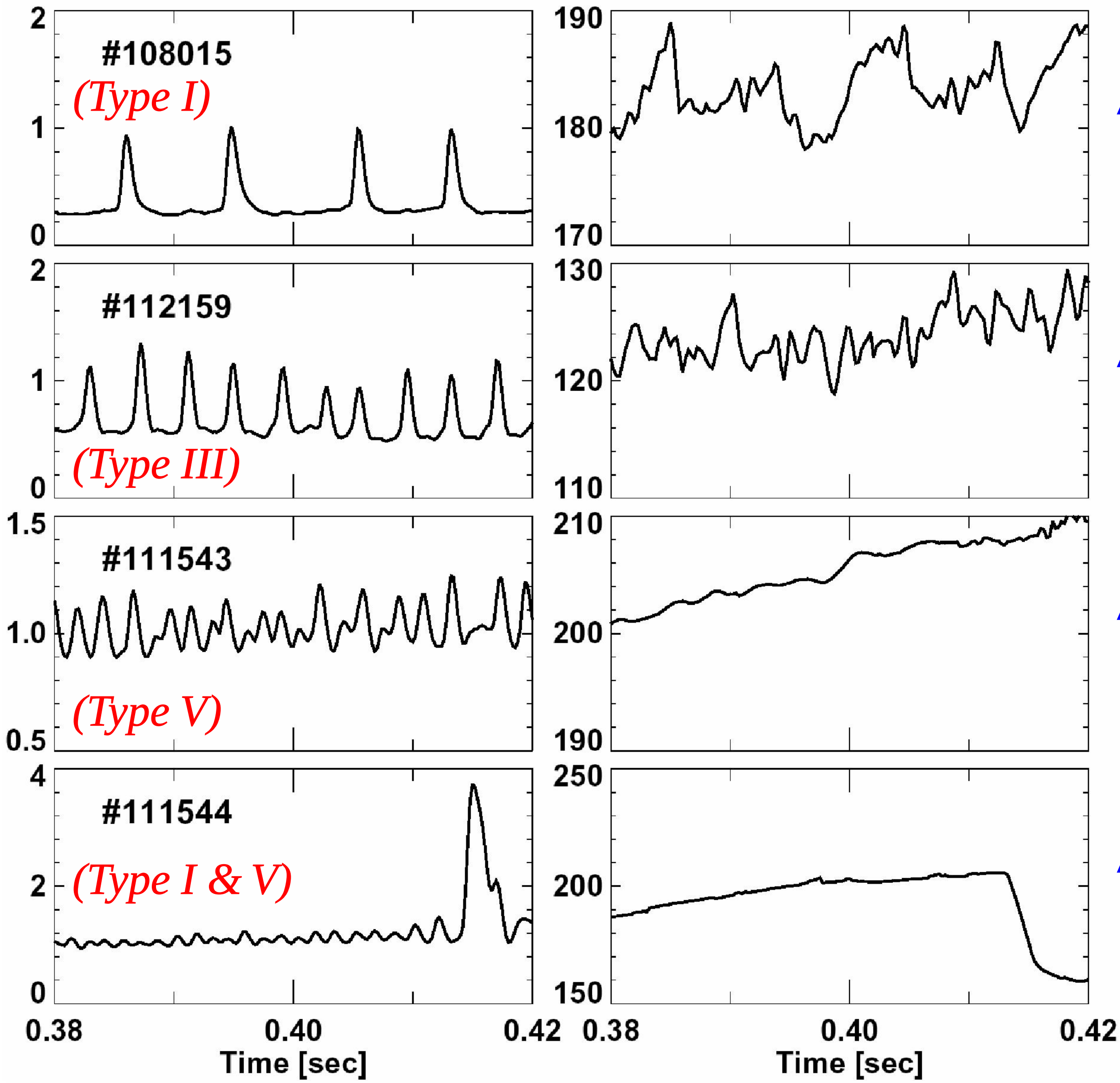
NSTX

Abstract

The National Spherical Torus Experiment (NSTX) experiences a range of edge localized mode (ELM) behavior during different regimes of H-mode operation. While many of the ELM types demonstrate similar characteristics to those observed in other devices, at low collisionality $(\nu_*^e \leq 1)$ large Type I ELMs can occur that cause a significant reduction in plasma total stored energy, $\Delta W_{tot}/W_{tot}$~15-30%. This energy loss from the plasma is primarily due to a loss of electron thermal energy, evidenced by a global drop in the electron temperature profile as measured by a multipoint Thomson scattering system (MPTS), and is considerably larger than the proportional energy loss observed during Type I ELMs in other tokamak devices. Additionally, this energy loss is not accompanied by any large scale MHD activity. Though the MPTS system can provide detailed profile "snapshots" before and during an ELM, the Ultra Soft X-ray (USXR) system can provide continuous, spatially resolved measurements that are also sensitive to the electron temperature and density with time resolution of a few microseconds. Because the stored energy loss from these perturbations is primarily through the electron thermal channel, *a relationship between the electron thermal transport, and more specifically, the perturbed electron thermal transport, and the severity of the event as measured by the total plasma stored energy loss, $\Delta W_{tot}/W_{tot}$, is suggested*.

NSTX Observes Various ELM Types

D_α (arb.units) W_{MHD} (kJ)



$\Delta W_{MHD}/W_{MHD} \sim$ 3-15%

$P_{heat} >> P_{L\text{-}H}$

$\Delta W_{MHD}/W_{MHD} \sim$ 1-5%

$P_{heat} \geq P_{L\text{-}H}$

$\Delta W_{MHD}/W_{MHD} \leq$ 1%

Wide P_{heat} range

$\Delta W_{MHD}/W_{MHD} \leq$ 30%

High P_{heat} β_N

Maingi, *Nucl. Fusion* **45** (2005)

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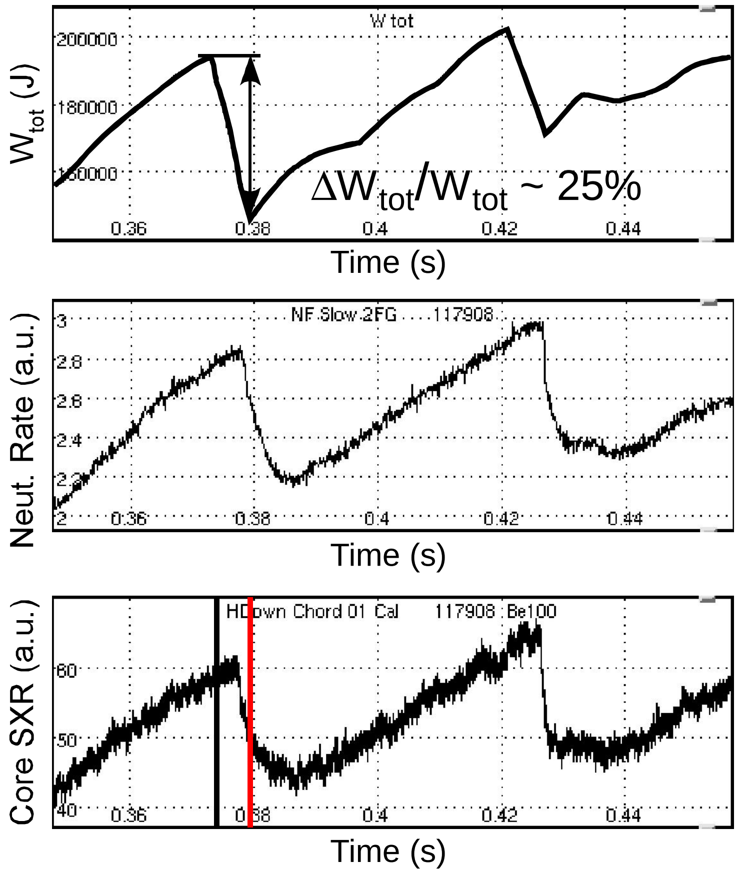
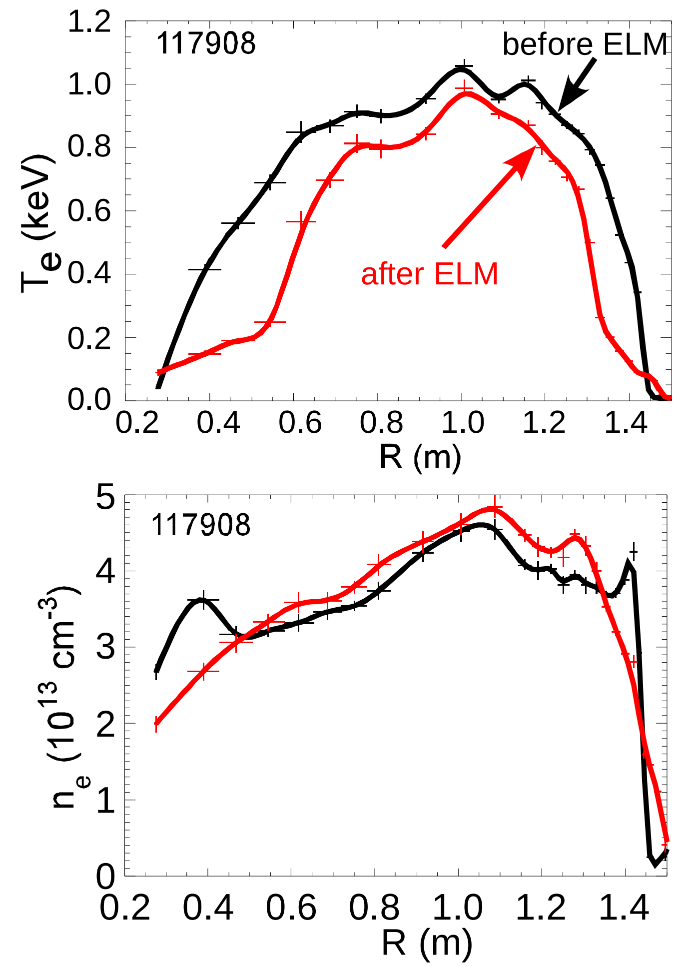
What Causes Type I ELM Variability?

- Type I ELMs can cause a range of energy loss from ~3-5% to >20%
  - Large energy loss corresponds with global drop of T_e profile
- Global T_e perturbation follows ELM event, related to transport not MHD
  - Only small precursors observed on Mirnovs regardless of ELM size
  - No large MHD modes seen on SXR arrays
  - Time scales of profile perturbation ~100's of msec
  - No corresponding global perturbation of n_e profile
  - Controlled edge perturbations using pellets show same perturbation behavior
- Is there a relationship between the severity of the ELM and electron transport?
  - Varying rates of cold pulse propagation related to stored energy loss
  - Stability calculations indicate different growth rates at short wavelengths
  - High-k measurements show increased fluctuation levels during cold pulse

'Giant' Type I ELMs Cause Fast Cold Pulse Perturbation

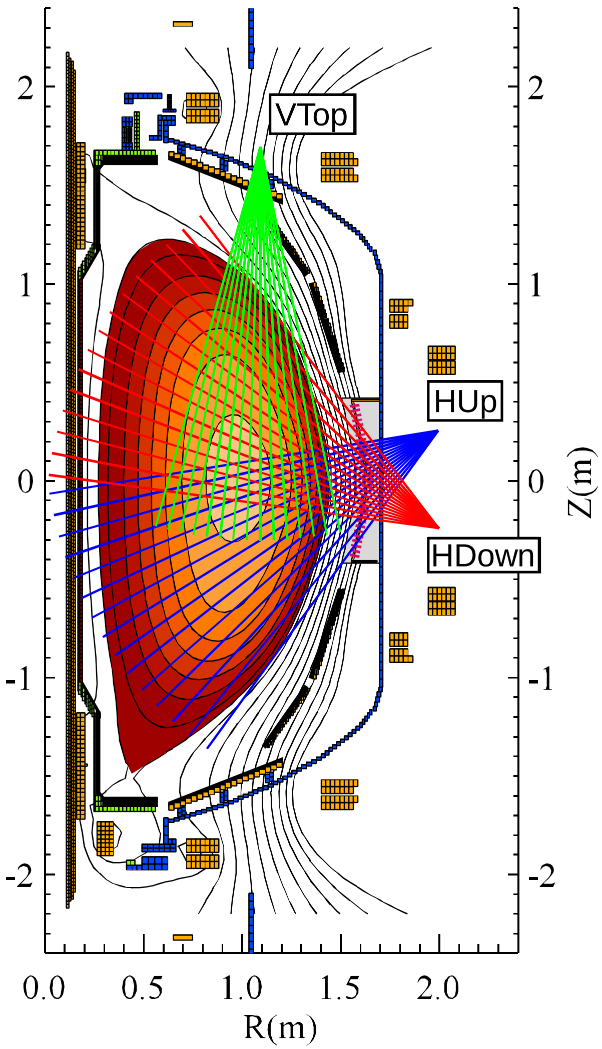




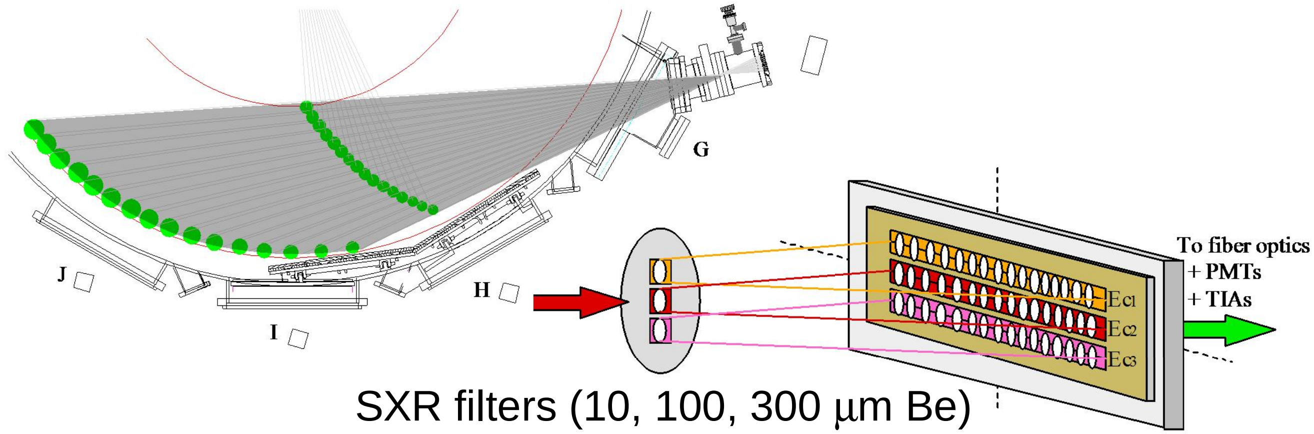
- Perturbation has large effect on W_{tot} and T_e profile
- n_e global profile relatively unchanged
- Ultra Soft X-ray system tracks T_e perturbation on few μsec timescale

Multicolor SXR Diagnostic for Fast T_e Measurements

Poloidal USXR Array



Multicolor Tangential Optical Soft X-ray Array



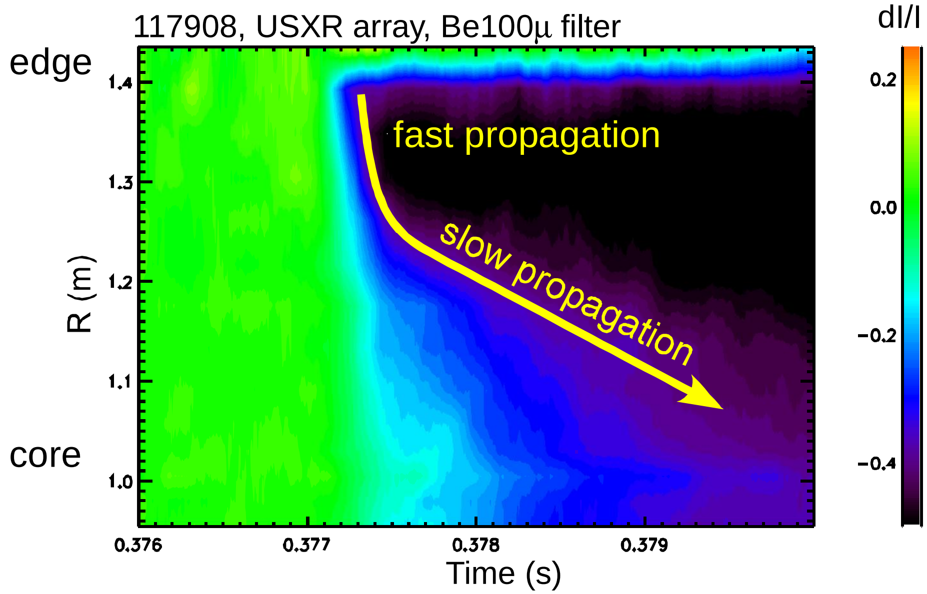
SXR filters (10, 100, 300 μm Be)

$\text{Energy}_{\text{cutoff}}$ (0.6, 1.6, 2.4 keV)

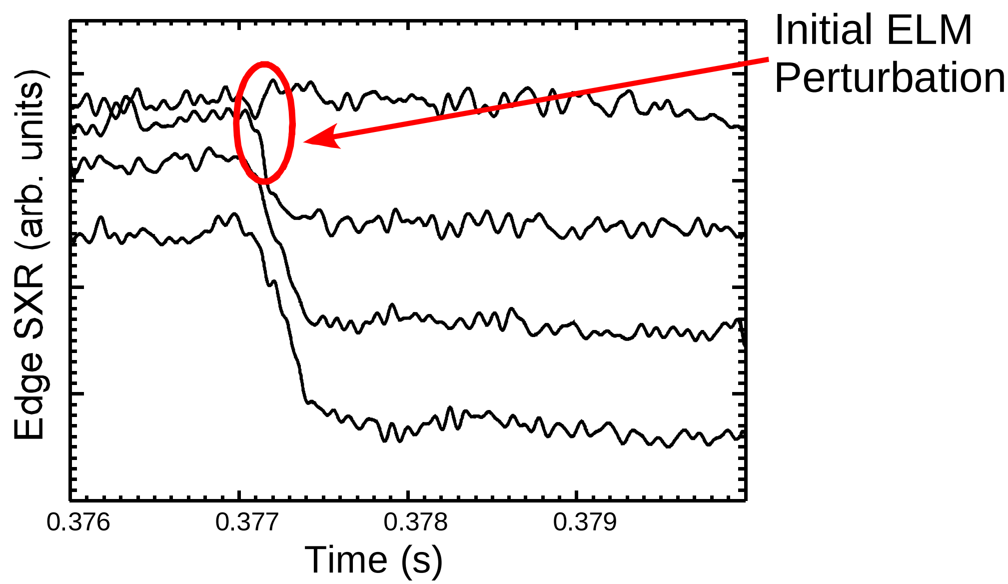
- "Multicolor" filter set simultaneously samples same plasma volume
- Time propagation of normalized Thomson profiles extracts fast T_e information from SXR
- Poloidal system improves edge spatial coverage

SXR Data Follows Rapid Cold Pulse Propagation

Relative change of SXR signal



Edge USXR Intensity



- T_e crash propagates from edge to core (~1m in 2ms)
- Initial ELM MHD mode causes prompt (few 10's μs) drop at edge
- First phase of cold pulse reaches mid-radius ~few 100μs
- Propagation slows as it reaches magnetic axis
- Modeling used to estimate perturbed electron thermal transport

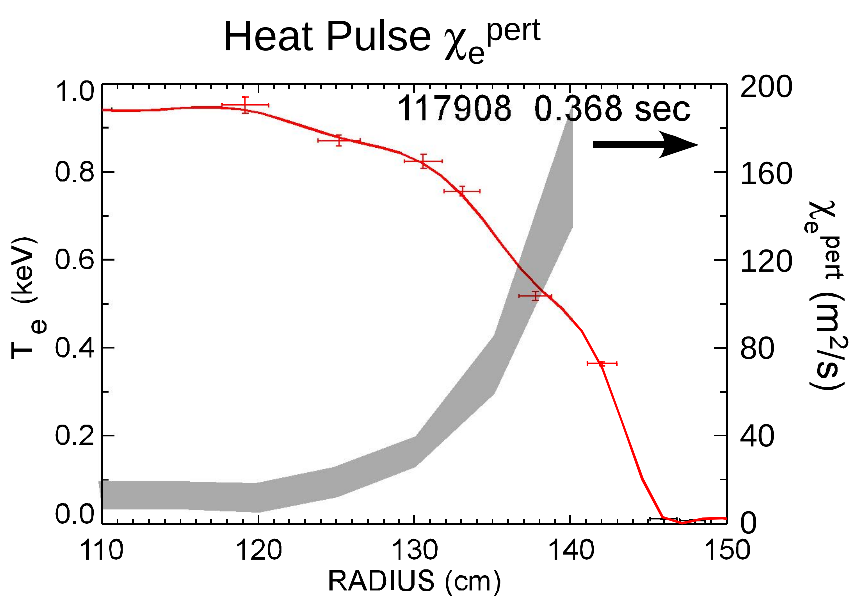
Sawtooth Model Used to Calculate χ_e^{pert}

$$\chi_e^{pert} \approx \frac{\Delta r_{eff}^2}{8\Delta t_{peak}}$$

$$\Delta r_{eff}^2 \approx 4\Delta r^2$$

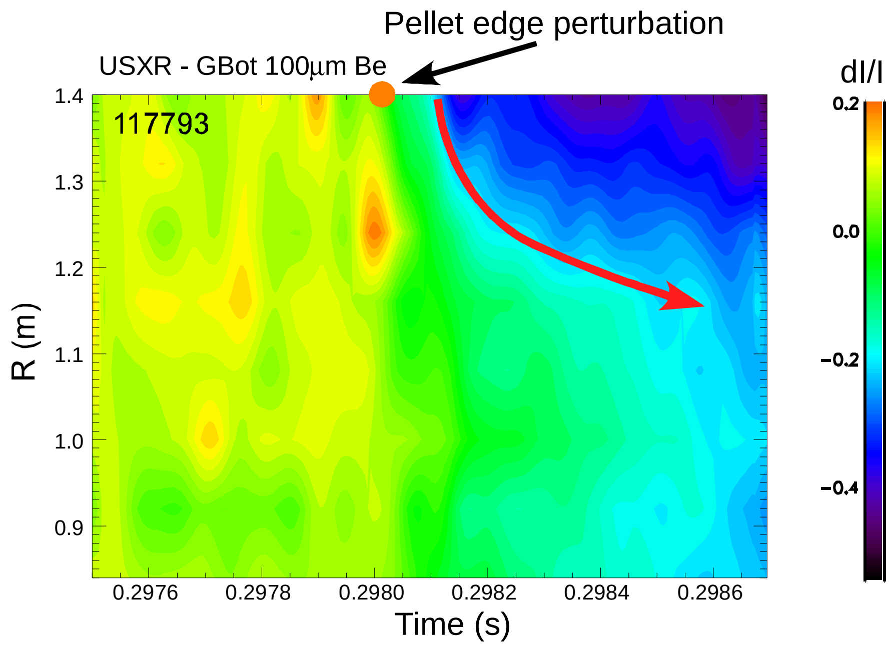
- Model uses TTP (time-to-peak) and radial extent of cold pulse peak
- High elongation and Shafranov shift modifies "effective" radial position of perturbation

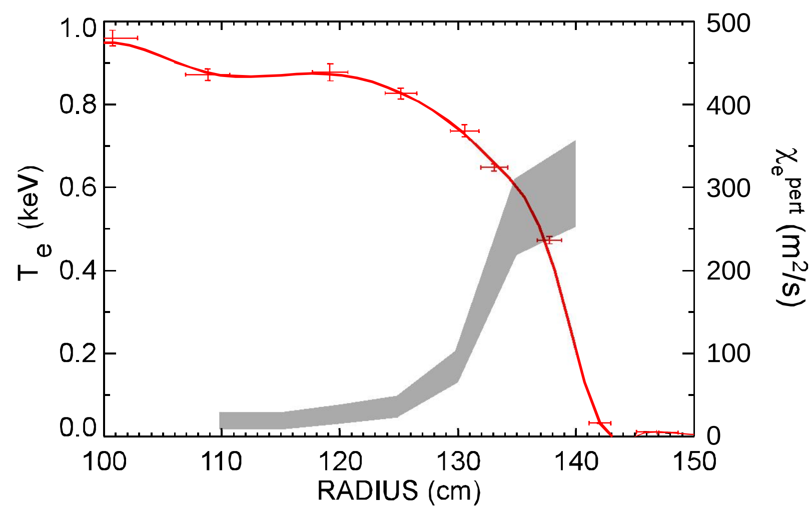
(M. Soler, J.D. Callen, *Nucl. Fusion* **19** 1979)

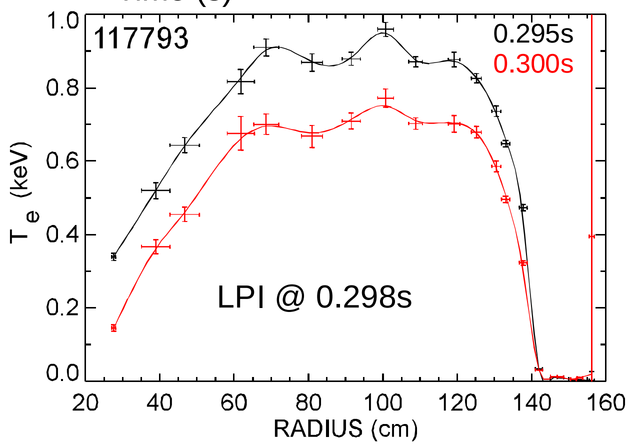


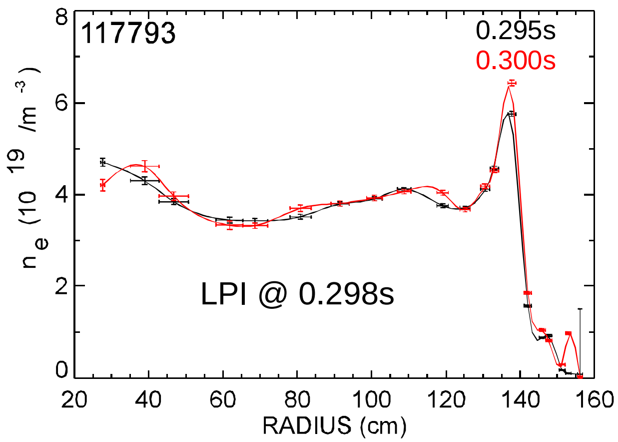
- Calculations show perturbed transport high in edge T_e gradient region
- χ_e^{pert} in core ~10-20 m^2/s
- $\chi_e^{pert} \propto \nabla T_e$ suggests "avalanche" transport processes

Lithium Pellet Perturbation Similar to Type I ELM



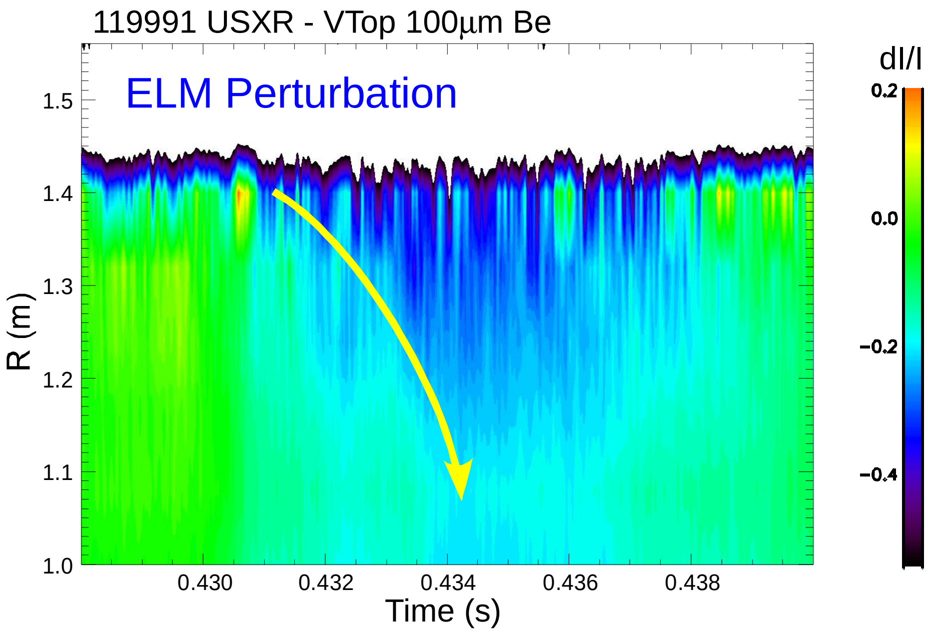


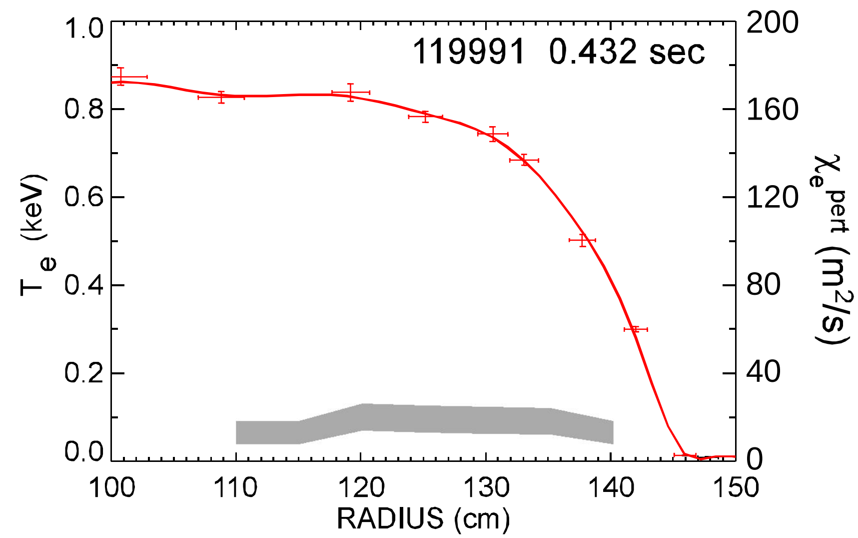


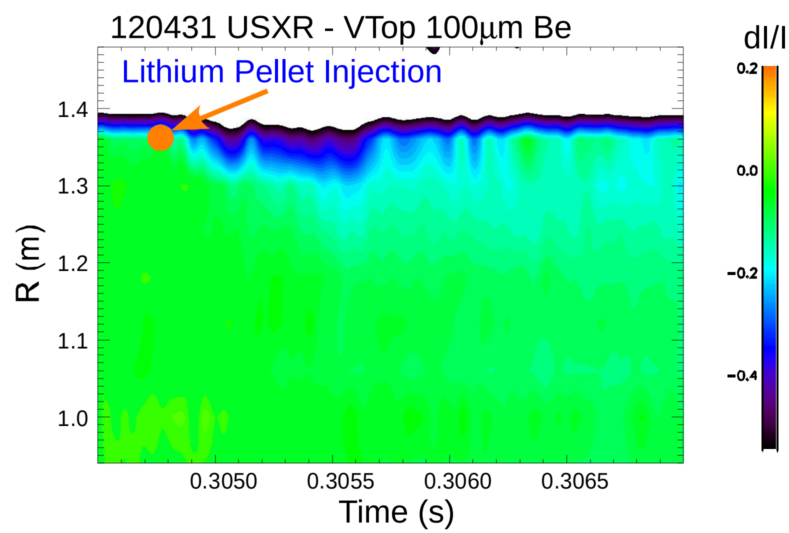


- Pellet perturbations not ELMs (no edge n_e loss, no MHD precursors)
- Pellets used to probe χ_e^{pert} with controlled, small edge perturbation
- Plasma energy loss appears related to perturbed electron transport

High-δ DND Plasmas Show Reduced ELM Severity



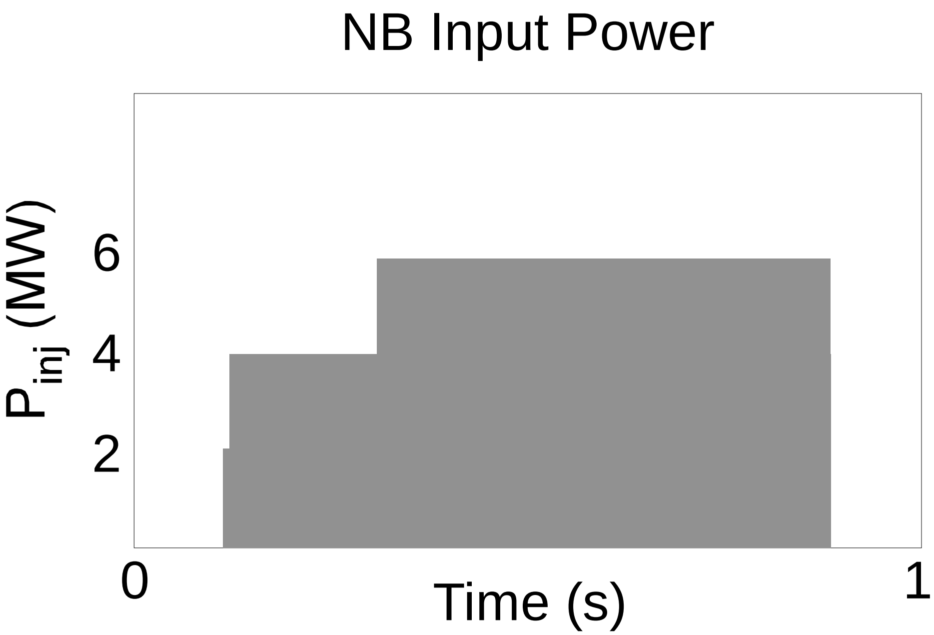


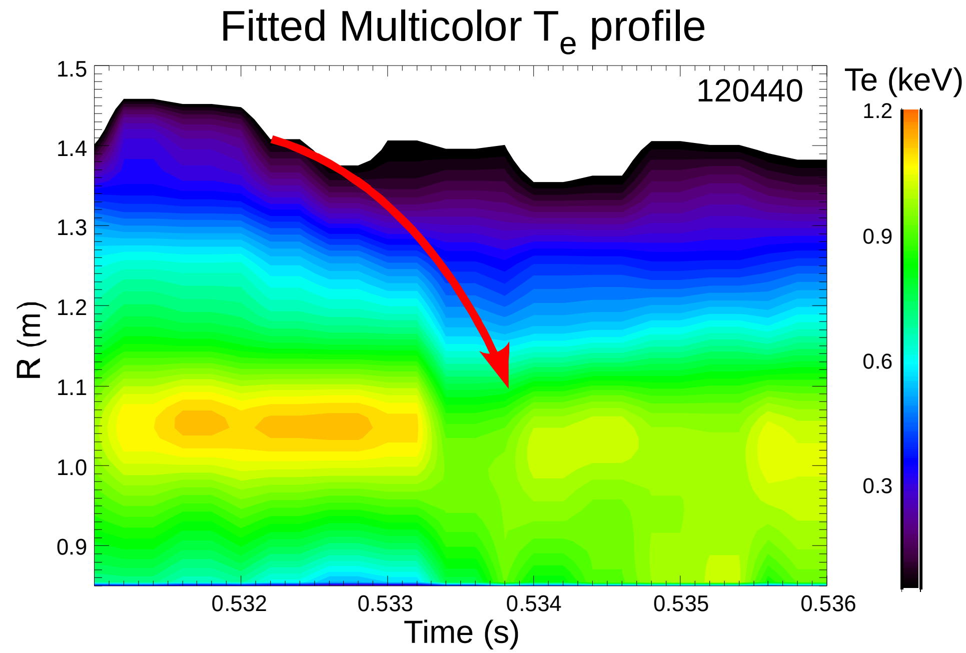


- $\Delta W_{tot}/W_{tot}$ ~3-5%
- No fast edge propagation
- χ_e^{pert} ~10's m²/s across T_e profile
- Pellet injection has reduced perturbation

- ELM severity reduced when perturbed electron transport is reduced

χ_e^{pert} and ELM Severity Also Change During NB Power Scan

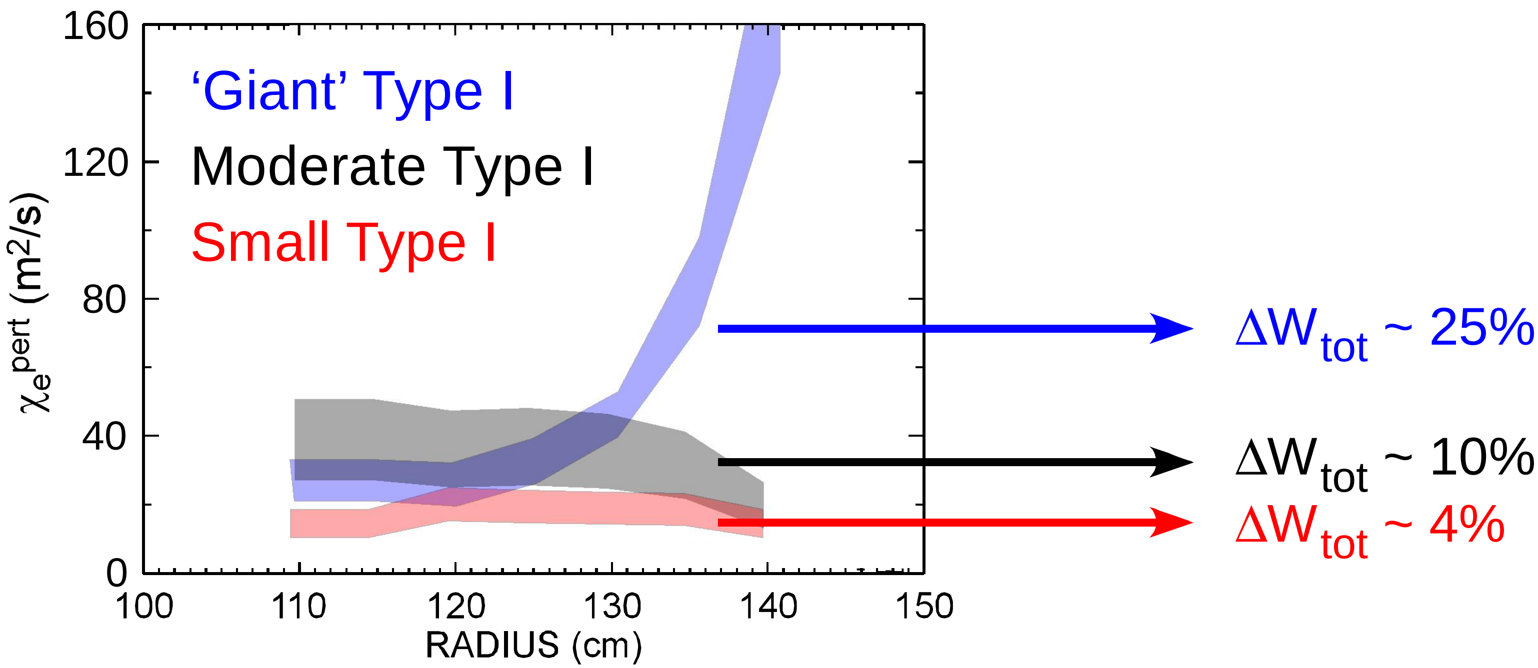




- P_{NB}, q-profile scan used to vary χ_e^{pert} (see D. Stutman P2.061)
- Both pellet injection and ELMs show differences in perturbations
- Shots with moderate ELMs ($\Delta W_{tot}/W_{tot}$) have intermediate cold pulse propagation times
- Modeling calculates χ_e^{pert} ~20-40 m^2/s over plasma profile

$\Delta W_{tot}/W_{tot}$ Appears Roughly Proportional to χ_e^{pert}

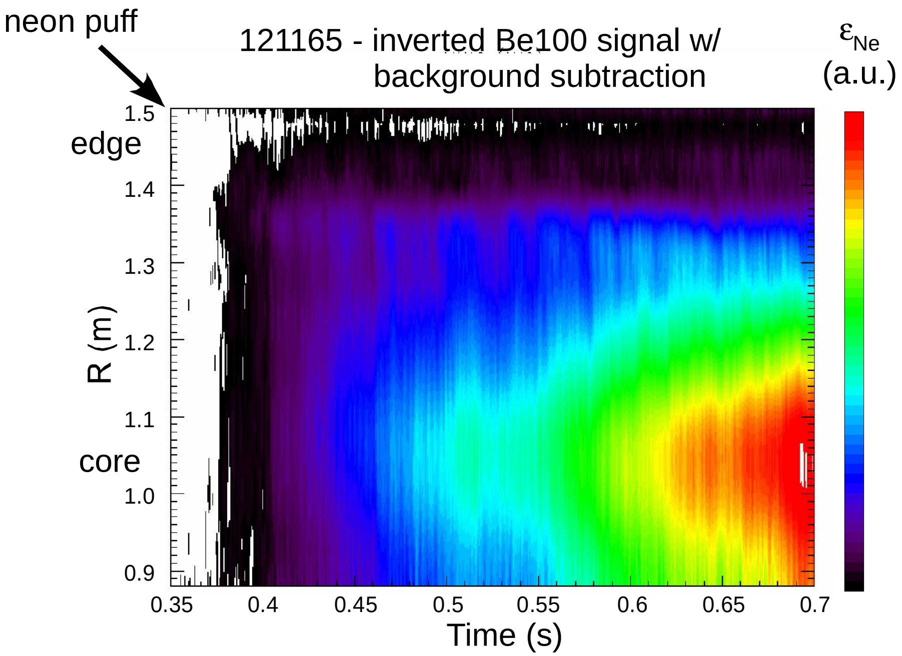
Comparison of ELM severity



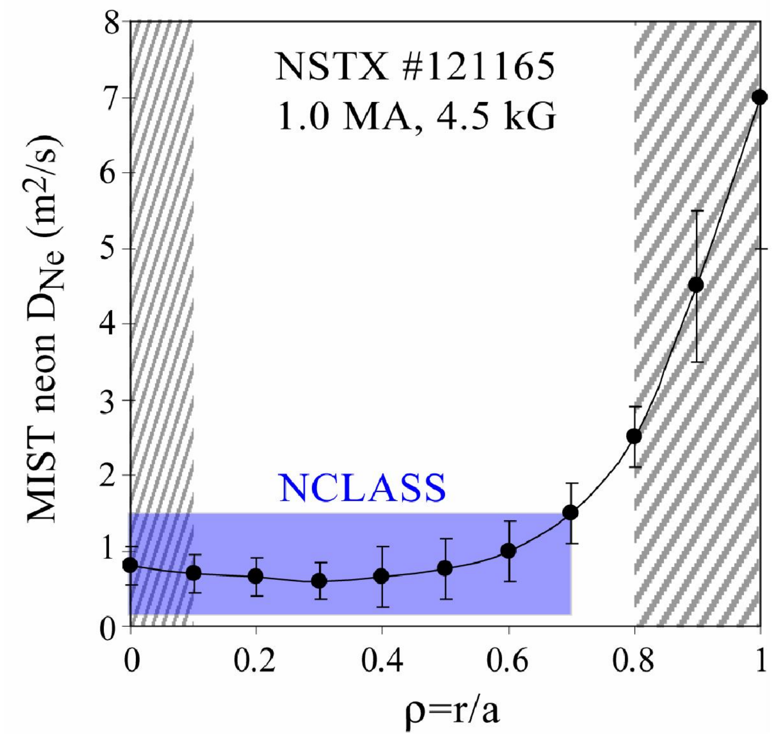
- Supports hypothesis relating ELM severity to perturbed electron transport
- Important when optimizing ELM for particle control vs. heat exhaust
  - What does this mean for ITER?

Impurity Transport Much Lower Than Electron Thermal Transport

SXR Neon Emissivity



Ne diffusion over 100's of ms

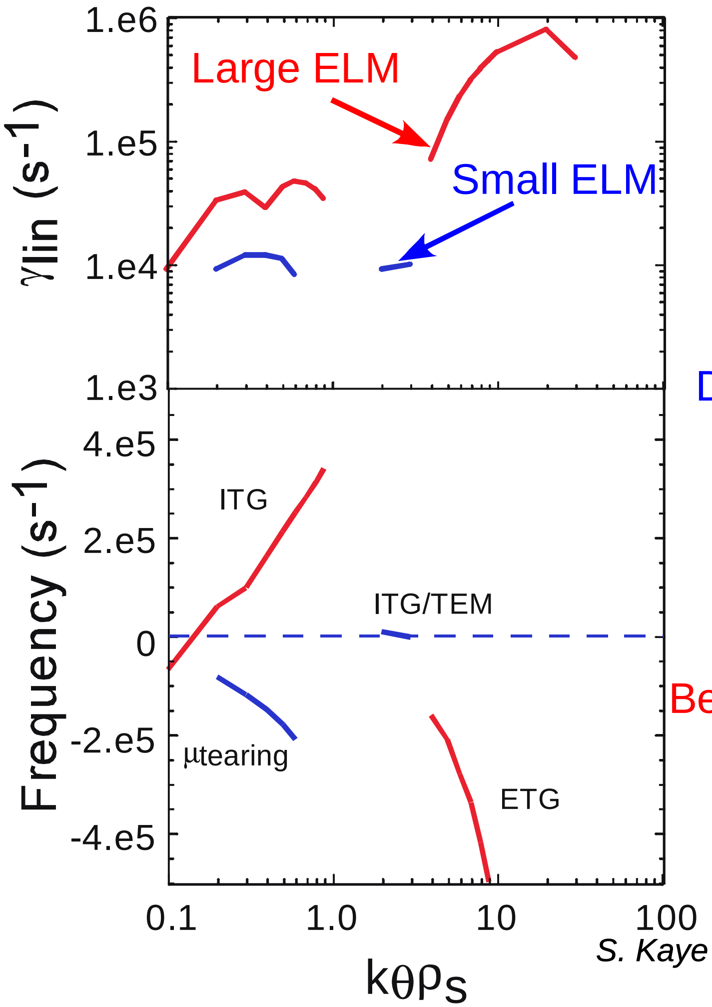


- D_{Ne} in the neoclassical range (*see P02.050 - L. Delgado-Aparicio*)
- χ_e^{pert} >> D_{Ne} suggests suppression of low-k turbulence
- Energy loss possibly related to high-k and/or magnetic transport

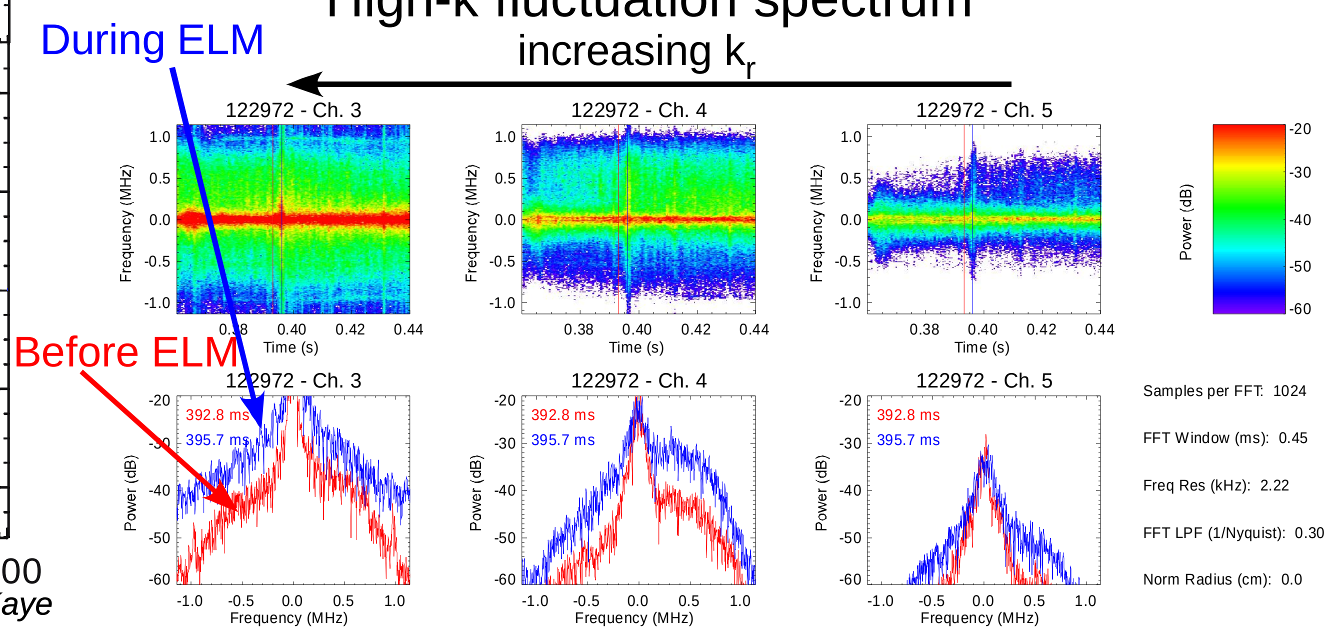
GS2 Calculations Indicate Difference in Growth Rates

- Discharge with large ELM severity shows large ITG/ETG growth rates during perturbation
- ‘Small’ Type I ELMs have little µtearing, no ETG instability

GS2 Linear Calculations



High-k fluctuation spectrum

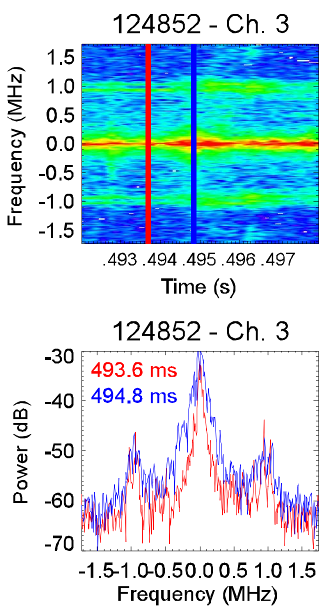


- During ELM cold pulse propagation high-k measurements show increased fluctuations at short wavelengths $k_r \sim 14\text{-}16\ cm^{-1}$

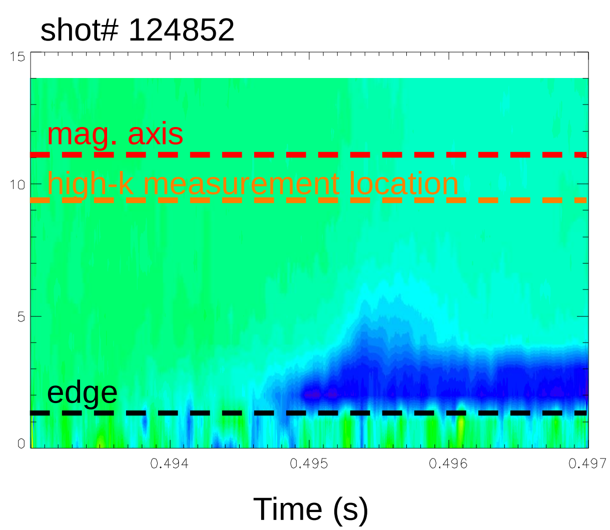
USXR and High-k Show Differences with ELM Severity

- Microwave scattering system measures burst of short wavelength activity at ELM
- Higher severity ELM shows faster cold pulse and increased high-k fluctuations during propagation

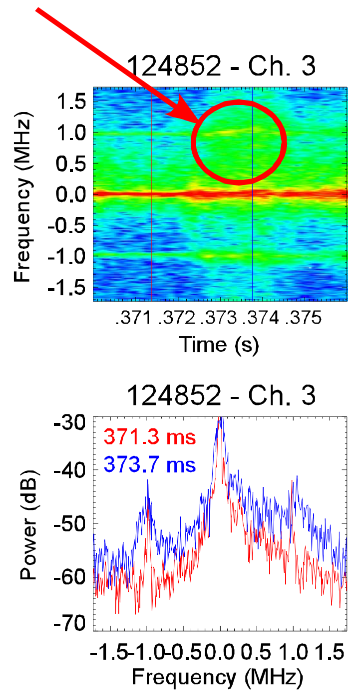
increased high-k activity during cold pulse



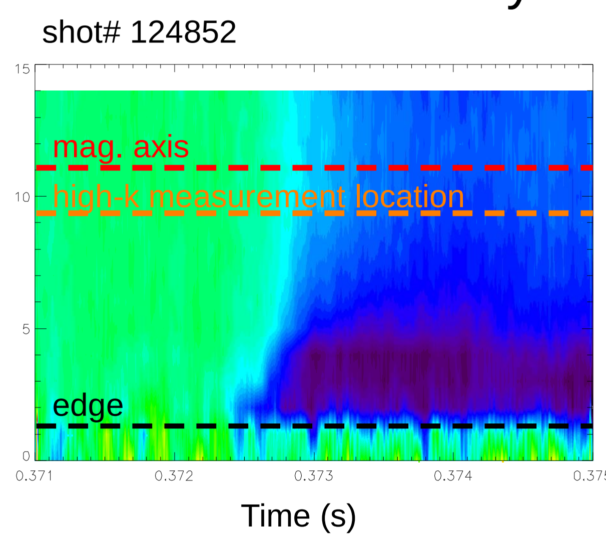
rel. USXR Intensity



$\Delta W_{tot}/W_{tot}$ ~ 6-8%



rel. USXR Intensity



$\Delta W_{tot}/W_{tot}$ ~ 16-20%

Summary

- "Multicolor" USXR technique enables investigation of perturbed transport with good spatial and temporal resolution

- Type I ELM severity appears related to perturbed electron thermal transport:

  i) 'Giant' Type I ELMs have strong χ_e^{pert} at r/a > 0.5

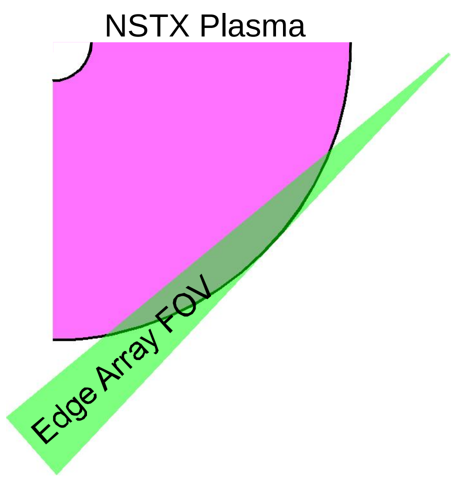
  ii) Pellet injection has the same perturbative effect in the same plasmas

  iii) χ_e^{pert} and $\Delta W_{tot}/W_{tot}$ seem to directly correlate

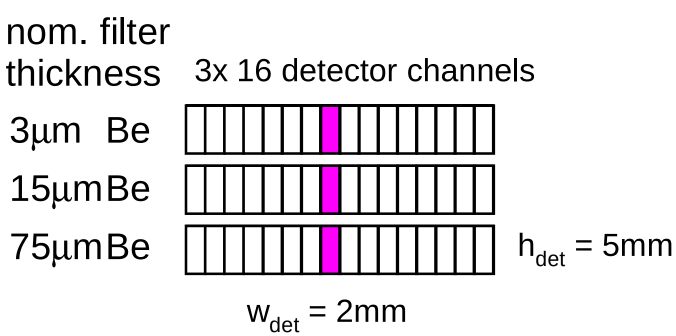
- $D_{Ne} << \chi_e^{pert}$ suggests high-k or magnetic turbulence may be involved

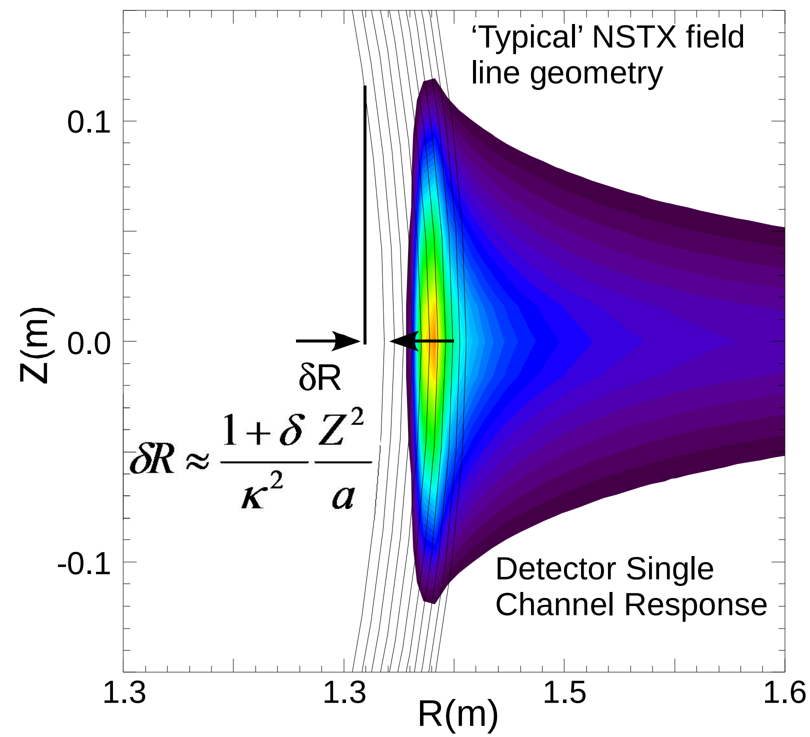
- GS2 linear calculations and high-k measurements indicate short wavelength fluctuations may be important during ELM perturbation

Edge SXR Array Planned for High Resolution Edge T_e



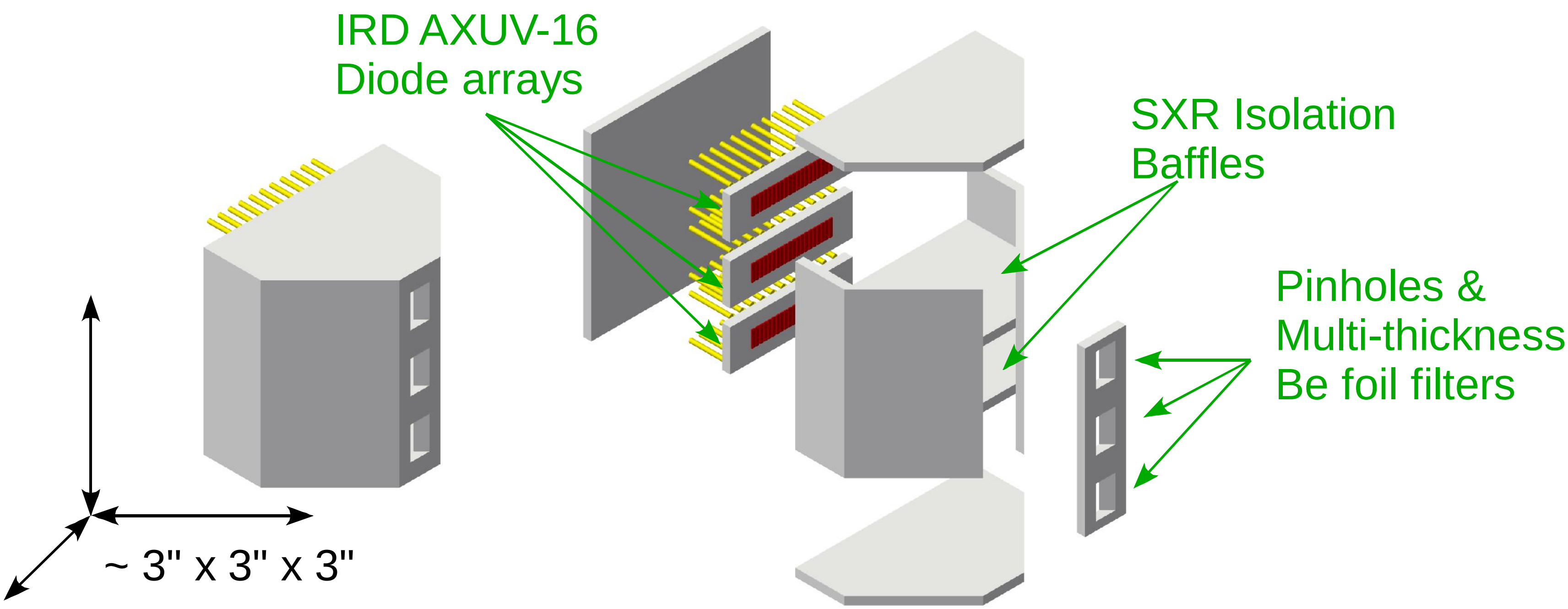
- Multi-color edge array designed for tangential view of plasma edge ~135-150cm
- Pixels are rectangular for high radial spatial resolution and increased throughput
- Spatial resolution ~1cm desired to resolve edge gradients





- Field curvature can "smear" radial resolution ~δR if 3-D response not evaluated

Compact, Modular Design Increases Flexibility



- Thick copper shell eliminates electrostatic and dB/dt pickup
- Compact design allows for in-vessel placement
- Close-packed, multicolor arrays provide high-resolution, fast T_e profiles