Characterization of ELMs and their Effects on NSTX using Multi-color Ultrasoft X-ray Imaging

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Abstract

A variety of ELM phenomena is observed in NSTX, ranging from large "Type I" to less perturbative "Type III" and the recently identified "Type V". The effects these ELMs have on the plasma temperature and density profiles are assessed using multiple ultrasoft X-ray (USXR) arrays operated in a 'multi-color' (multi-energy) configuration. 1-D flux surface inversion is used to obtain the local emissivity, which is then modeled using perturbed T_e, and density profiles. Fitting the 'multi-color' USXR data enables separately constraining the T_e and n_e x n_Z perturbation and for instance 'propagating' the equilibrium Thompson temperature and density profiles over an ELM event. Additionally, 2-D tomographic inversion is used to assess poloidal asymmetries in the perturbations. Large Type I ELMs typically result in a crash in the SXR emission throughout the bulk plasma on a few ms timescale, which contrasts with the faster, edge-localized nature of the Type V perturbation.

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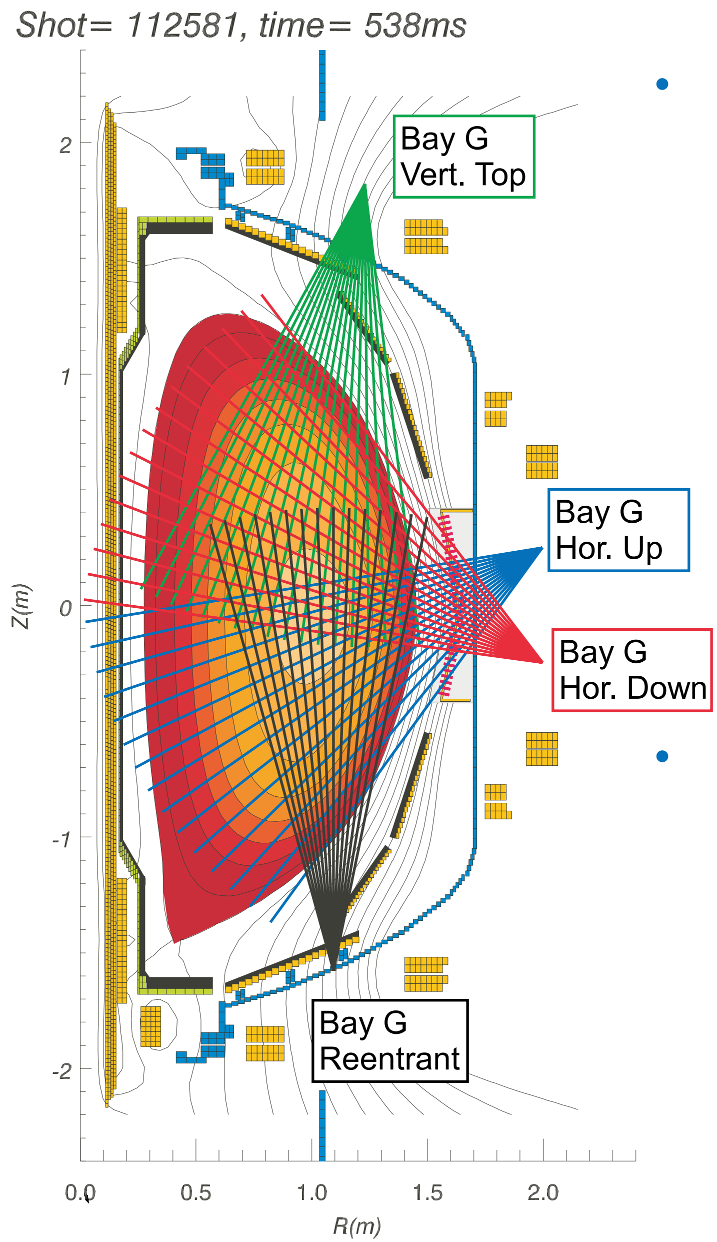
Outline

- USXR system upgrades and setup
- Identification of distinct ELM regimes in NSTX
- Characterization and imaging of small ‘Type V’ ELMs
- Characterization and imaging of ‘Type II/III’ ELMs
- Characterization of ‘Type I’ ELM perturbation
- Tomographic reconstruction of Type I ELM event evolution
- Two-color USXR modeling of T_e perturbation
- Summary

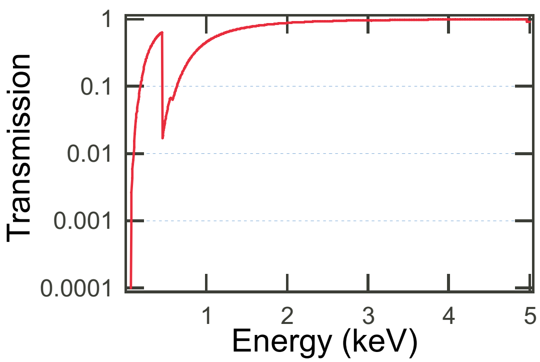
Upgraded Bay G USXR System Provides Improved Spatial Coverage

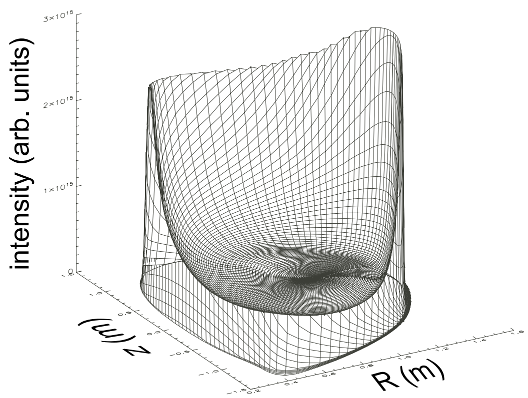


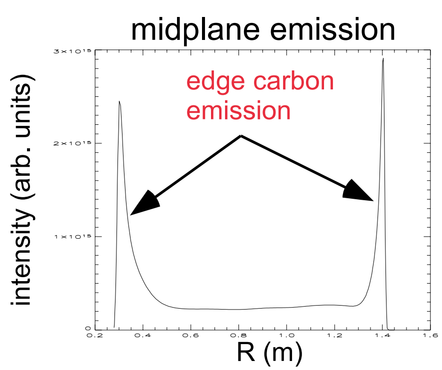
- Imaging and tomographic reconstruction used to analyze plasma activity
  - Oscillatory events (MHD modes, islands)
  - Intermittent events (sawteeth, ELMs, reconnections)
  - Slow phenomena (rotating/locked modes, RWMs)
- Arrays utilize variable filter settings to change plasma region focus
  - 0.3μm Ti filter views primarily edge C emission
  - 5μm Be filter passes X-rays from bulk plasma
  - 100μm Be filter focuses on core plasma emission

Various Filters Isolate X-ray Contribution from Different Regions of Plasma

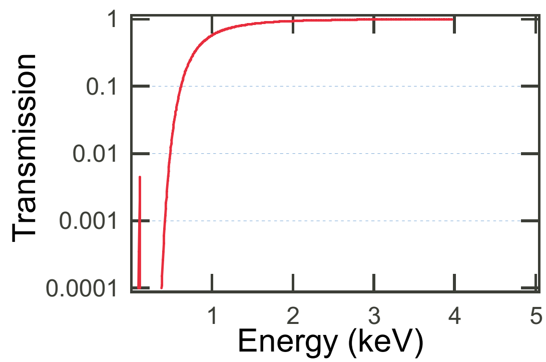
Ti 0.3µm

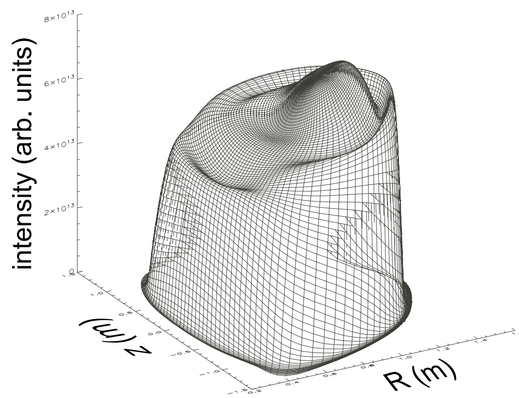


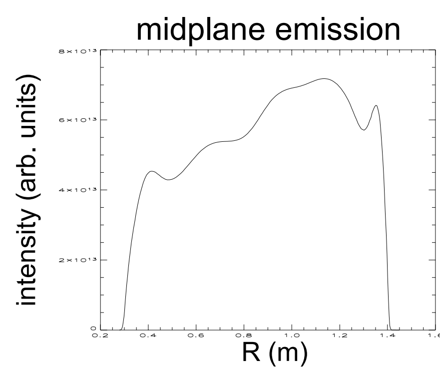




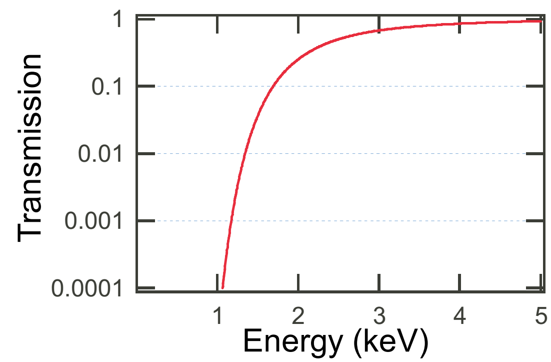
Be 5µm

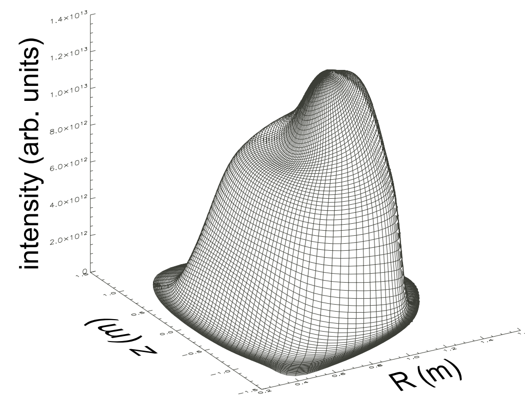


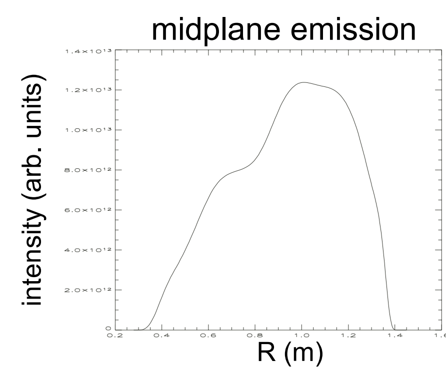




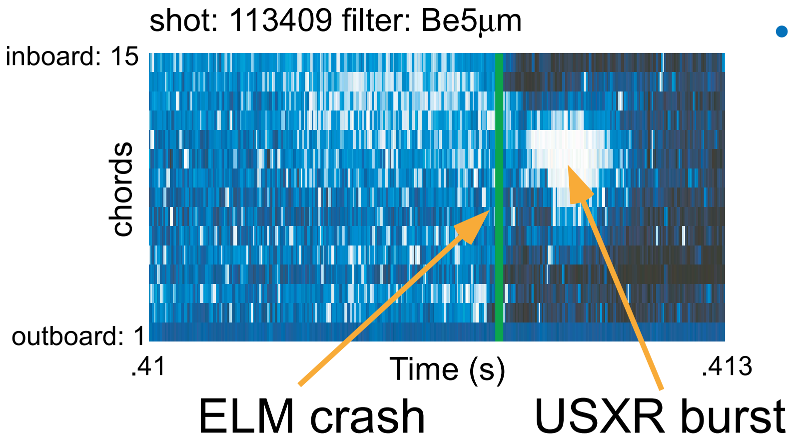
Be 100µm







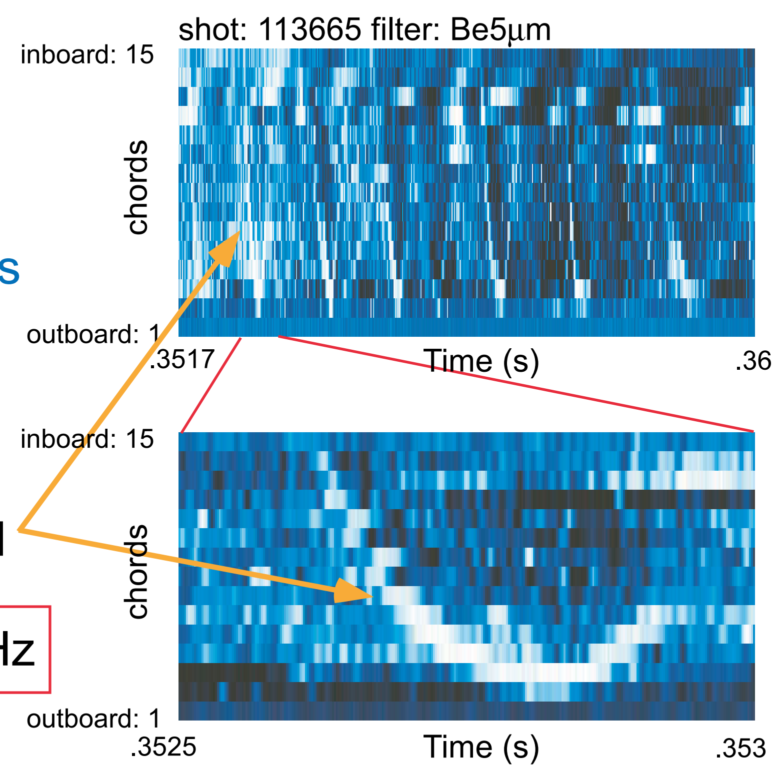
Addition of High-speed Reentrant Array Improves Imaging Capabilities



Localized USXR emission burst ~500µs after Type III ELM event

- Reentrant diode array uses AXUV-16 from IRD
  - Fast, low-noise amplifiers have ~300kHz bandwidth
  - High speed PCI digitizer board samples at 600kHz
  - Necessary to resolve outboard plasma edge

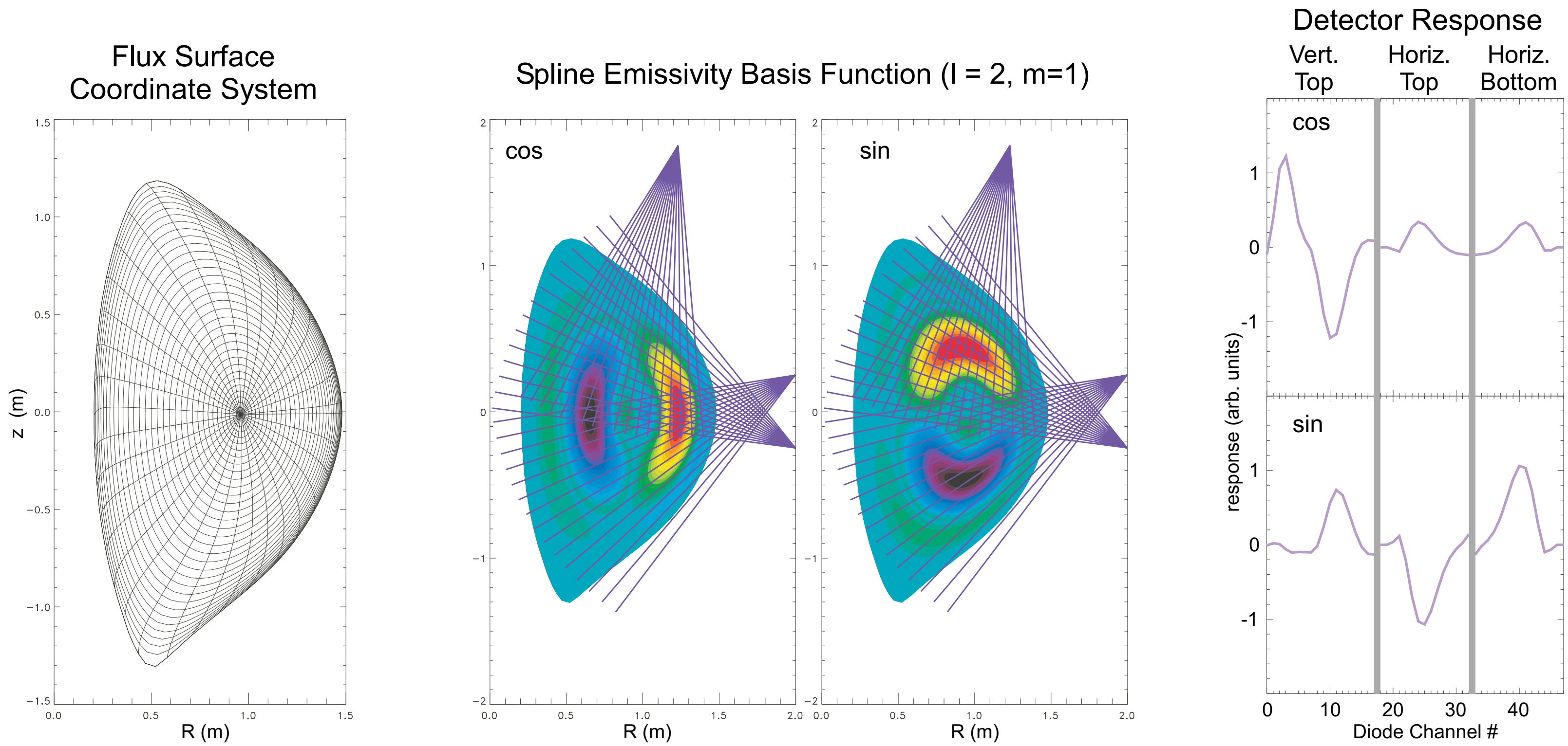
- Fast sampling improves imaging of Type V ELMs
  - Reentrant array helps pinpoint ELM origination
  - Improves measurement of event propagation



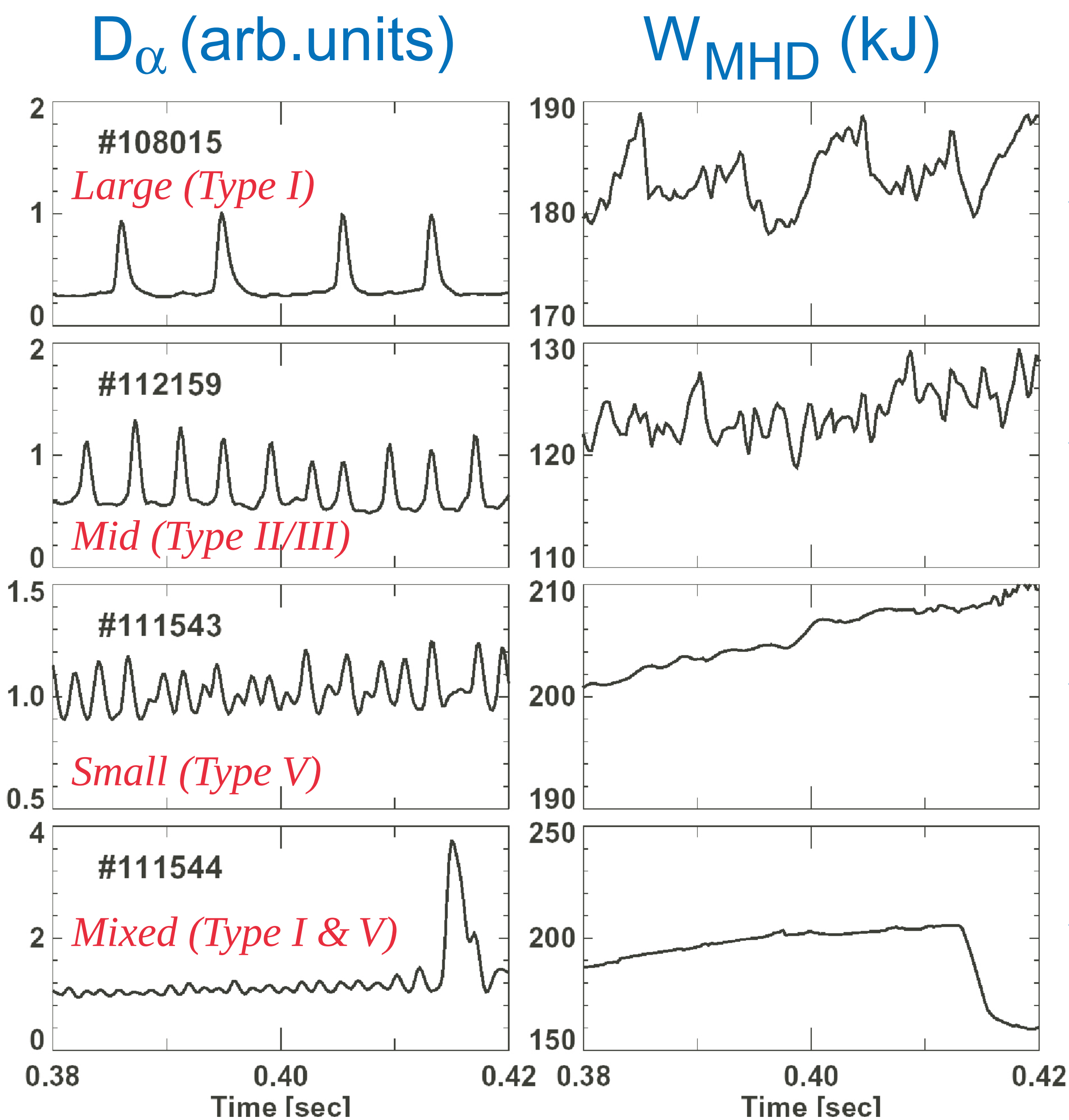
Reentrant array sampling at 600kHz

Spline-based Tomography Algorithm Adapted to Reconstruct SXR Emission

- Algorithm modified from R., Granetz code (MIT)
  - Ling Wang; Granetz, R.S., Rev. Sci. Instrum., **62**, 1115 (1991)
- Spline basis functions allow for mode localization
  - Number/position of detector sightlines determines number of radial knots (l) and poloidal harmonics (m)
- Flux-surface based coefficient response matrix speeds computation



Many Different ELM Types Observed in NSTX



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

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

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

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

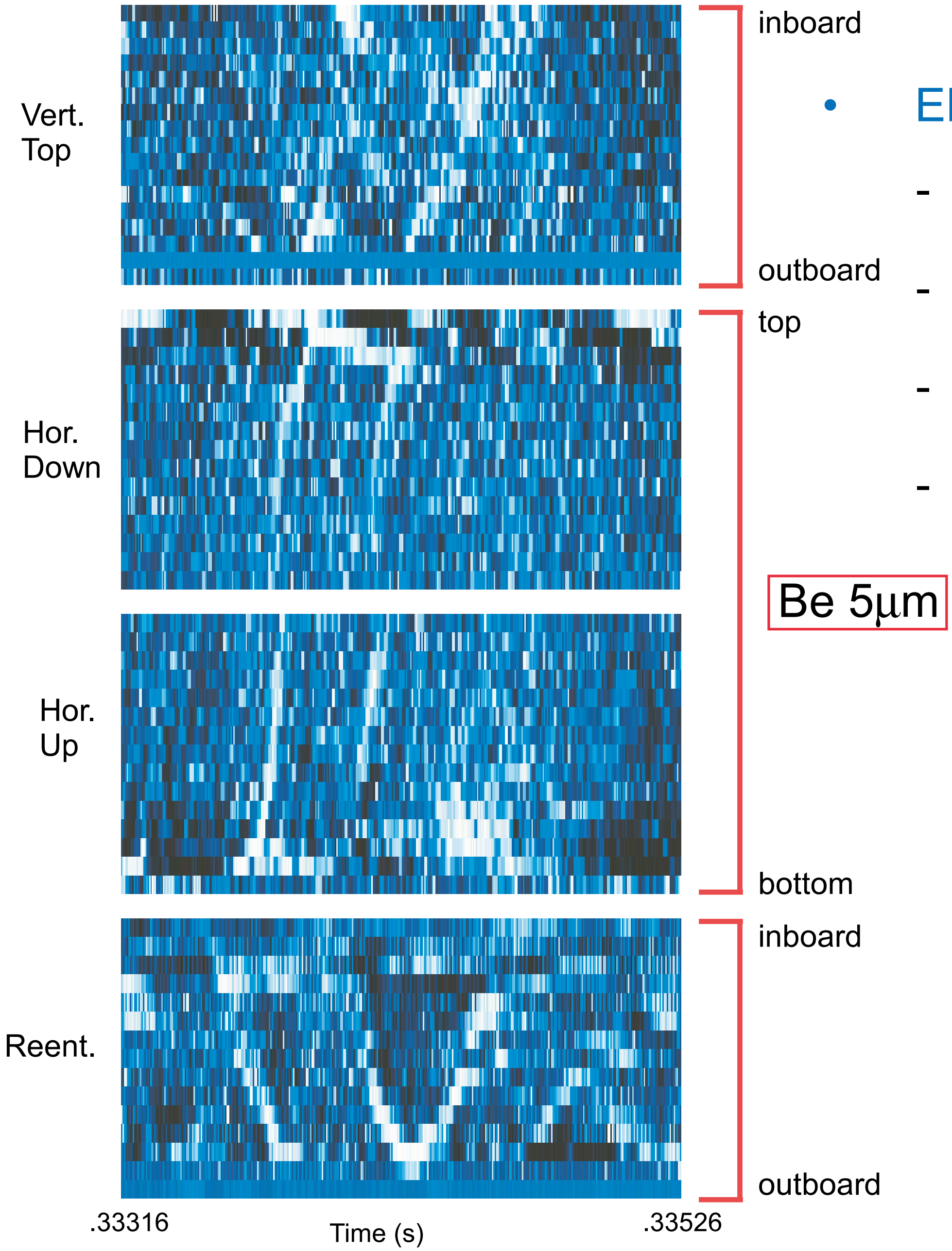
$\Delta W_{MHD}/W_{MHD} \leq 1\%$

Wide P_{heat} range

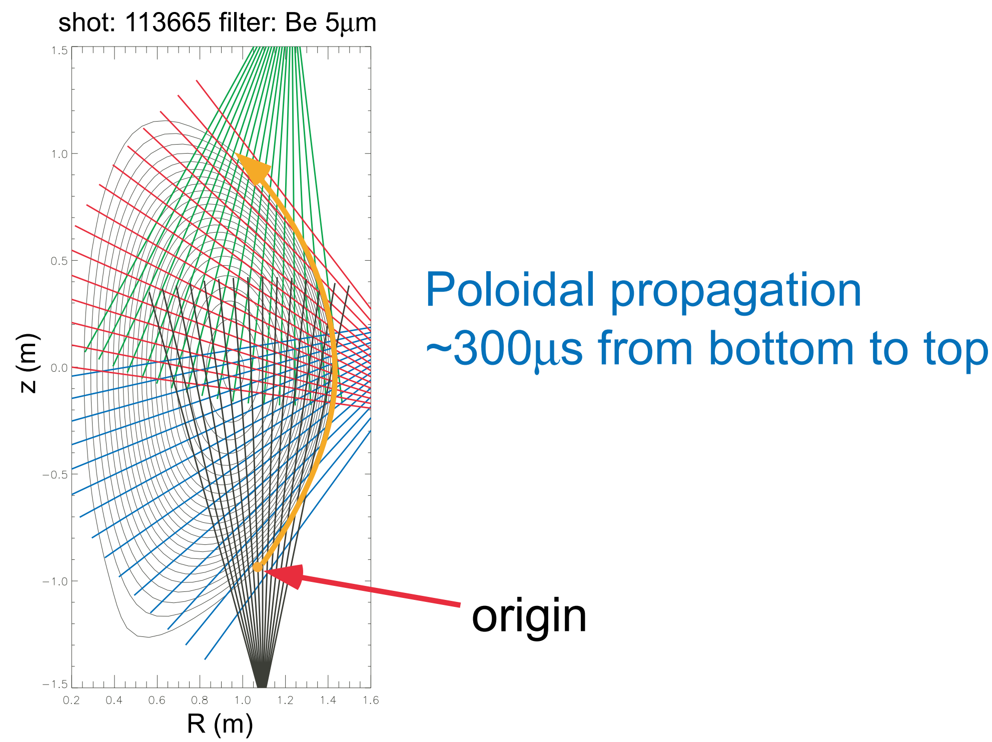
$\Delta W_{MHD}/W_{MHD} \leq 30\%$

High P_{heat} β_N

Imaging of Type V ELMs show Poloidal Propagation

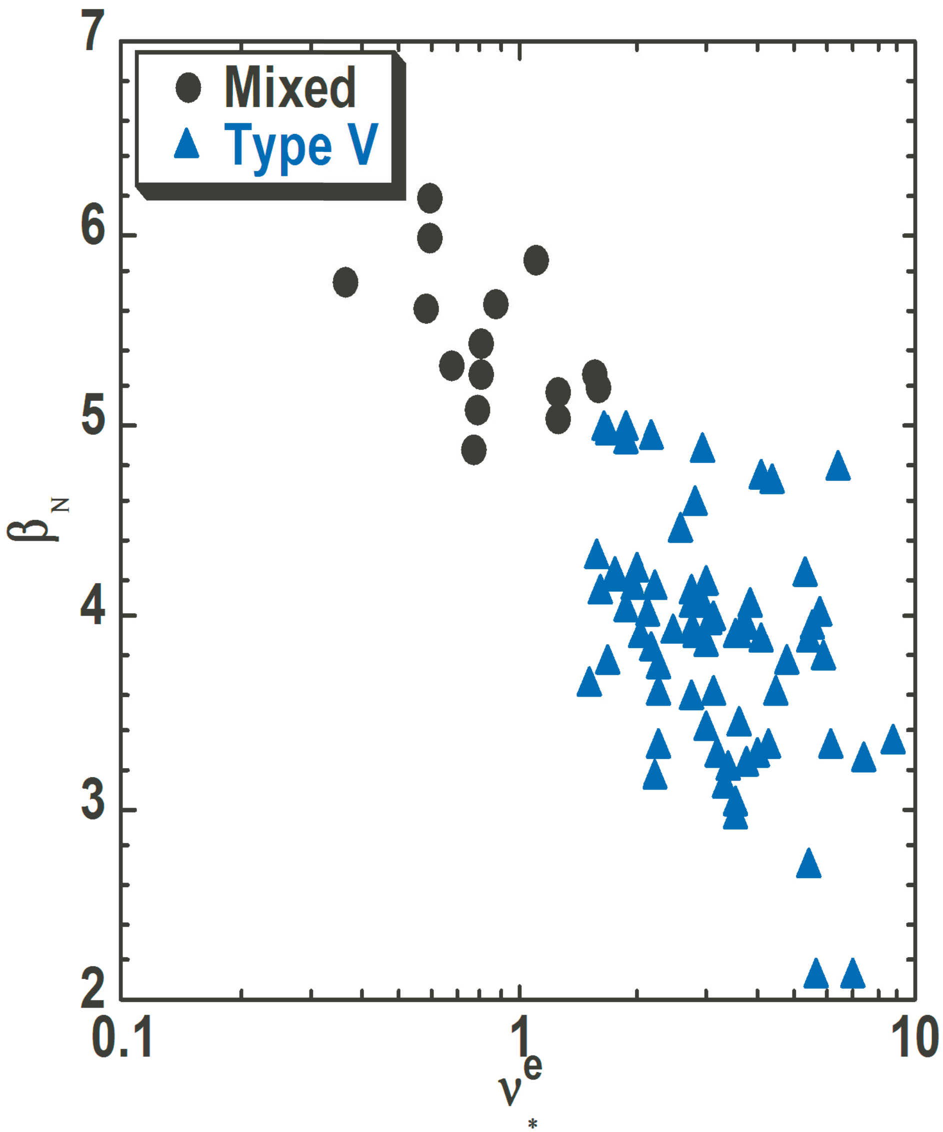


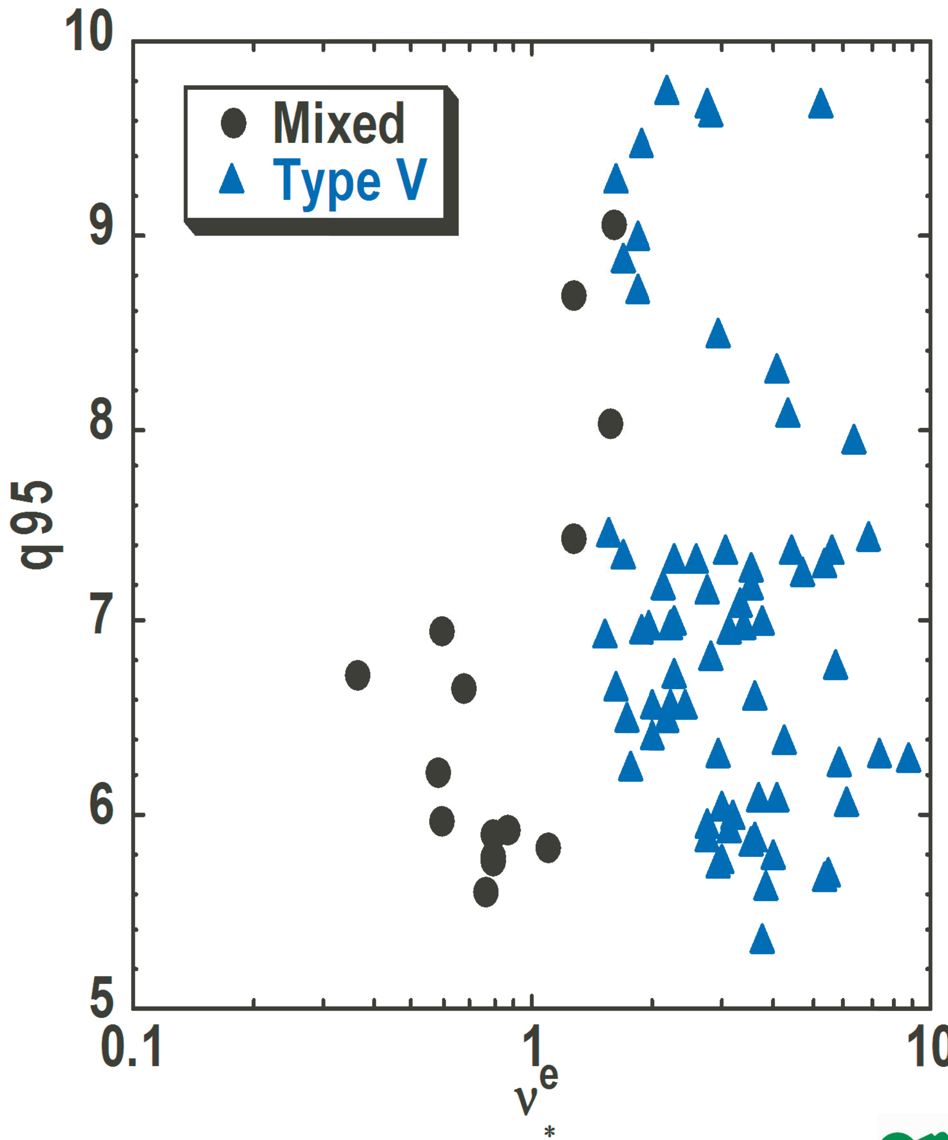
- ELM characterized by small edge perturbation
  - ELMs originate typically in lower plasma region
  - Propagate counter-clockwise poloidally
  - Have negligible effect on bulk plasma (T_e, W, ...)
  - Regime often contains intermittent Type I events



Pedestal ν_*^e ~ 1 Divides Type V and Mixed ELM Regimes

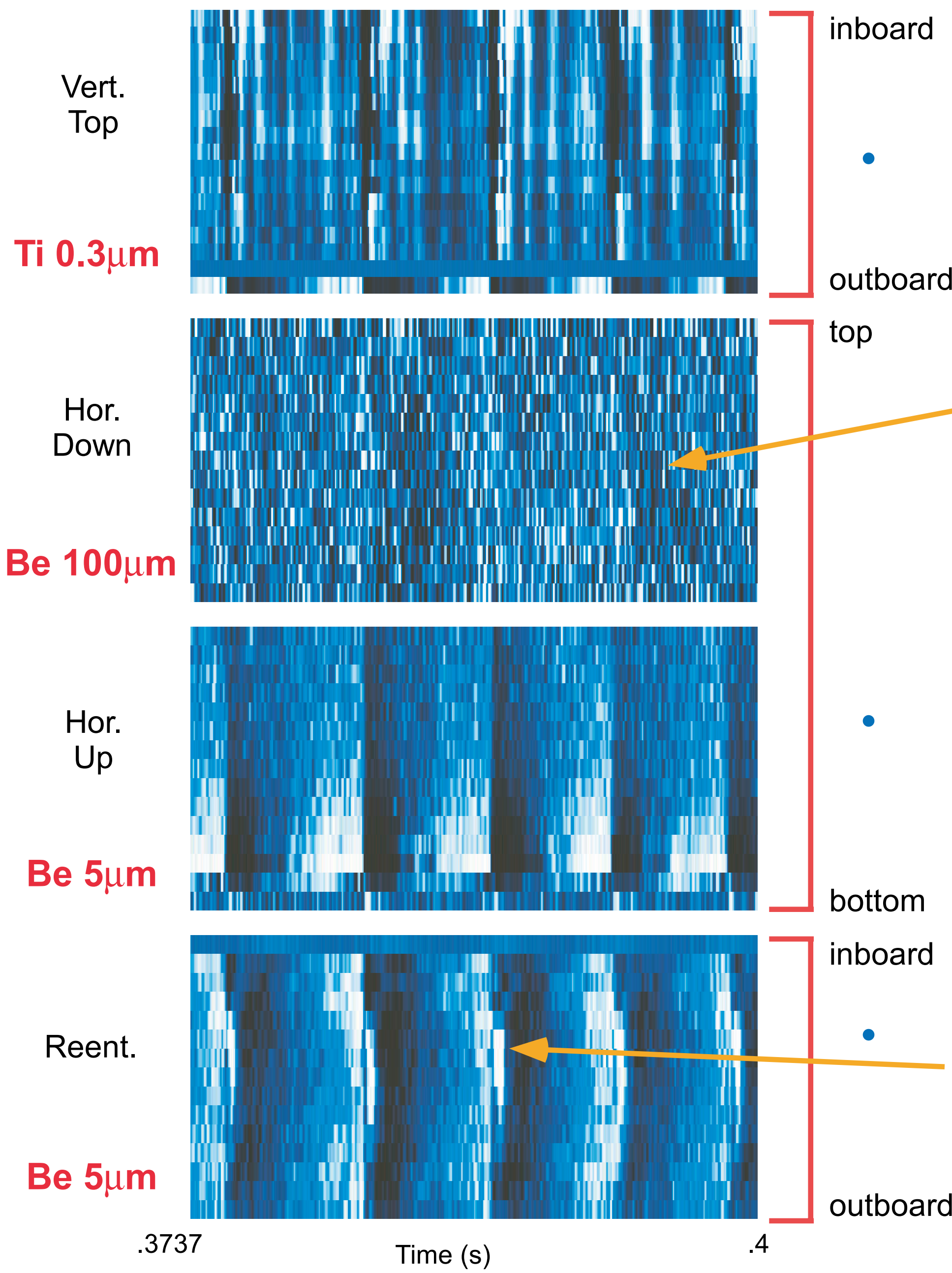
I_p: 0.6-0.9 MA, B_T = 0.45T, P_{NBI}: 2-6 MW, LSN, κ = 2.0, δ = 0.4





Maingi, APS2004

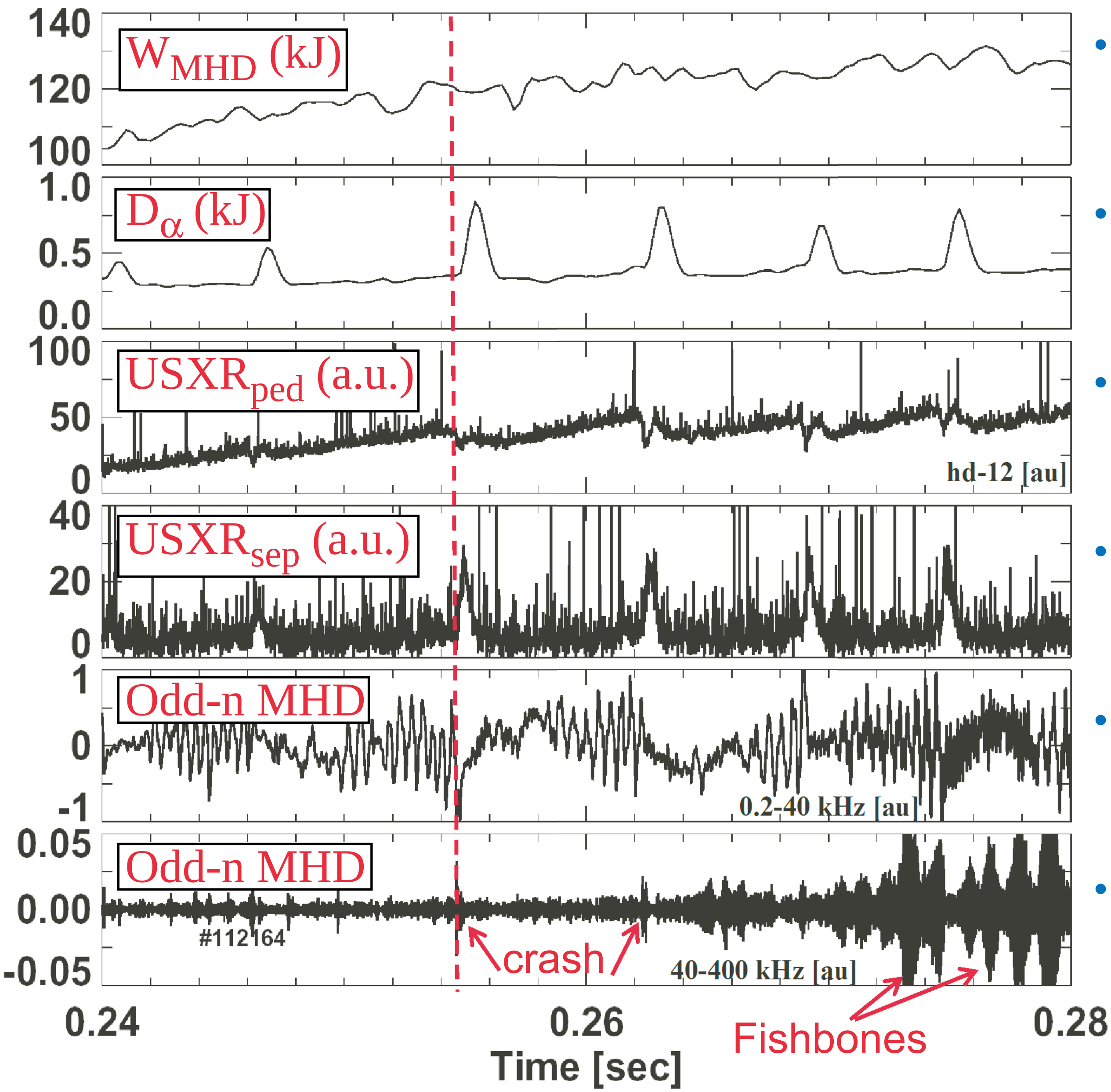
Type II/III ELM Correlates with Edge n_e/Impurity Crash



- USXR data suggests ELM has negligible effect on bulk n_e, T_e
  - Neutron rate unaffected
  - High energy filter shows little/no evidence of ELM
- ELM frequency increases from ~100Hz to ~300Hz throughout shot (consistent with density increase)
- Localized USXR emission bloom robust, post-ELM feature

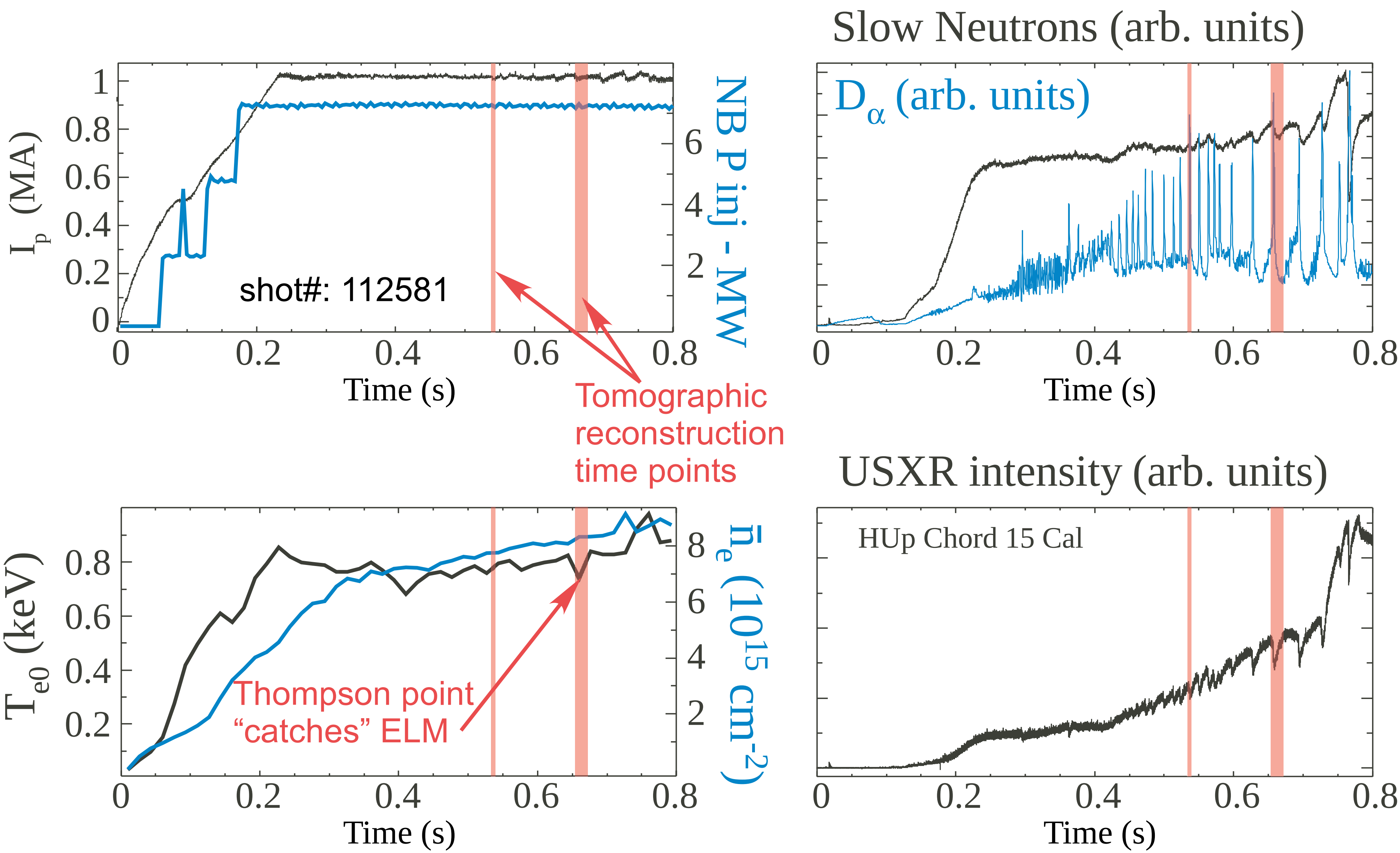
shot# 113406

Characteristics of Type II/III ELMs



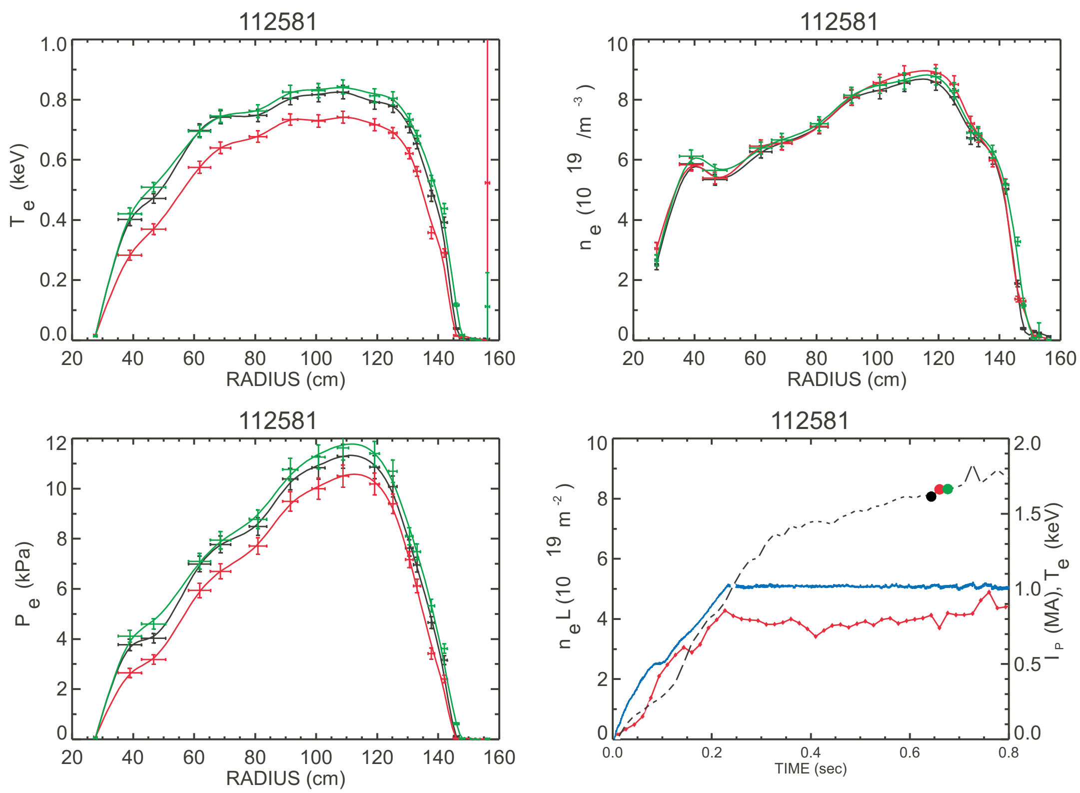
- Little impact per ELM on W_{MHD}
- D_α spike correlates with USXR ELM events
- USXR drop shows power out-flow from plasma pedestal
- Edge USXR shows power influx to SOL/separatrix
- Existence of low-frequency precursor before ELM
- High frequency MHD activity occurs at beginning of ELM

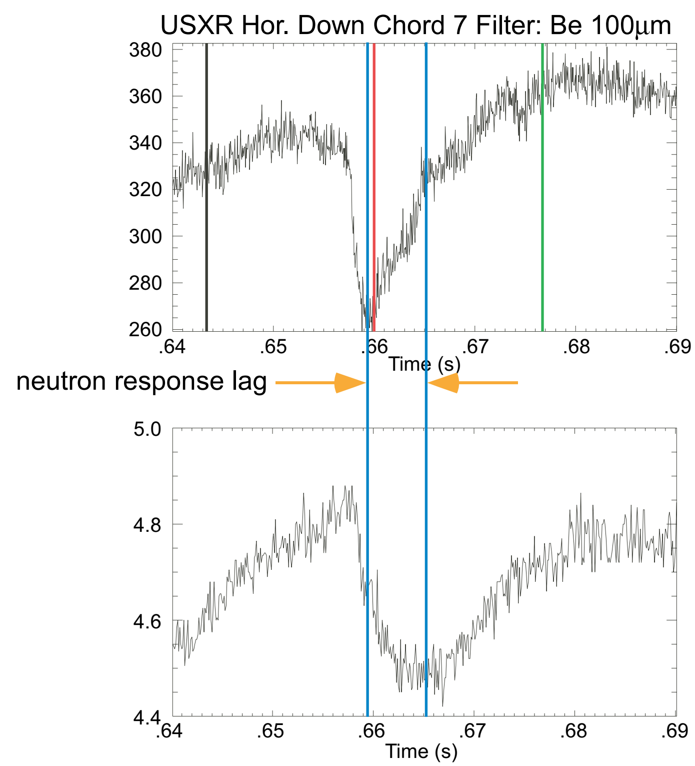
‘Type I’ ELMs Often Observed in High Performance NSTX Discharges



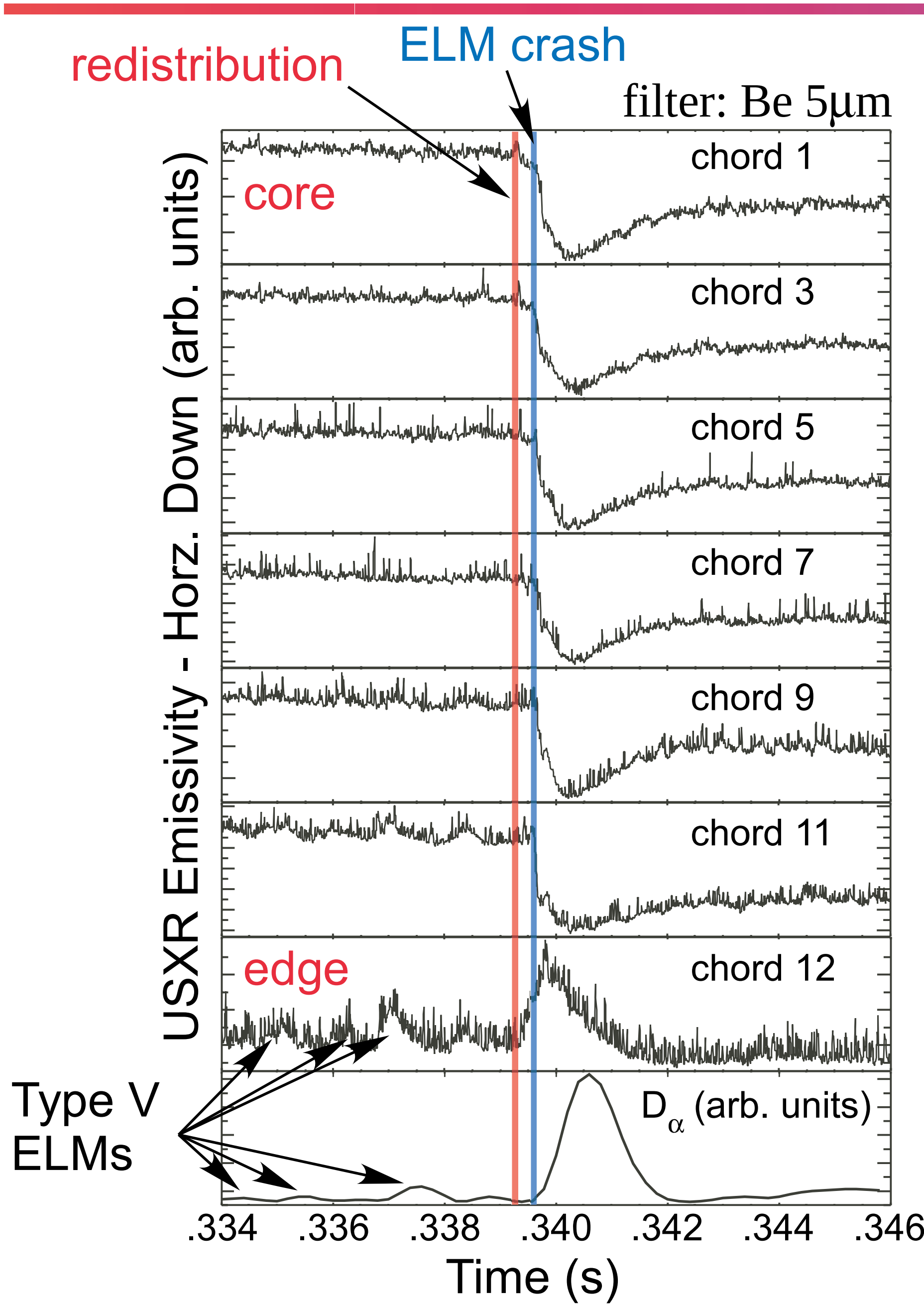
Type I ELM often Accompanied by Global T_e Perturbation

- Thompson measures drop in $T_e(r)$ on the order of 10-20% ($\Delta T_{core} \sim \Delta T_{edge}$)
  - n_e measured before, during, and after ELM shows little change (slight peaking?) pure conductive ELM? (i.e. $n\nabla T$ change only)
  - Neutron response lags T_e profile (decline by ~1ms, minimum by ~5ms)
  - Not all T_e perturbations reach core (e.g. shot 113665 @ 0.377s, 112581 @ 0.537s)





USXR Indicates Redistribution of Emission Prior to Main ELM Event



- Redistribution of SXR emission occurs ~few 100ms before ELM crash
  - Core emission shows modest decline
  - Edge SXR emission increases, peaks shortly after ELM crash
  - D_α burst corresponds to ELM crash NOT increase in SXR edge emission
- Outflow of power into SOL occurs at ELM crash

shot# 112503

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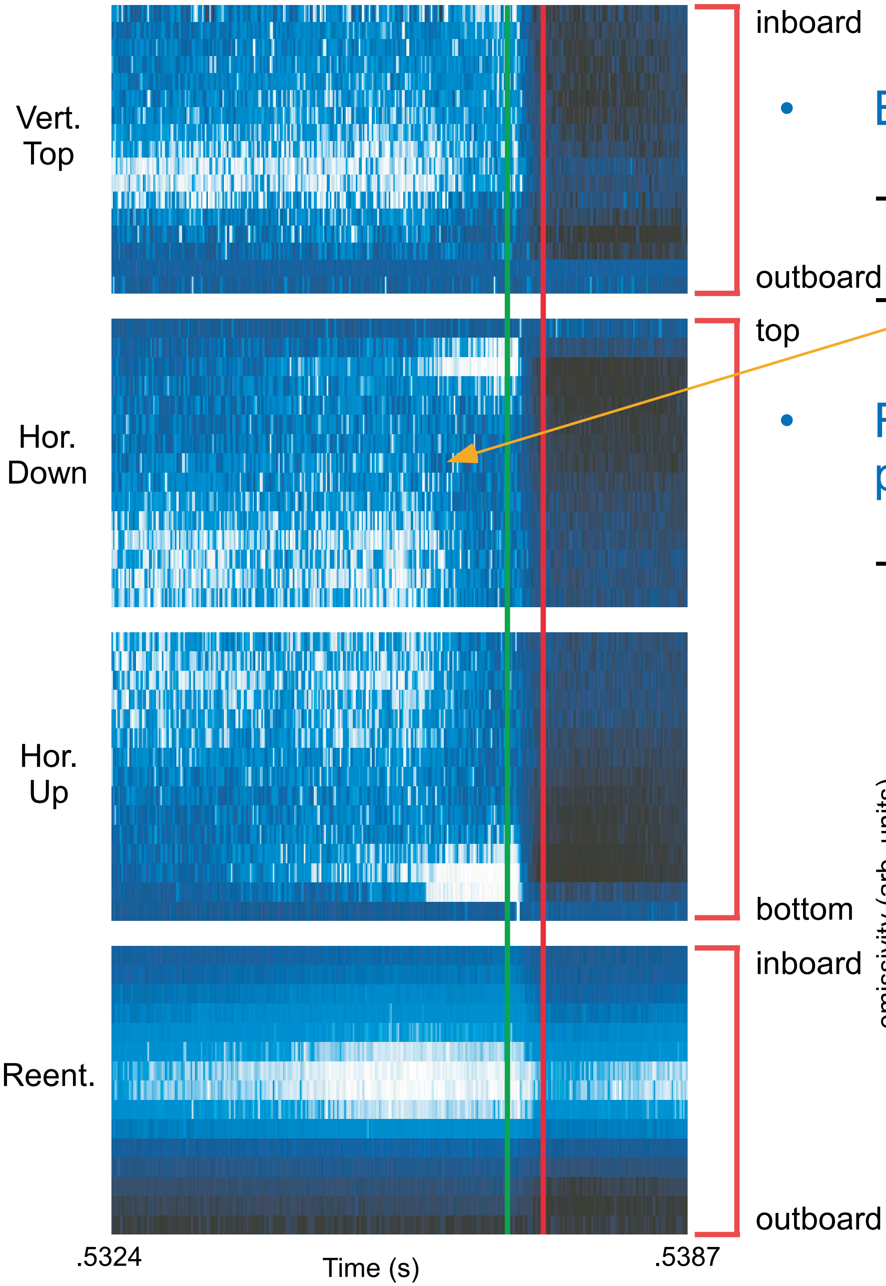
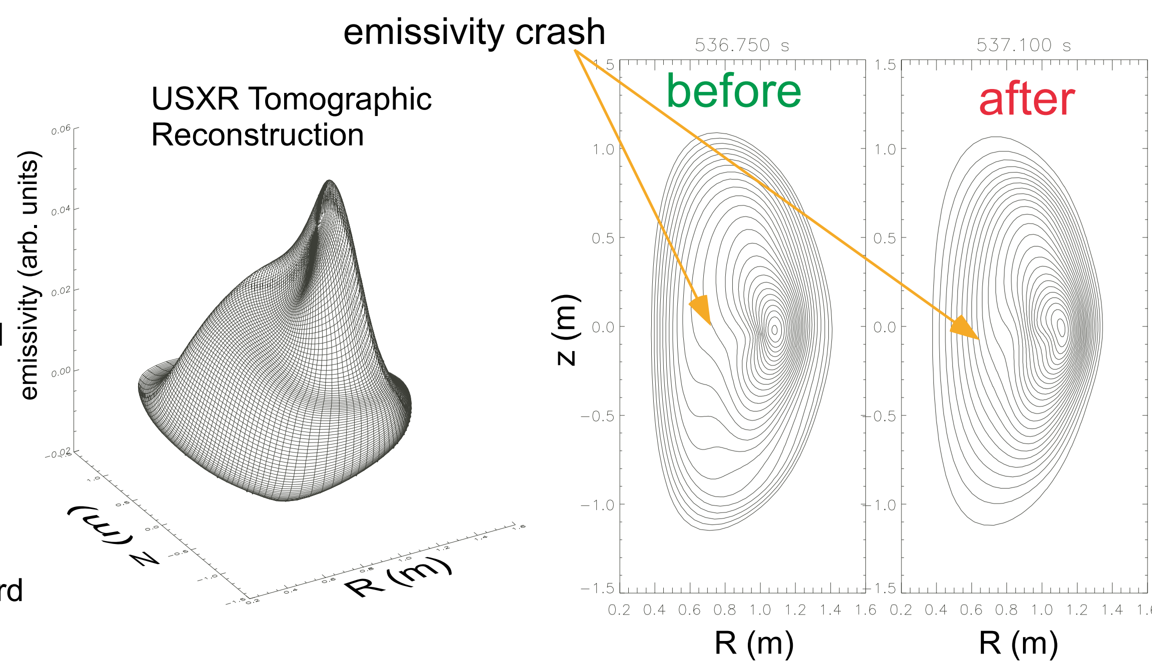
USXR Arrays Allow Tomographic Reconstruction of Type I ELM Perturbation



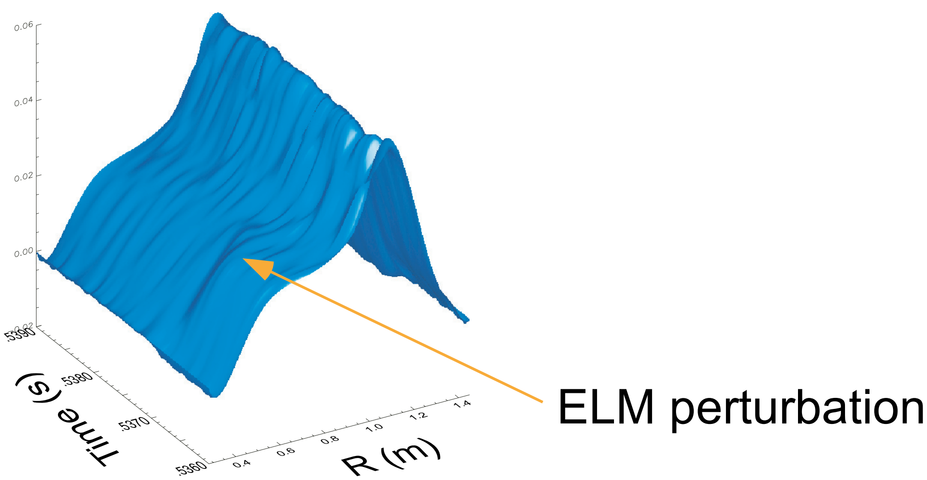
- Be 100µm filters focus on core emission
  - Reconstructed emissivity consistent with USXR model
  - Evidence of redistribution precursor (not always present)
- Reconstructions before and after ELM show perturbation activity at inboard side of plasma
  - Two-color analysis necessary for T_e perturbation study



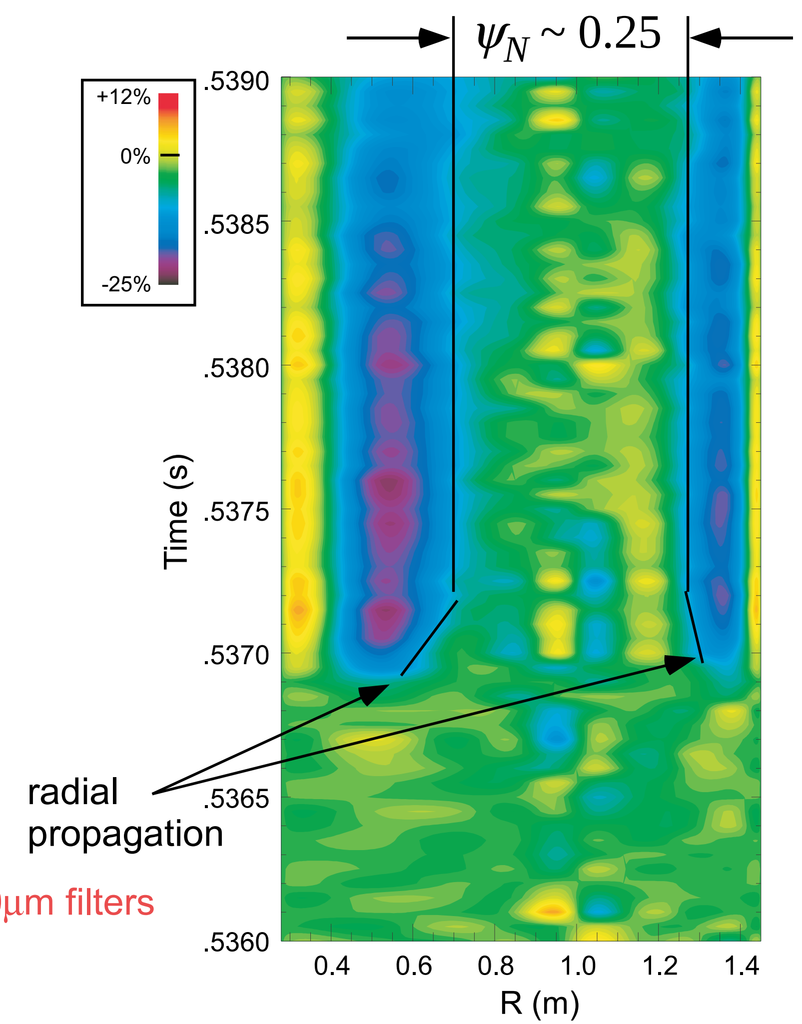
Not All Perturbations Feature Propagation to the Core

- ELM erodes “bump” at inboard of plasma
  - Perturbation reaches $\psi_N \sim 0.25$ (0.7m inboard, 1.27m outboard)
  - Radial propagation ~few 100µs
  - Preliminary hints that ELM size/ propagation boundary related to I_p

Reconstructed midplane intensity



Relative midplane intensity change

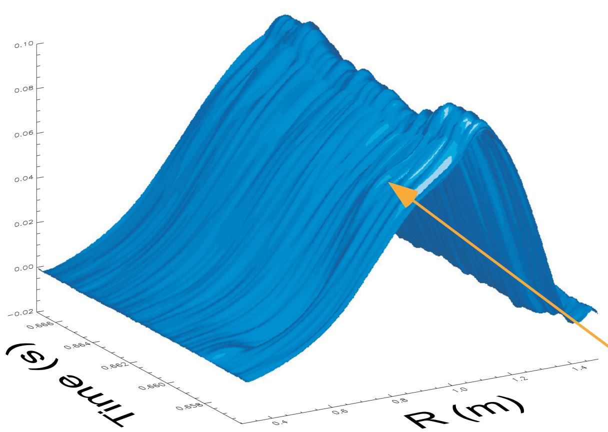


Tomographic reconstruction of shot 112581 @ .536s, Be 100µm filters

Larger ELM Events Indicate Penetration of Perturbation to Core

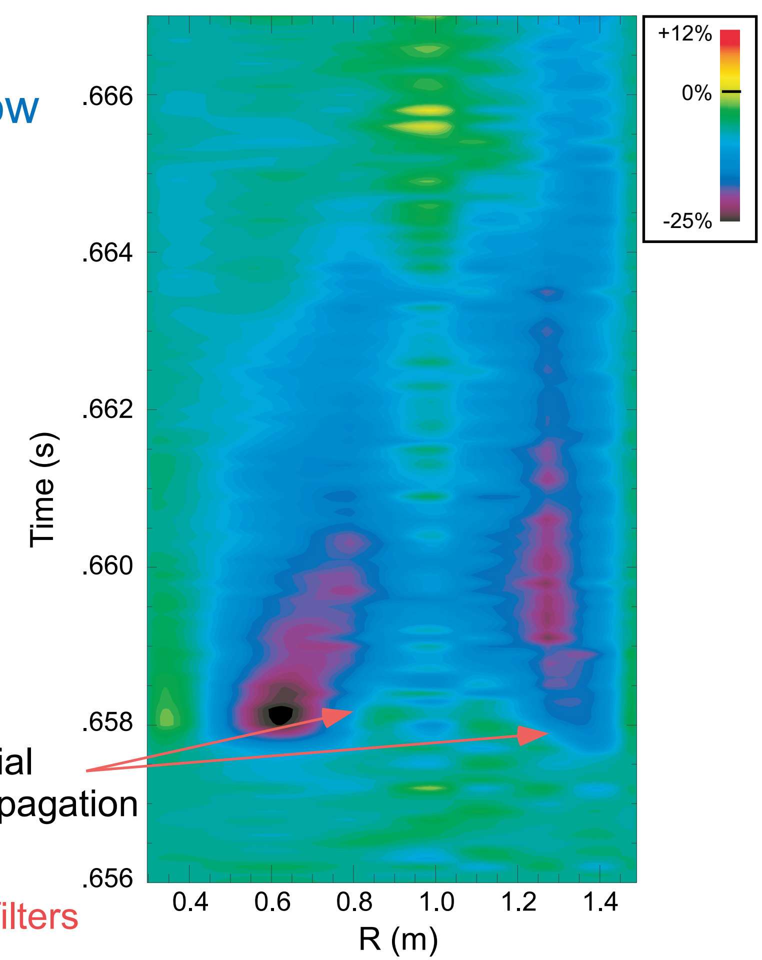
- Core emission crashes ~1ms after edge
  - Larger decrease in neutron rate compared to 0.537 event (~20% vs ~3%)
  - Consistent with multi-color T_e modeling
- Radial propagation of perturbation appears to slow in plasma core

Reconstructed midplane intensity



ELM perturbation

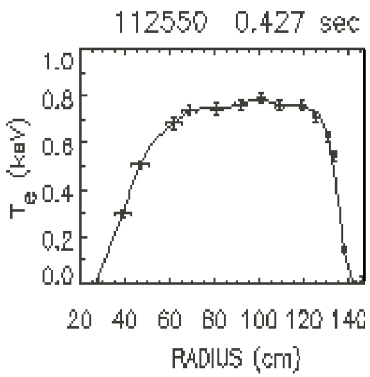
Relative midplane intensity change

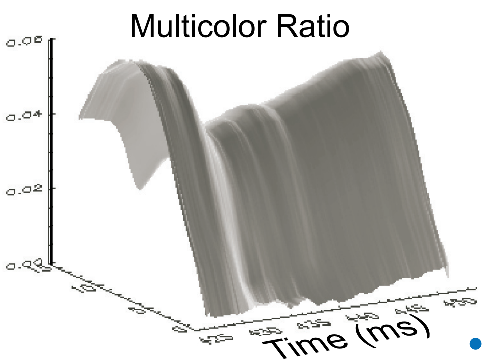


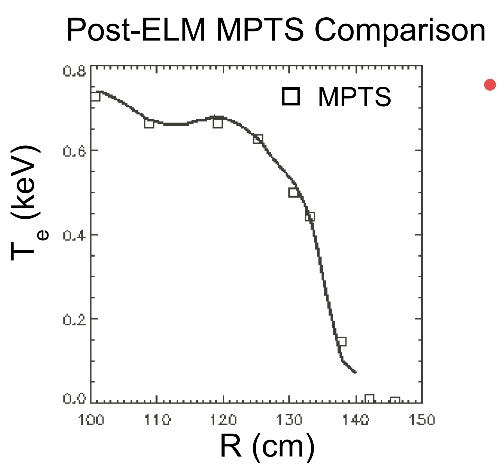
radial propagation

Tomographic reconstruction of shot 112581 @ .656s, Be 100µm filters

MPTS T_e profile 'propagated' by 2-color USXR modeling







- Pre-ELM MPTS profiles used to fix n_e, n_z in USXR model
  - USXR profiles modeled using C, O and B coronal equilibrium radiative coefficients and magnetic surface mapping
- Ratio of Be 100μm/5μm filters sensitive function of T_e
  - 2-color modeling provides $T_e(R,t)$ with good temporal resolution
  - T_e crash in pedestal ~40-80%, core ~10-20% $\left(\frac{\Delta T}{T_{core}} \neq \frac{\Delta T}{T_{edge}}\right)$
  - Core perturbation consistent with ~20% reduction in neutron flux
- Propagated $T_e(R)$ matches well with subsequent MPTS profile
- Limitations of technique
  - Crossed arrays allow only 1-D modeling
  - Assumption of no asymmetric density shifts or plasma movement
  - Set of multi-color arrays would alleviate these limitations

Planned Experiment: Characterization and Scaling of Type I ELMs on NSTX

- ## Motivation

  - ELM phenomena on NSTX appears different from conventional tokamaks (e.g. size scaling, perturbative penetration)
  - On conventional tokamak, ELM is mixture of n_e, T_e perturbation and relative proportion scales with collisionality
  - Effects of conductive ELMs more damaging to power handling structures

- ## Goals

  - Understand the scaling of conductive/convective ELM proportionality on NSTX
  - Investigate the dependence of the propagation and penetration of the Type I ELM perturbation

Summary

- Upgraded USXR set provies good plasma coverage
  - High-speed reentrant array boosts fast imaging capabilities
  - Some portions of plasma volume still under-sampled
- Various ELM phenomena have been imaged using the USXR arrays
  - Imaging of Type V ELMs show poloidal propagation
  - Type III ELMs correlate with edge n_e perturbation and subsequent localized USXR emission bloom
  - Type I ELMs often accompanied by a global T_e perturbation
- Multi-color USXR modeling is a powerful tool for fast T_e profile analysis
- Planned experiment will investigate scaling and characterization of Type I ELM perturbation