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ELM Detection and Correlation with Rotating MHD Modes for Disruption Event Characterization and Forecasting

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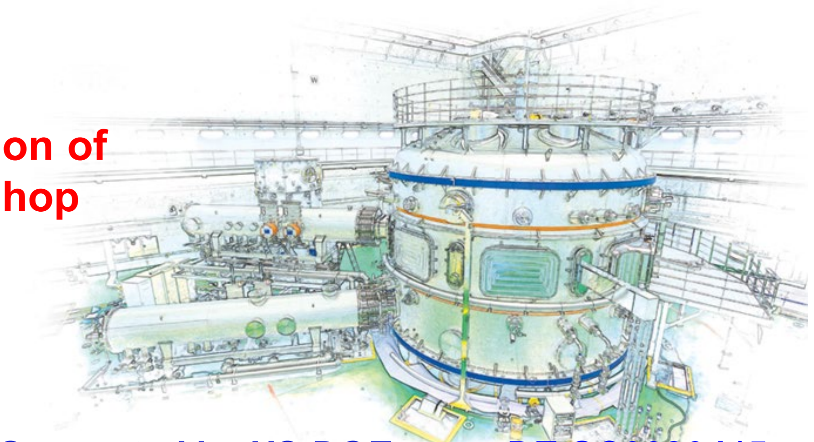

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Outline

- ☐ Motivation & objective
- ☐ Role of ELM detection in DECAF
- ☐ ELM detection algorithm
- ☐ ELM detection case-studies
- ☐ Summary, active and future work

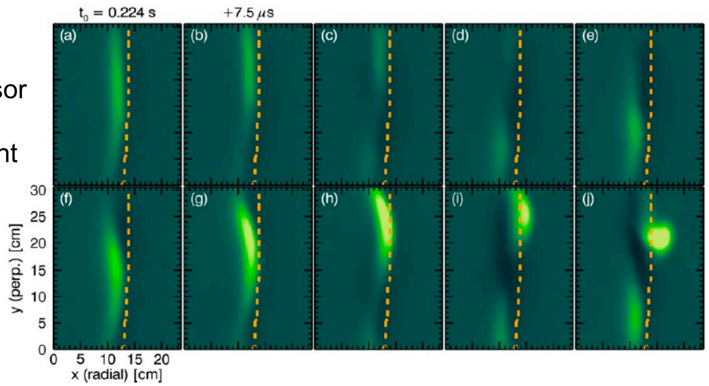
ELMs can potentially trigger or seed disruption-capable modes

- The Disruption Event Characterization and Forecasting (DECAF) code works to resolve, characterize, forecast, and glean physics insight to event-chains that result in disruptions by studying large, cross-machine databases[1]
  - a favorable formalism to study possible *seeding* of detrimental instabilities
- Not typically directly disruptive, but ELMs have long been thought to be a potential trigger for more detrimental plasma instabilities[2,3]
- Recent progress in theory proposes possible mechanism for ELM triggering of NTMs[2,5]
- The potential of ELMs to seed modes that can result in plasma termination interests DECAF in a high-fidelity ELM-detection capability
  - gives rise to DECAF ability to study correlation of ELMs with disruptive plasma events

Goal: Reliably detect and characterize ELMs in DECAF

- Reliable ELM detection and characterization requires distinguishing between events that may share diagnostic signal characteristics
  - A high time-resolution diagnostic to detect edge energy transients is the D_α diagnostic
  - E(dge)LM: loss of *pedestal* energy → Expect ELMs to exhibit edge-localized profile drops following ELM crash
  - Strong D_α emission transients w/out edge-localized profile changes through mode dynamics still useful – info passed to other DECAF events (NTM, LTM, RWM, etc.)

Figure 1:
ELM event precursor oscillations and subsequent filament ejection in NSTX (Sechrest et al)



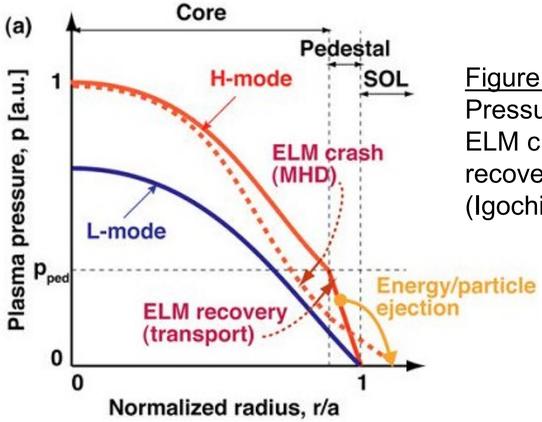
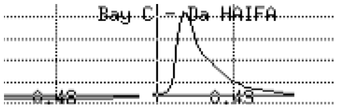


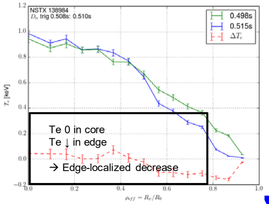
Figure 2:
Pressure profile before ELM crash and its recovery (Igochine et al)

ELM Identification Algorithm

Key:
- Implemented
- Under Development

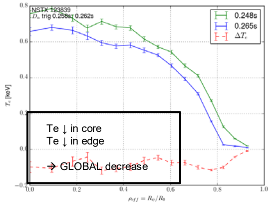


D_α emission transient



Te 0 in core
Te ↓ in edge
→ Edge-localized decrease

ΔT_e, Δn_e edge localized



Te ↓ in core
Te ↓ in edge
→ GLOBAL decrease

Global ΔT_e or otherwise not edge-localized ΔT_e

Relatively large ∂Slow Neutrons/∂t drop

In H-mode

In *dithering* H-mode

In L-mode

Not an ELM

ELM

Send compiled D_α spike info to other DECAF events
→ NTM? RWM? LTM?

If still in H-mode, expect additional ELMs to follow

ELM

ELM Identification Results

- Demonstrate ELM identification capability and characteristics by examining performance on several shots
  - 2 NSTX discharges with bona fide ELMs[3]
  - 2 NSTX discharges with D_α emission signatures similar to that of ELMs
  - A representative KSTAR shot
- Examine plasma diagnostic signals through mode dynamics to determine physical nature of strong D_α emission transient (if not ELM, what is source of the emission?)
  - D_α
  - Slow neutrons
  - Magnetic pick-up coils
  - T_e profile
  - RWM and locked mode sensors
  - Plasma stored energy (W_{tot})

DECAF ELM detection capability classifies D_α spikes as global or edge-local based on plasma signals

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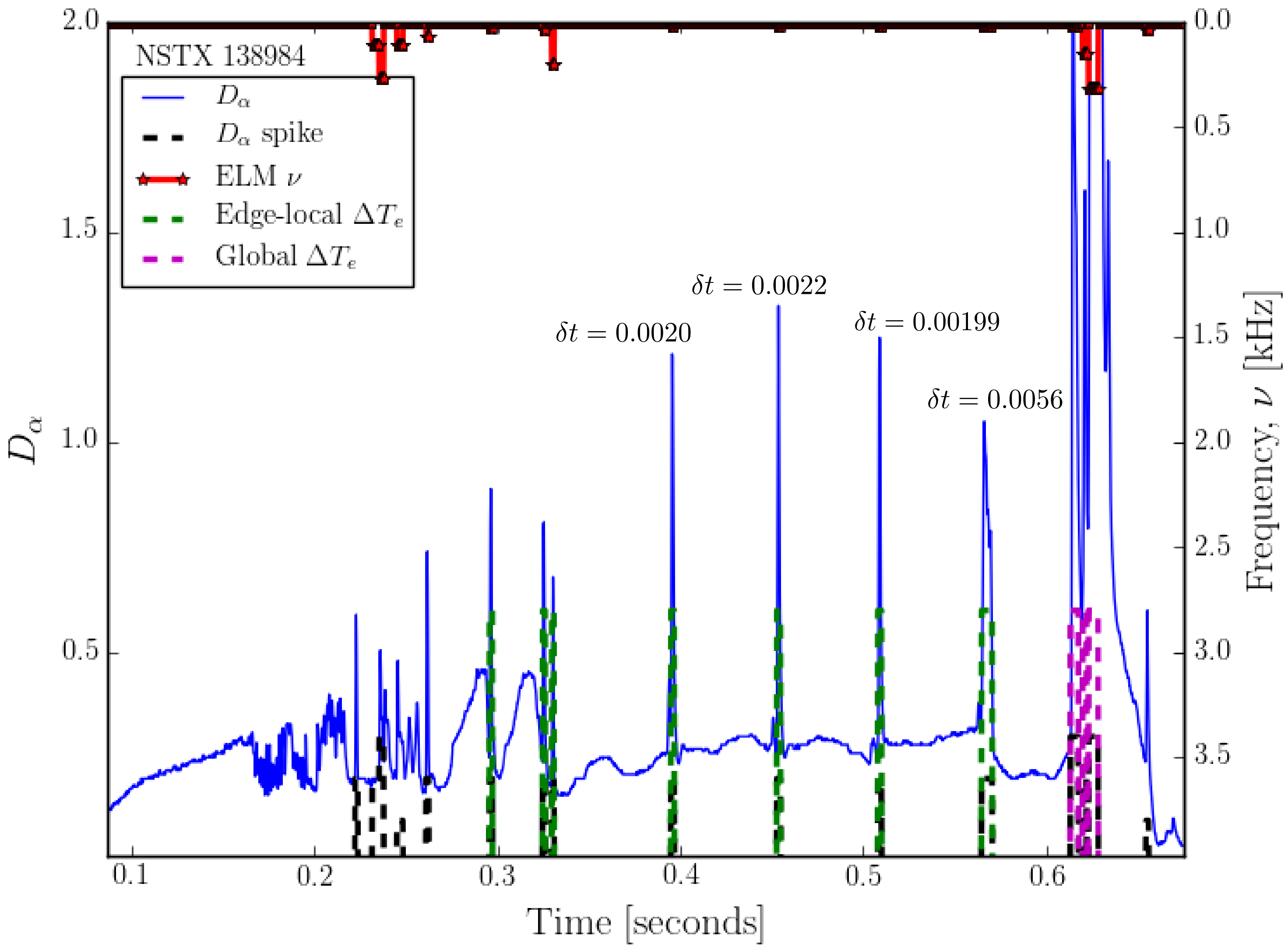
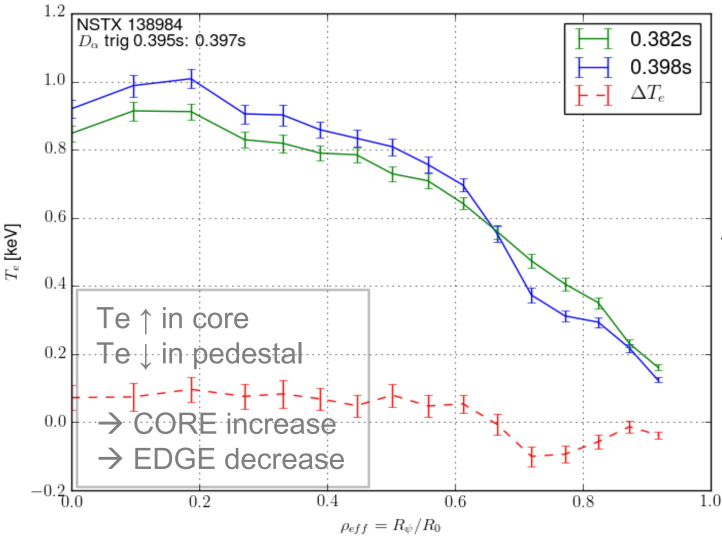
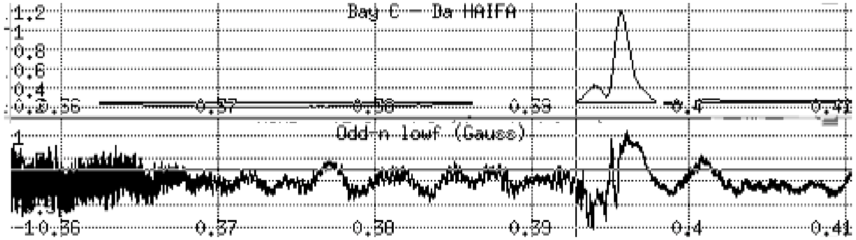
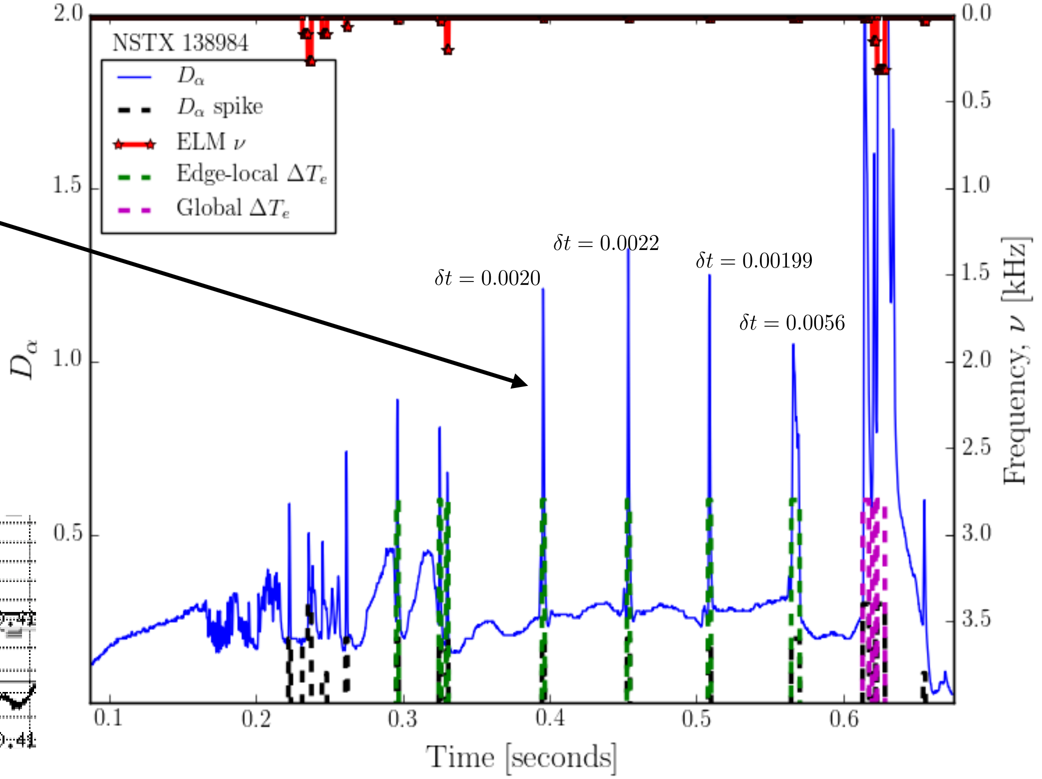


ELMs are *detected* when D_α spikes supported by edge-localized plasma signals

2/4



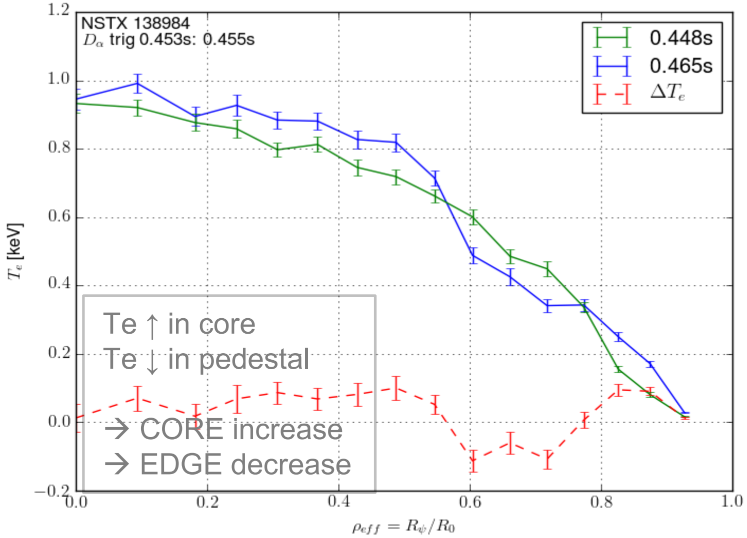




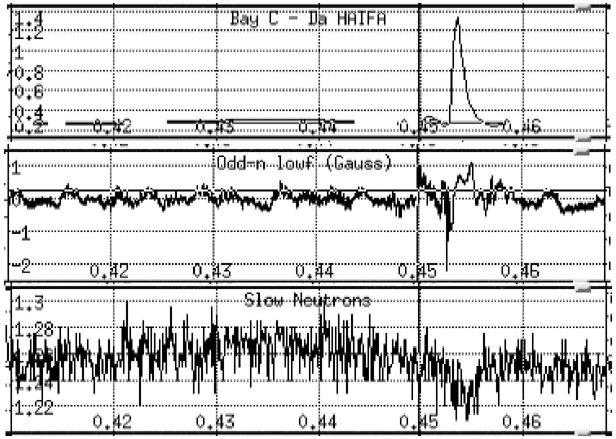
- **Transient low-f magnetics**
- **Edge-localized T_e drop**
- **No apparent ΔB_r or ΔB_p**
- **→ ELM**

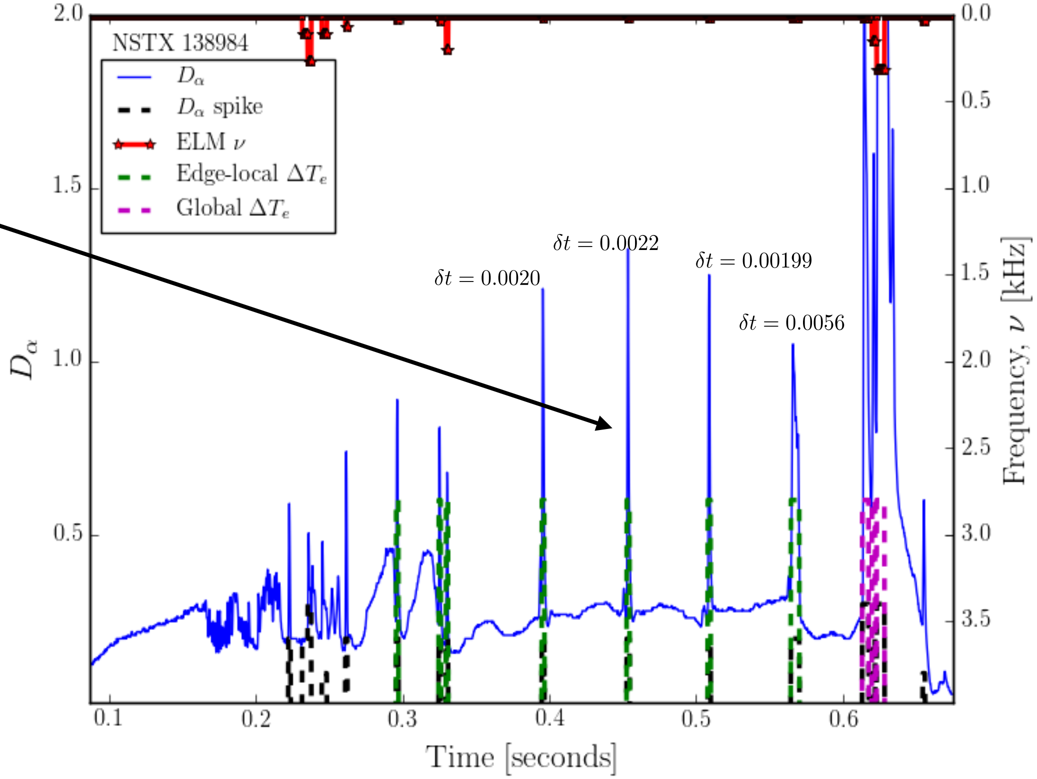
ELMs are *detected* when D_α spikes supported by edge-localized plasma signals

3/4



Te ↑ in core
Te ↓ in pedestal
→ CORE increase
→ EDGE decrease





- **Transient low-f magnetics & very small slow neutrons change**
- **Edge-localized T_e drop**
  Albeit w/ some edge-profile recovery, but note T_e 10ms after spike
- **No major ΔB_r or ΔB_p**
- **→ ELM**

ELMs are *detected* when D_α spikes supported by edge-localized plasma signals

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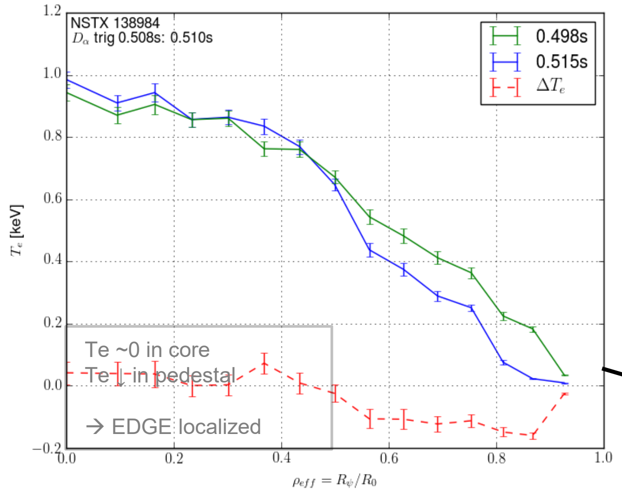
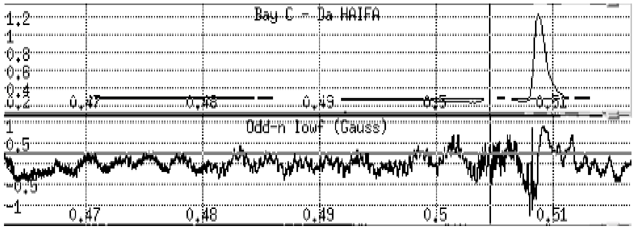
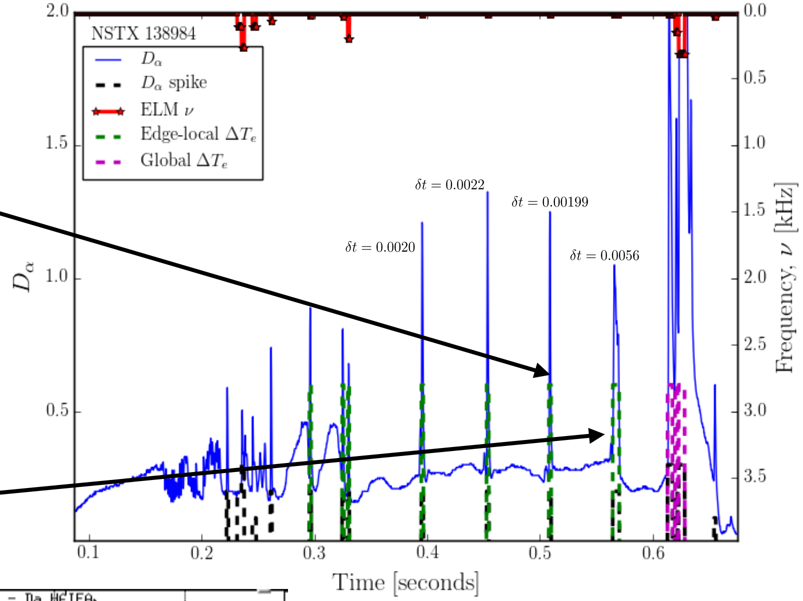


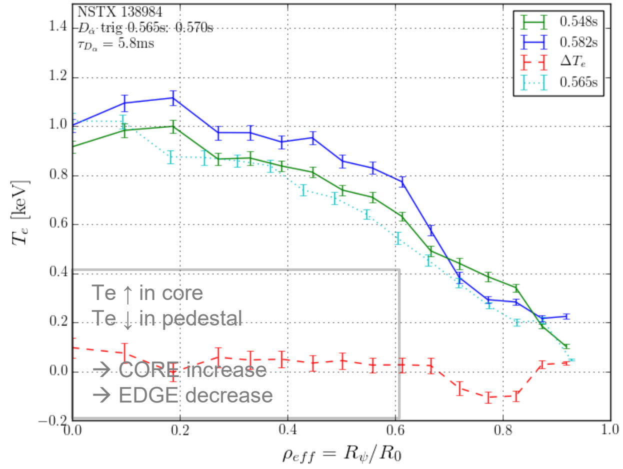
Te ~0 in core
Te ↓ in pedestal

→ EDGE localized



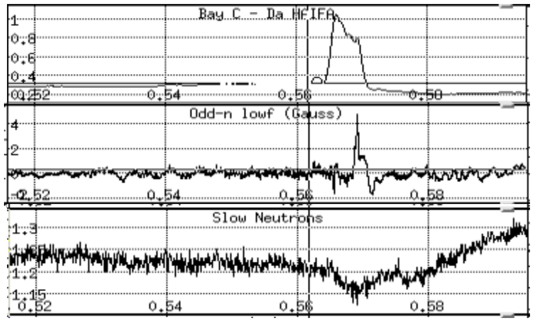
- Transient low-f magnetics
- Edge-localized T_e drop
- No apparent ΔB_r or ΔB_p
- → ELM





Te ↑ in core
Te ↓ in pedestal

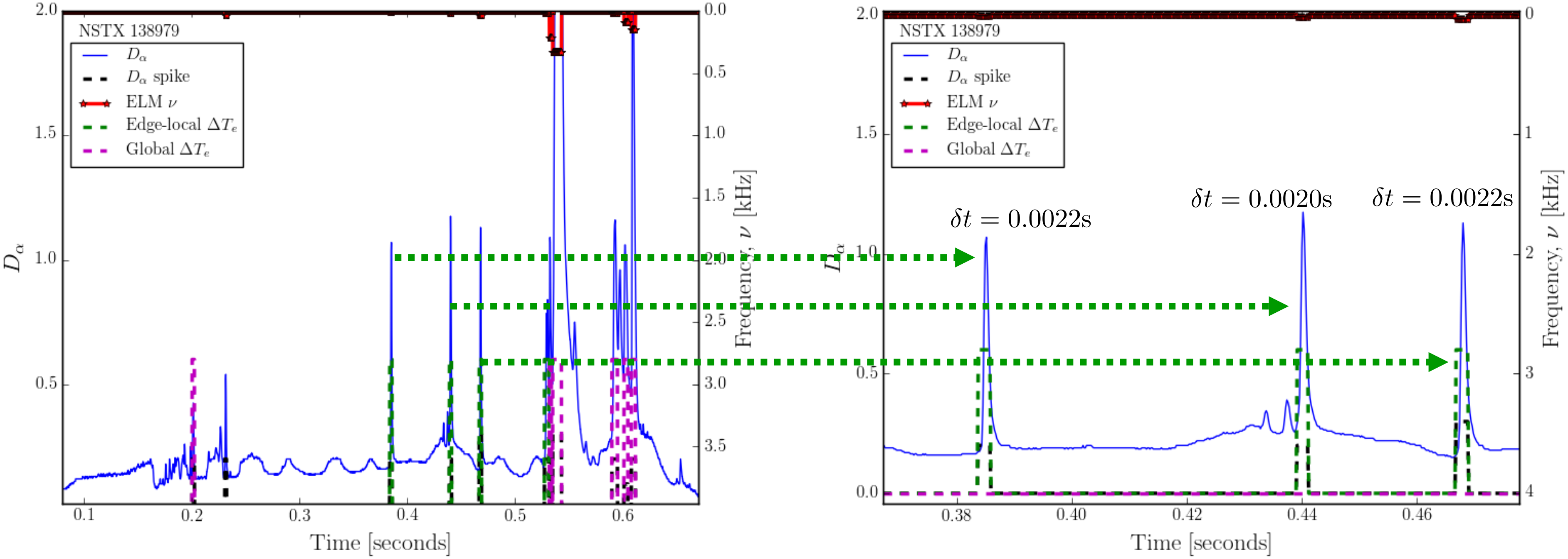
→ CORE increase
→ EDGE decrease



- Transient low-f magnetics
- Edge-localized T_e drop
  - *Albeit w/ some edge-profile recovery, but T_e 10ms after spike*
- Very small slow neutrons drop (≲ 5%)
- No apparent ΔB_r or ΔB_p
- → ELM *(+ potential other activity)*

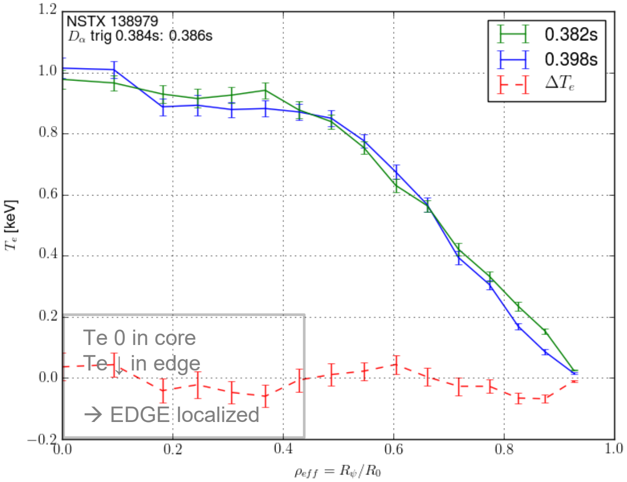
DECAF ELM detector computes D_α spike start- and end- times

1/3

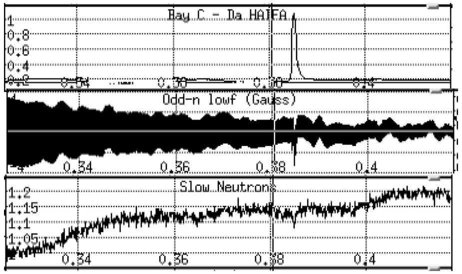


ELMs are *detected* when D_α spikes supported by edge-localized plasma signals

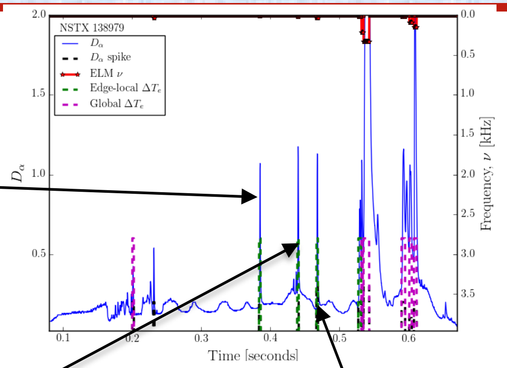
2/3

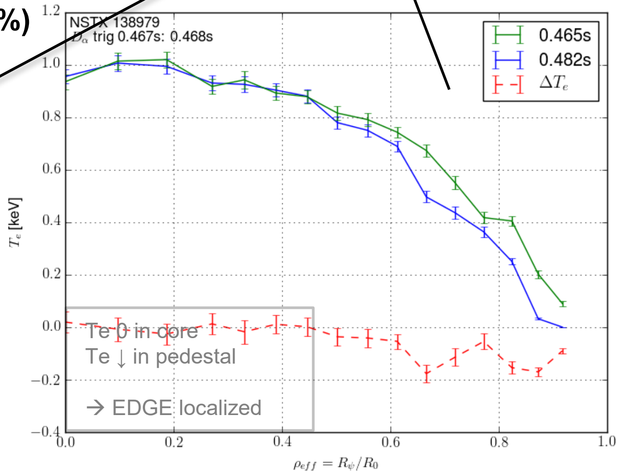


Te 0 in core
Te ↓ in edge
→ EDGE localized

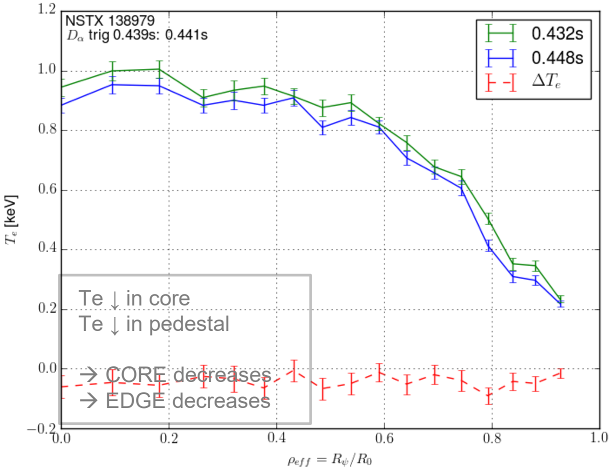


- Transient influence on low-f magnetics
- Edge-localized T_e drop
- Very small Slow Neutrons change (< 5%)
- No apparent ΔB_r or ΔB_p
- → ELM



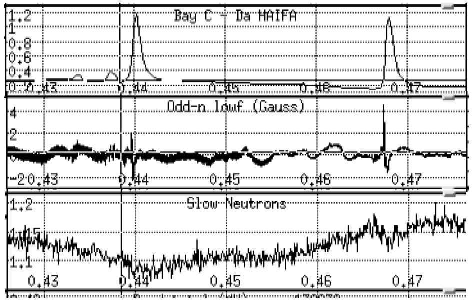


Te 0 in core
Te ↓ in pedestal
→ EDGE localized

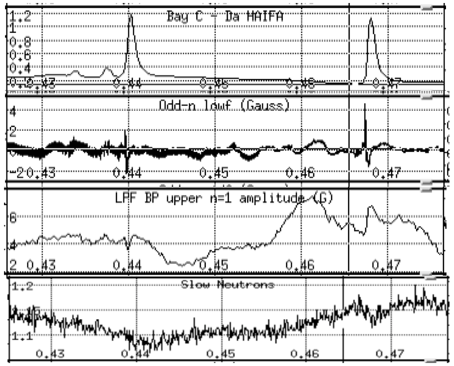


Te ↓ in core
Te ↓ in pedestal
→ CORE decreases
→ EDGE decreases

- Transient low-f magnetics
- Edge + Core T_e drop
- Very small Slow Neutrons change (< 5%)
- Small ΔB_r and ΔB_p
- → ELM



- Transient low-f magnetics
- Edge-localized T_e drop
- Very small Slow Neutrons change (< 5%)
- Small ΔB_r and ΔB_p
- → ELM



DECAF ELM detector discerns difference b/w global and edge-localized effects, and can provide D_α processing to other DECAF events

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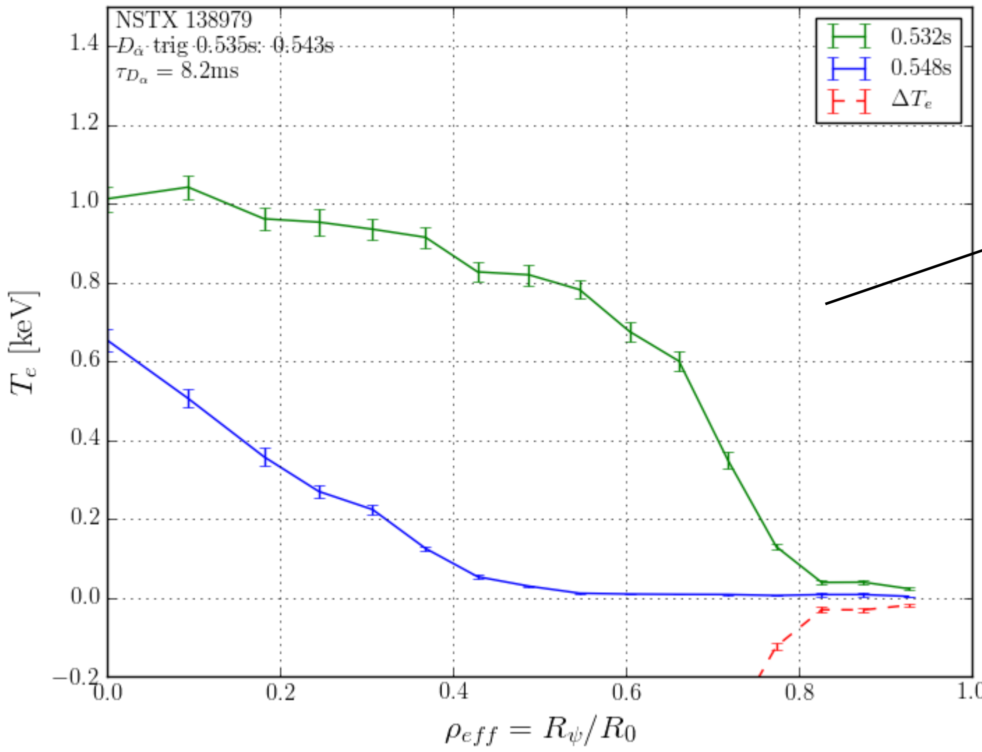

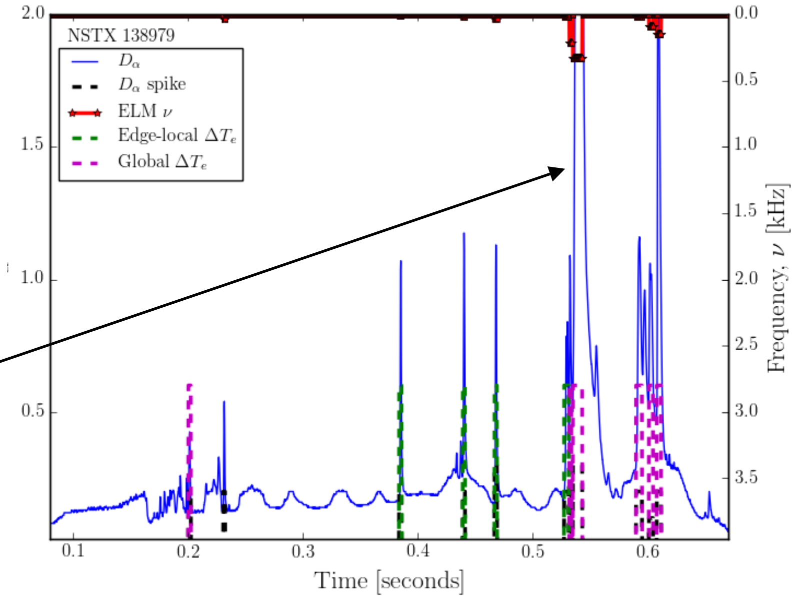

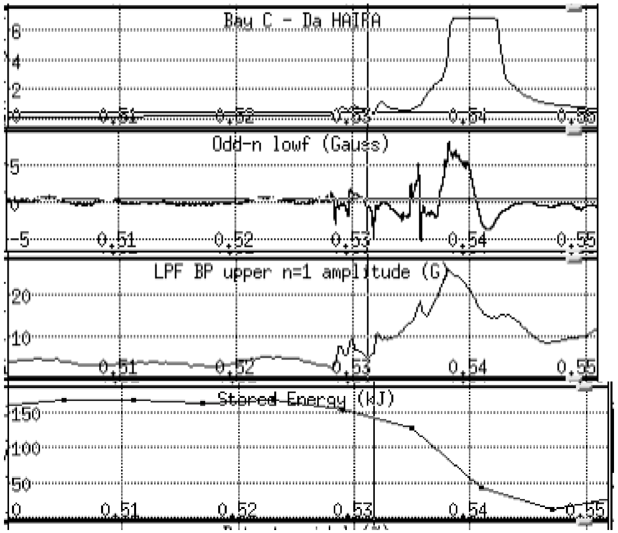

- T_e drop is global, Slow Neutrons exhibit major drop
  - → *D_α info now to be passed to other DECAF events*
- Low-f mode is born and quickly locks (w/in 15ms)
- Large Bp-U increase
- W_{tot} → 0 immediately with D_α spike
- → Probable LTM

Narrow-peaked, quasi-periodic D_α measurements may appear to be ELMs but DECAF detects global plasma profile changes

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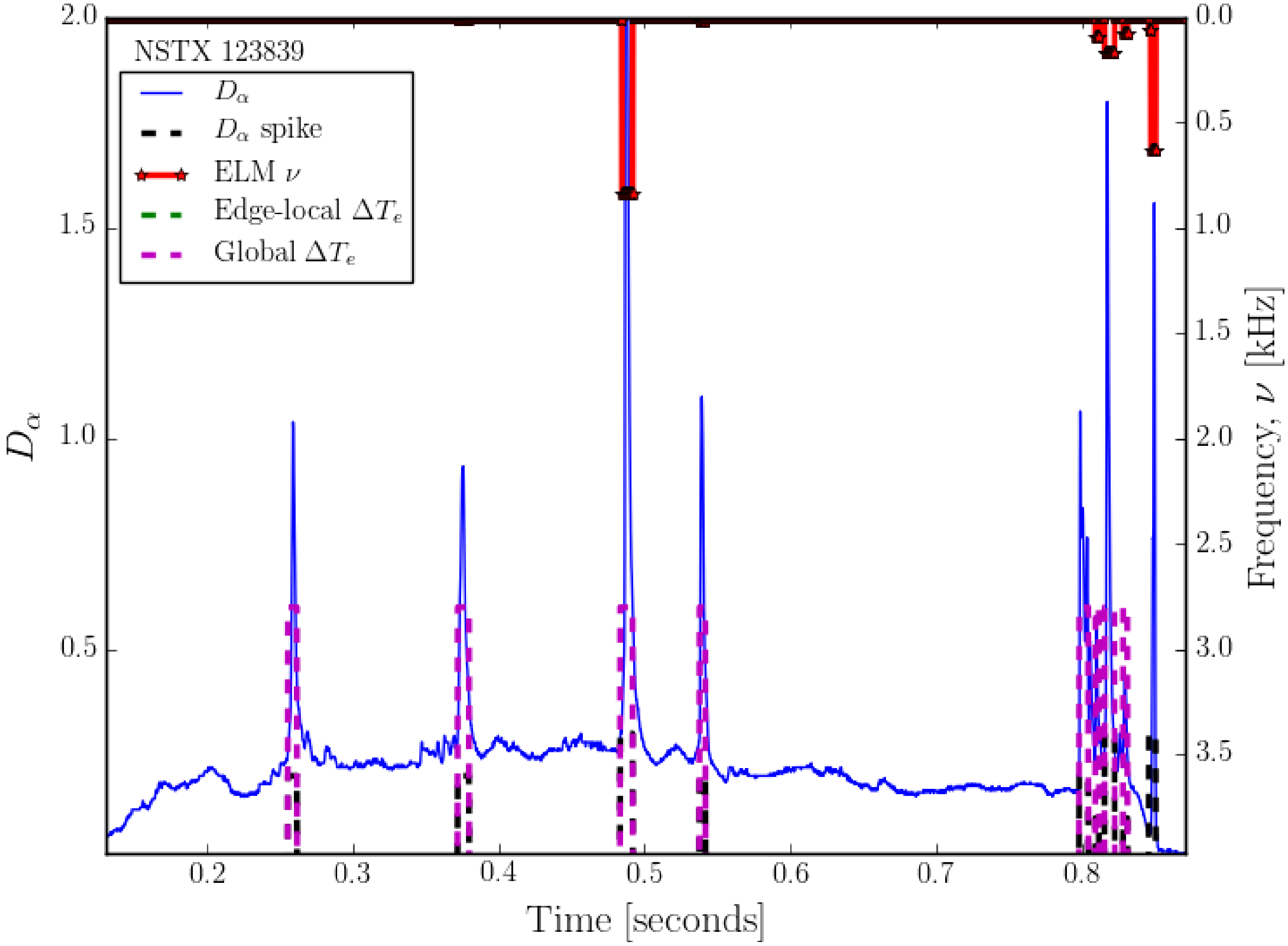
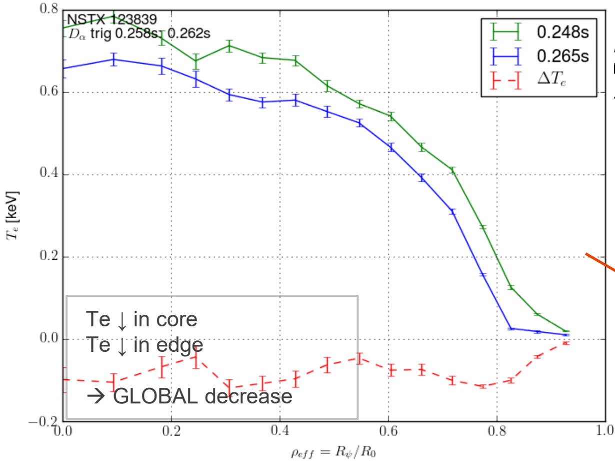
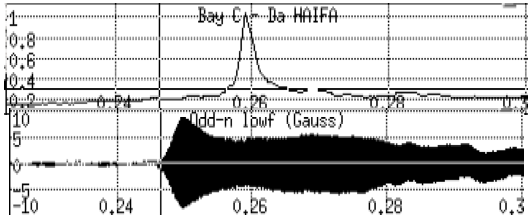
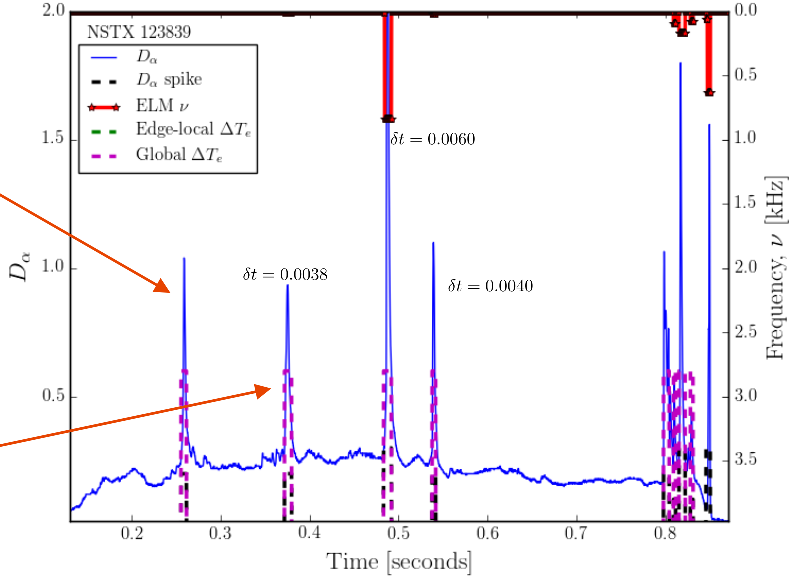


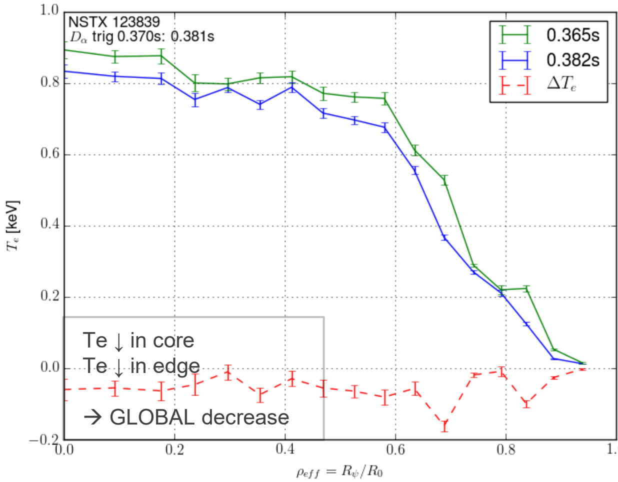
DECAF ELM detector filters out events not supported by edge-localized plasma signals despite ELM-characteristic D_α

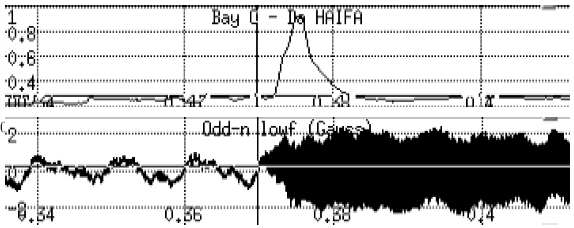




- Global T_e drop, Slow Neutrons exhibit major drop
  - → ***D_α info now to be passed to other DECAF events***
- High frequency, large amplitude *low-f* mode is born (NTM magnetic island)
- → Probable NTM

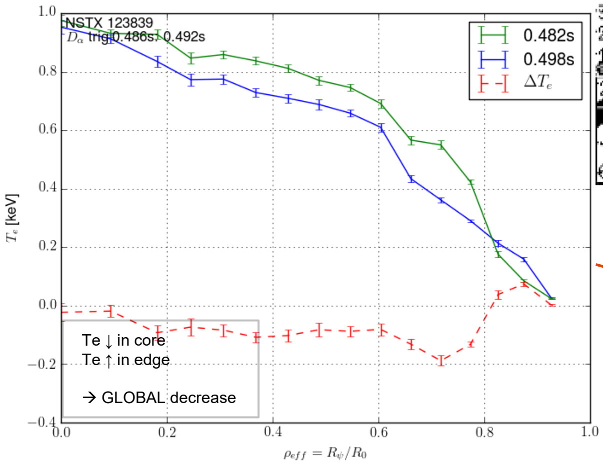


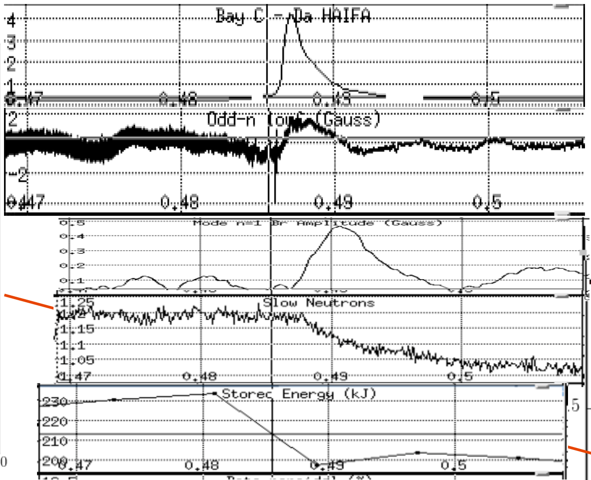




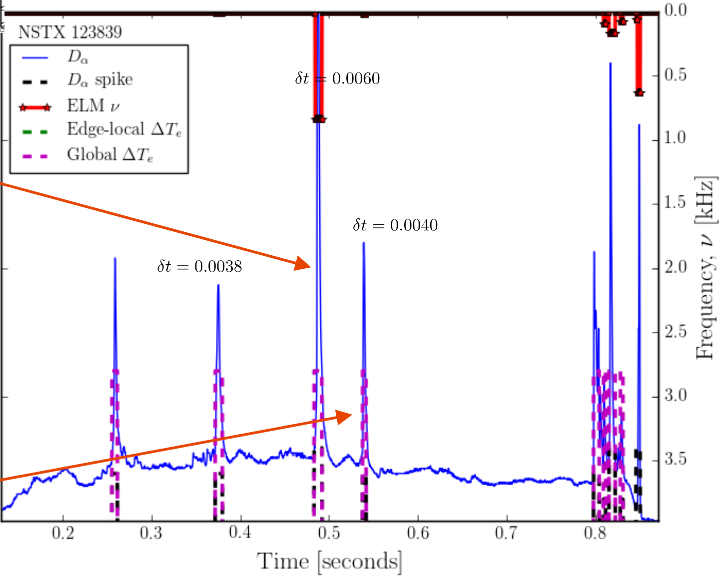
- Global T_e drop, Slow Neutrons exhibit major drop
  - → ***D_α info now to be passed to other DECAF events***
- High frequency, large-amplitude *low-f* mode is born (NTM magnetic island)
- → Probable NTM

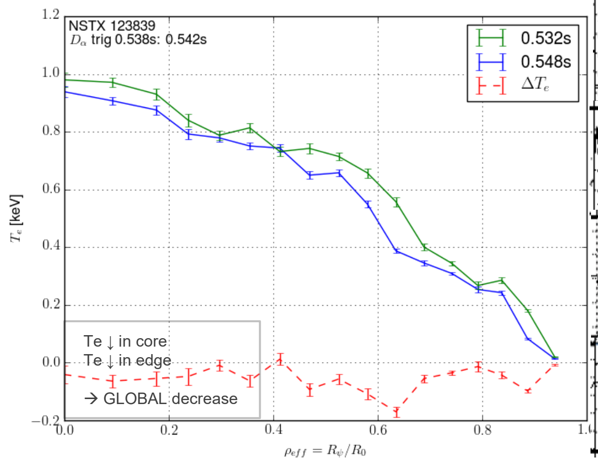
DECAF ELM detector filters out events not supported by edge-localized plasma signals despite ELM-characteristic D_α

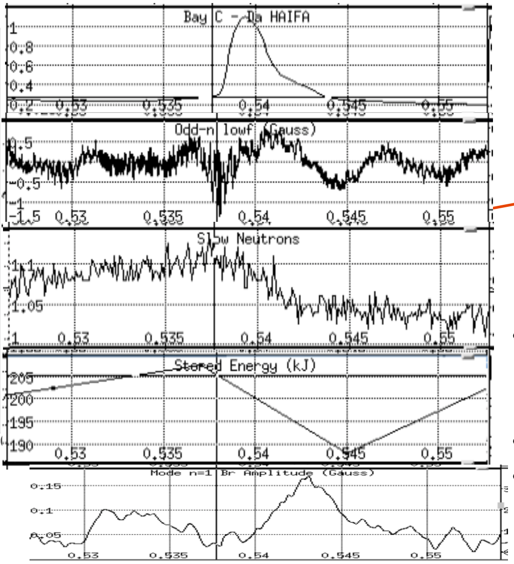




- **Global T_e drop, Slow Neutrons & W_{tot} exhibit large drop**
  - ***→ D_α info now to be passed to other DECAF events***
- **Low frequency *low-f* mode locks**
- **Large Br-U increase**
- **→ Probable LTM**







- **Global T_e drop, Slow Neutrons & W_{tot} exhibit minor drop**
  - ***→ D_α info now to be passed to other DECAF events***
- **Br-U increase**
- **→ Possible LTM**

Narrow-peaked, semi-regular D$_\alpha$ emission transients *look* like ELMing, but DECAF ELM detector claims otherwise

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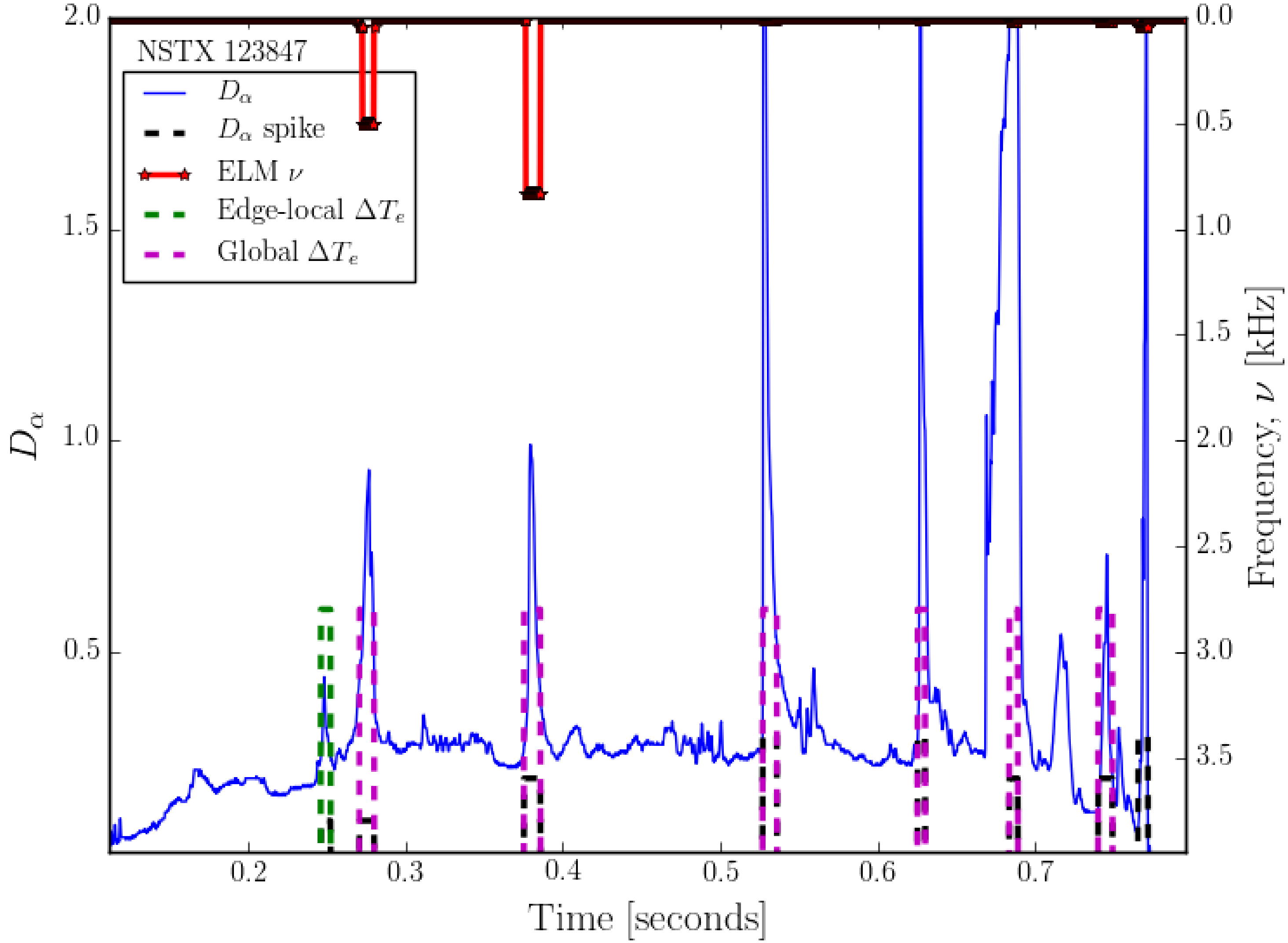

T_e profile provides critical support to ELM-detection by filtering events w/ D_α spike-ing but no edge-localized profile change

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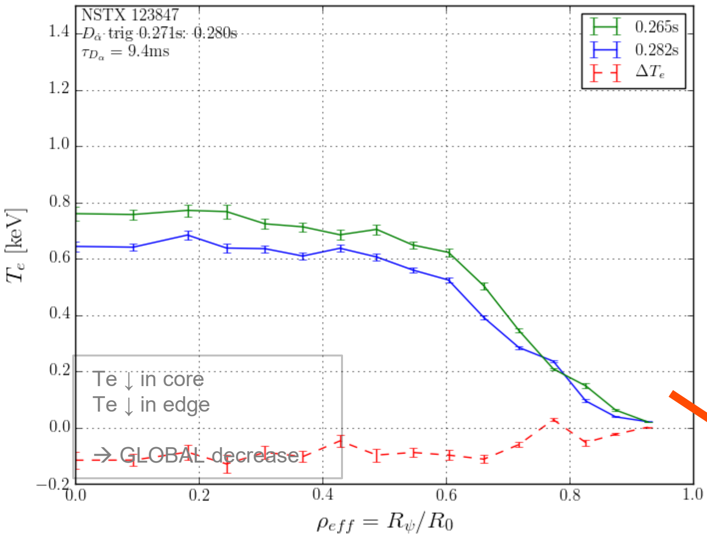
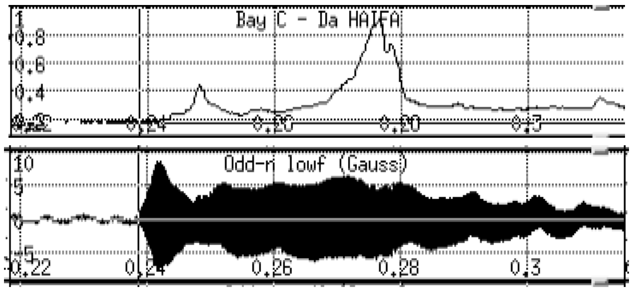
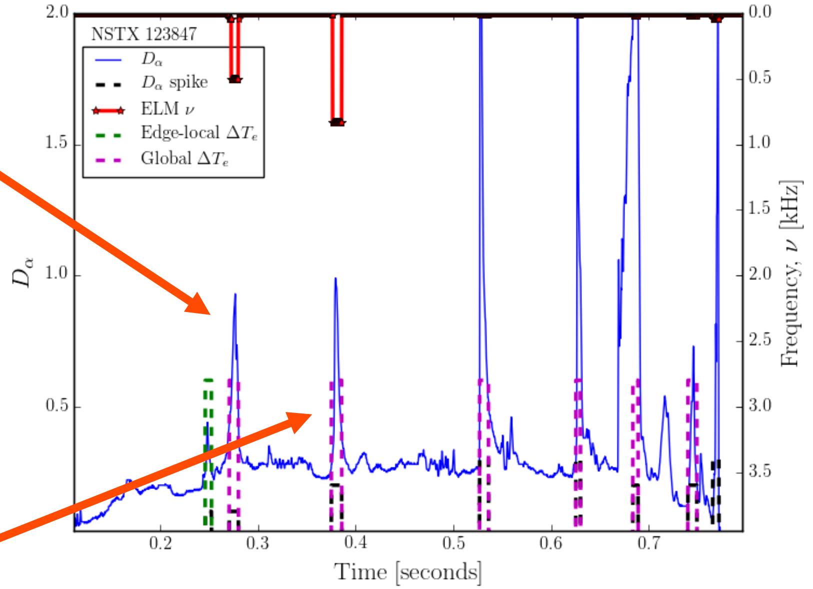
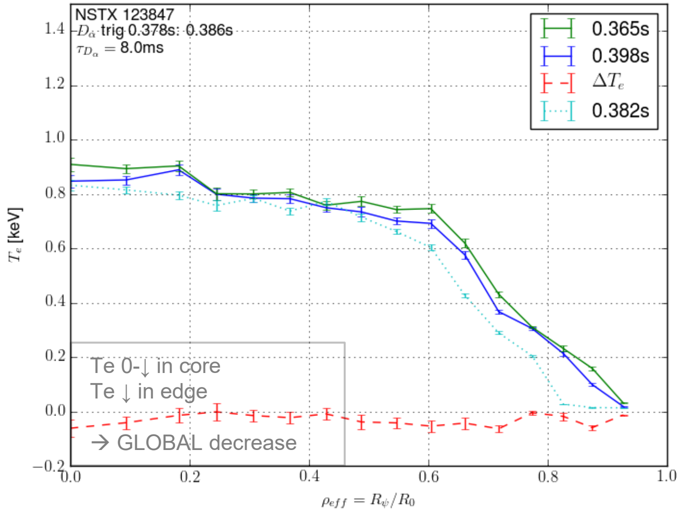


Te ↓ in core
Te ↓ in edge
→ GLOBAL decrease

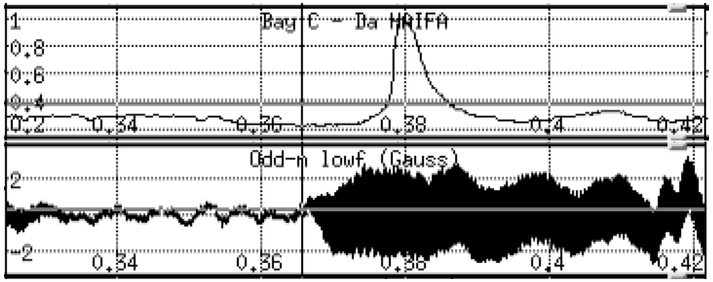


- **Global T_e drop, Slow Neutrons (& W_{MHD}) exhibit catastrophic drop**
  → *D_α info now to be passed to other DECAF events*
- **Low frequency, large-amplitude *low-f* mode is born (NTM magnetic island)**
- **→ Probable NTM**





Te 0-↓ in core
Te ↓ in edge
→ GLOBAL decrease



- **Global T_e drop, large slow neutrons drop**
  → *D_α info now to be passed to other DECAF events*
- **High frequency, large-amplitude *low-f* mode (NTM magnetic island) is either born or grows out of preceding, mostly-damped NTM**
- **→ Probable NTM**

T_e profile provides critical support to ELM-detection by filtering events w/ D_α spike-ing but no edge-localized profile change

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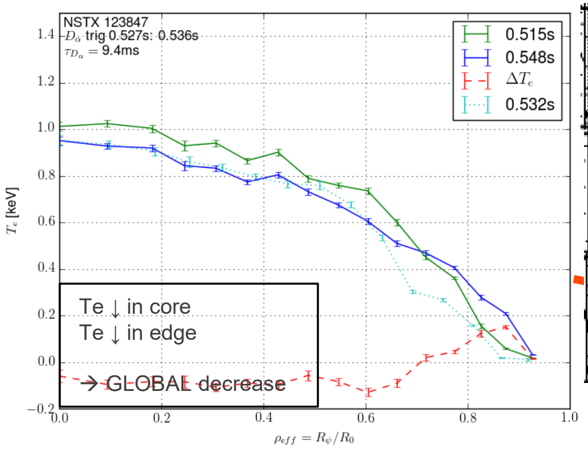

Te ↓ in core
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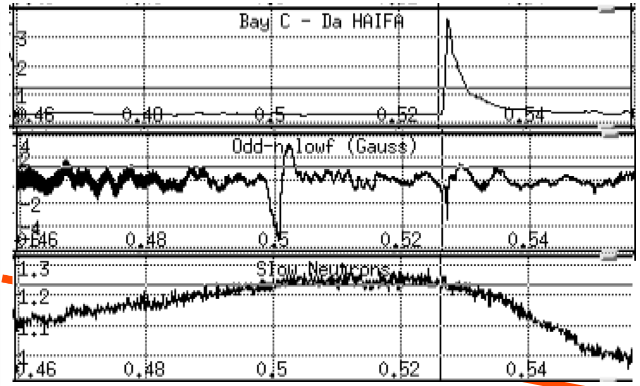
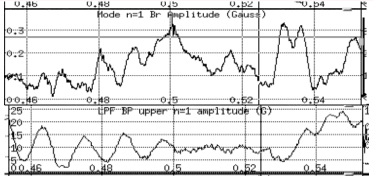
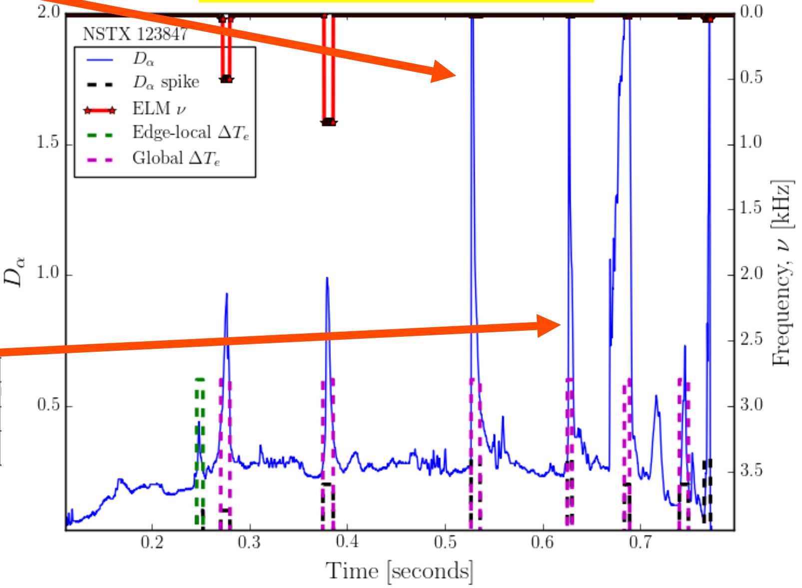
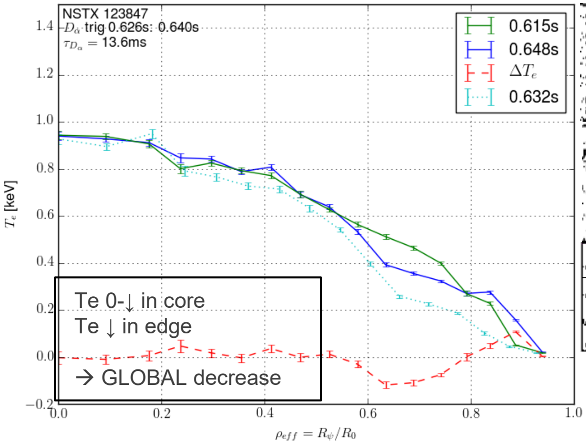
→ GLOBAL decrease



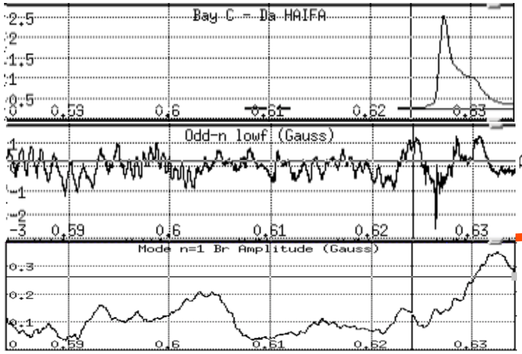


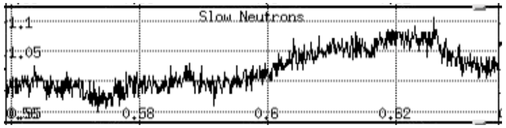
- Global T_e drop, large drop in slow neutrons
  - → *D_α info now to be passed to other DECAF events*
- Br & Bp increase (both B_R-L and B_R-U, but only Bp-L)
- **→Probable Metastable RWM**

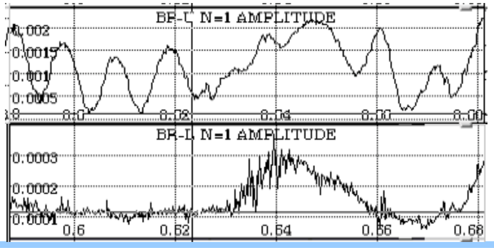




Te 0-↓ in core
Te ↓ in edge
→ GLOBAL decrease







- Global T_e drop, large slow neutrons drop (~10%)
  - → *D_α info now to be passed to other DECAF events*
- Br & Bp increase (both B_R-L and B_R-U, but only Bp-L)
- **→ Probable Metastable RWM**

T_e profile provides critical support to ELM-detection by filtering events w/ D_α spike-ing but no edge-localized profile change

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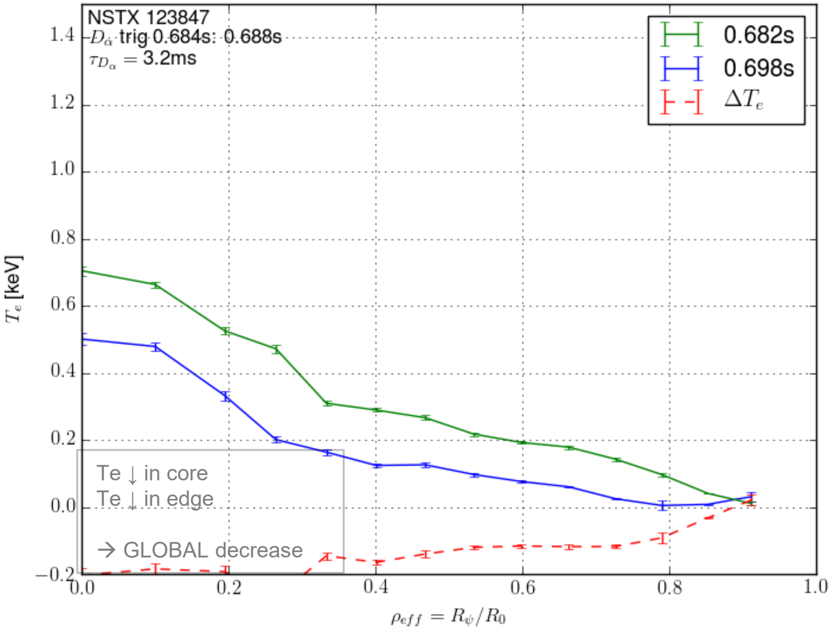
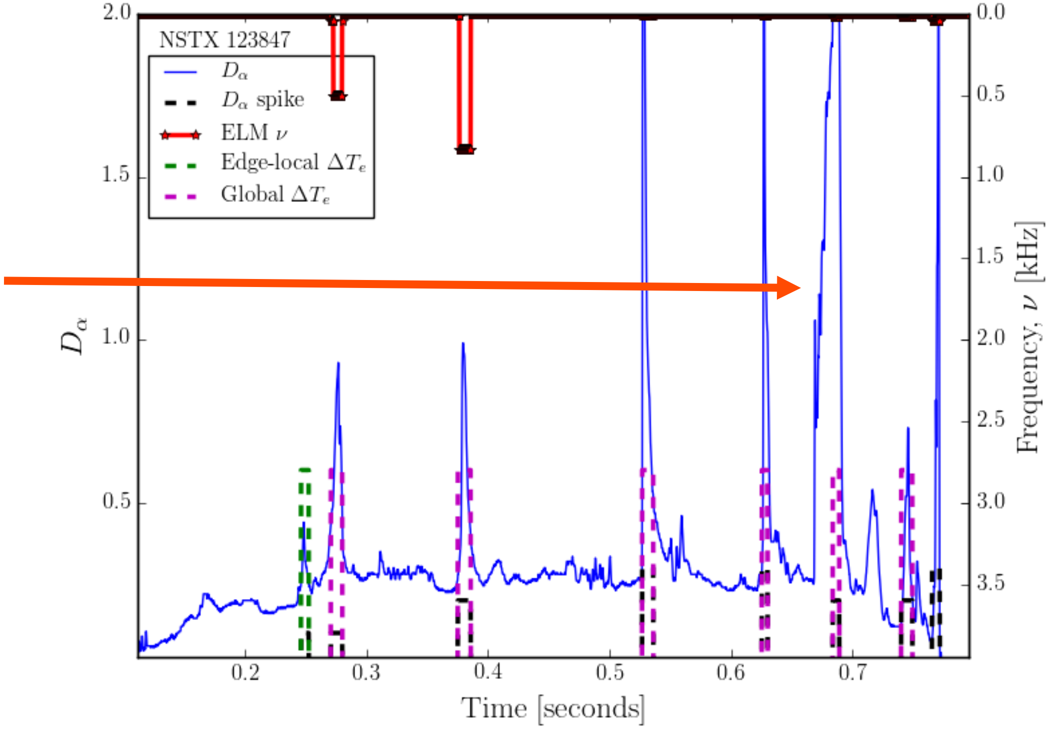
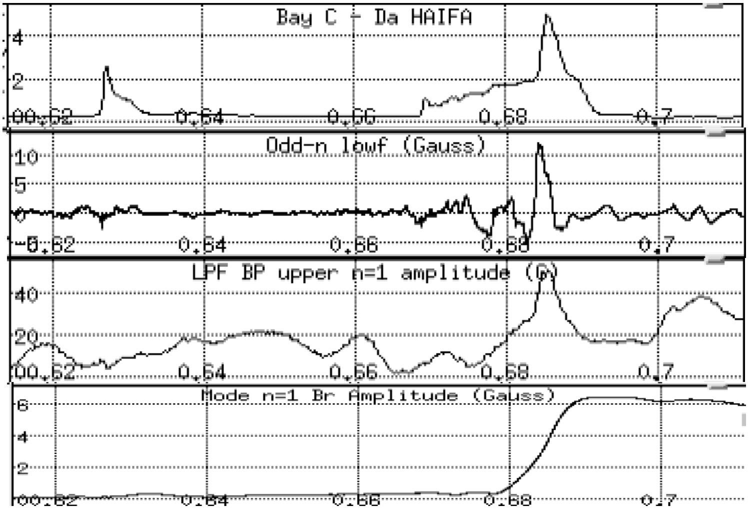
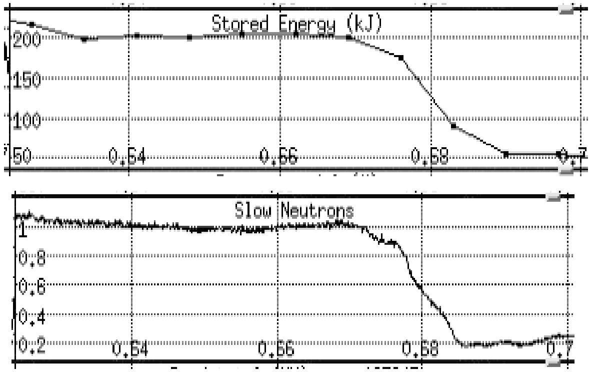


Te ↓ in core
Te ↓ in edge

→ GLOBAL decrease

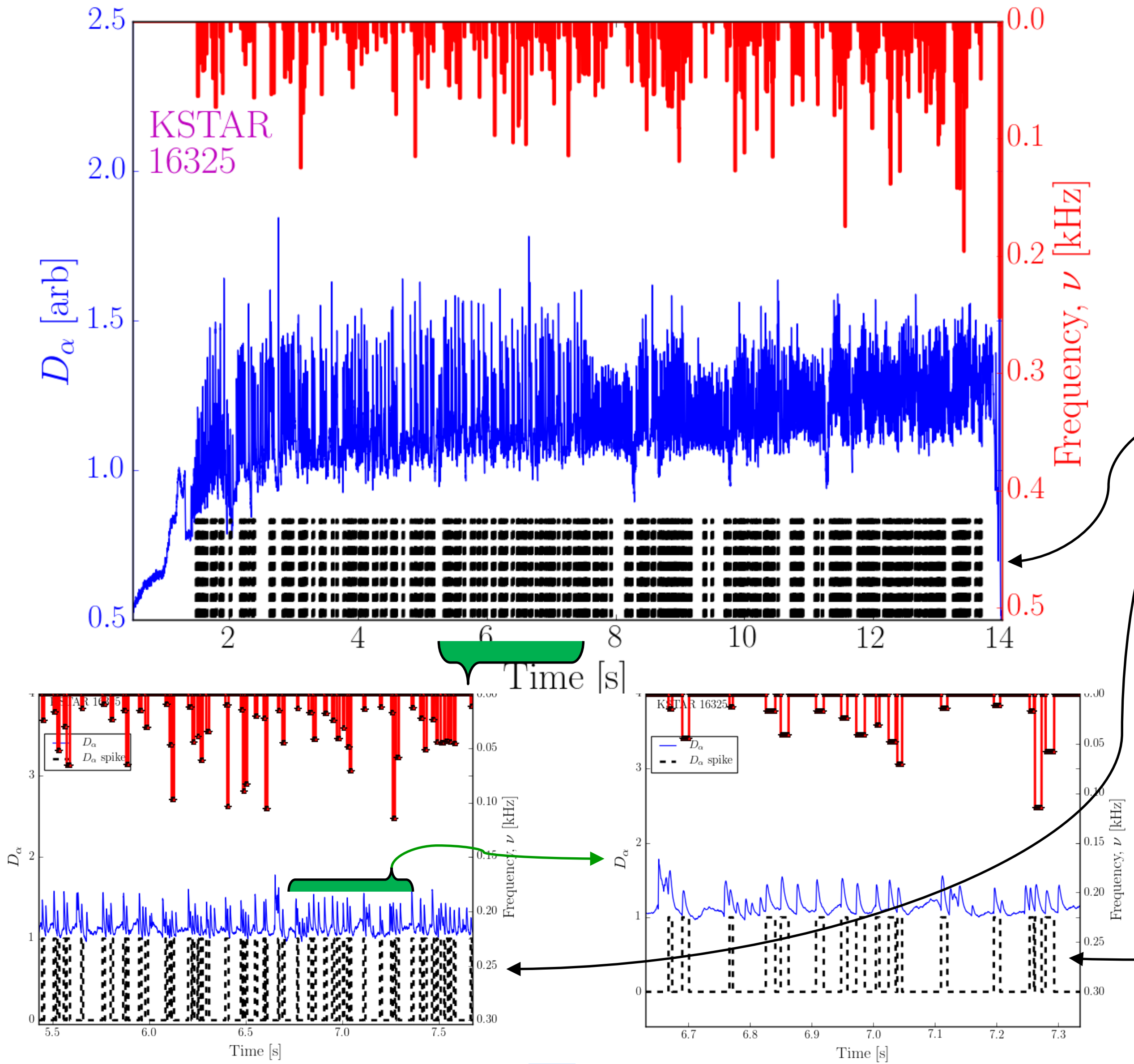






- Global T_e drop, Slow Neutrons (& W_{tot}) exhibit catastrophic drop
  - → *D_α info now to be passed to other DECAF events*
- Low frequency, large-amplitude *low-f* mode seems to be born (NTM magnetic island) and locks w/in 15ms
- Strong RWM sensor (B_R, B_p) signal increase
- → Possible RWM or LTM

DECAF ELM detection capability is machine-general



High frequency, long-duration ELMing on KSTAR

<u>Robust ELM-detection</u>

reliable ELM detection even for high-frequency, long-duration ELMing periods (KSTAR)

Summary, Active and Future Development

❑ Summary

- ❑ Results from DECAF’s ELM event demonstrates its ability to reliably detect ELMs with D_α, T_e, and slow neutrons as inputs
  - DECAF has access to many machines – ELM-event can be generally applied (e.g. KSTAR)
- ❑ Supports other DECAF events with D_α emission transient processing

❑ Active work

- ❑ Studying extent of correlation of ELMs with rotating MHD modes
  - Recent theory predicts MHD transients (e.g. ELMs) can abruptly induce E_r, radially-localized torque, and flows that reduce transient magnetic perturbation frequency → can allow metastable NTM to grow (as req’d by MRE)

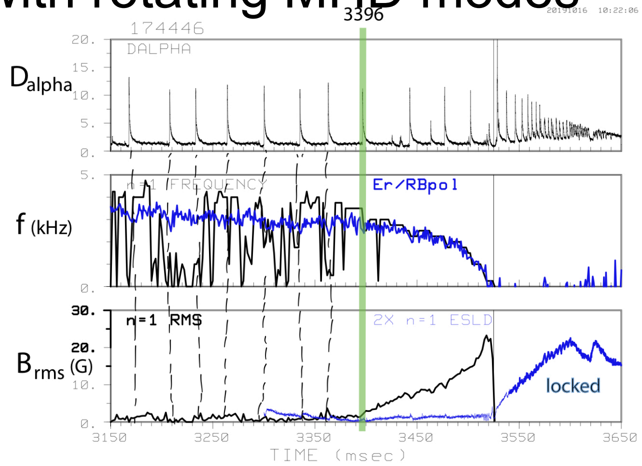


Figure 4: **174446 long time evolution; NTM grows robustly after ELM at 3396 ms.**

J.D. Callen et al, “How are NTMs seeded”, APS-DPP BP10.00028 (2019)

❑ Acknowledgements

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