Characterization of inter-ELM impurity transport following 3D-field-triggered ELMs in NSTX

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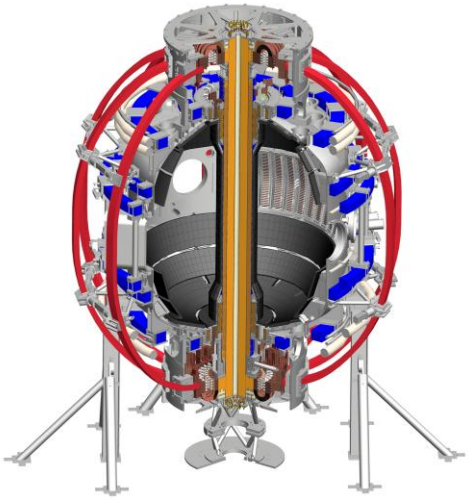
NSTX Upgrade



Fusion Energy Sciences

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PPPL

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Abstract

The response of electron temperature and density profiles to edge localized modes (ELMs) triggered by 3D fields and the inter-ELM impurity transport are studied in NSTX H-mode discharges. 3D magnetic perturbations (n=3) were used in lithium-conditioned ELM-free H-mode discharges to trigger ELMs (f_{ELM}=10-62.5 Hz) and mitigate core impurity buildup [Canik, PRL 2010]. For 10 Hz triggering, impurity flushing was observed for ψ_N>0.5 following the ELM crash, with up to a 30% drop in carbon density at the pedestal top and comparable effects on the T_e, n_e, T_i, v_Φ profiles. The increase in the triggered ELM frequency progressively reduced the total carbon inventory, affecting profiles at inner radii. Carbon transport during and following the ELM crash is modeled using the impurity transport code MIST. Transient perturbations to the steady state particle diffusivity D and convective velocity v are applied to simulate the effect of the ELM on the carbon density evolution. An inward (convective) transport perturbation for ψ_N<0.5 and an outward (diffusive and/or convective) transport perturbation for ψ_N>0.5 are needed to reproduce the carbon density profile temporal evolution. While the equilibrium v/D ratio is inferred from the steady state carbon density profiles, the profile recovery following the ELM crash is used to estimate absolute values of the transport coefficients.

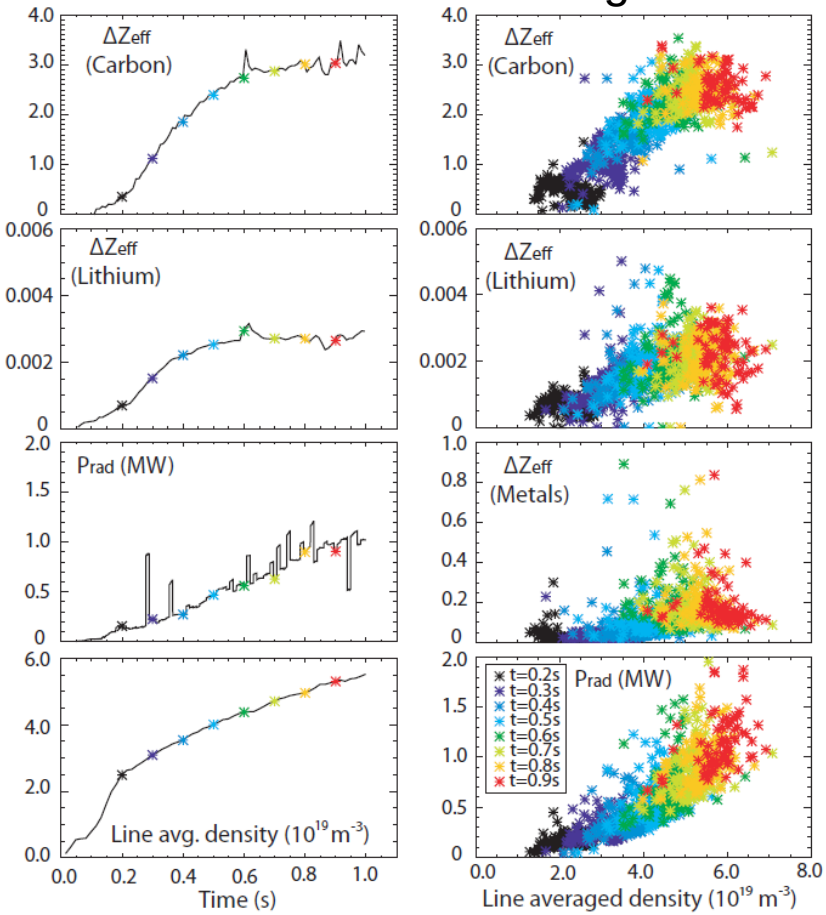
Summary/Outline

- NSTX H-mode discharges characterized by limited density control
- Lithium-conditioning + RMP-triggered ELMs candidate scenario for particle control in NSTX-U
- Changes in impurity density profiles associated to changes in neoclassical transport due to changes in main ion profiles following ELMs
- MIST simulations also suggestive of change in impurity transport as a result of 3D-fields triggered ELMs

NSTX H-mode discharges characterized by limited density control

- NSTX H-mode discharges lacked density control
  - Uncontrolled D inventory w/ boronized PFCs (ELMy)
  - Uncontrolled C inventory w/ lithiated PFCs (ELM-free)
- Baseline scenarios in NSTX-U:
  - D control via cryopump w/ boronized PFCs
  - Impurity control techniques w/ lithiated PFCs
- Techniques considered are based on:
  - Enhanced core impurity transport:
    - Triggered ELMs via 3D fields or lithium granules
    - Controlled lithium introduction (natural ELMs)
  - Reduction of sources:
    - Divertor detachment
    - Upward lithium evaporation
  - Reduction of divertor impurity leakage:
    - Deuterium divertor gas puff

ELM-free lithiated discharges



F. Scotti, NF 2013.

3D-fields-triggered ELMs applied on NSTX to mitigate impurity accumulation

- Magnetic perturbations produced via external midplane coils (4 ms, 3 kA, n=3) [1]
- ELM-pacing up to 62.5 Hz was achieved [2,3]
- Large ELMs induced by magnetic perturbations
  - $\Delta W/W \sim 15\%$ at $f_{ELM} = 10$ Hz
  - $\Delta W/W \sim 5\%$ at $f_{ELM} = 60$ Hz
  - Overall reduction of 10-15% in stored energy at high f_{ELM}
- No enhanced particle transport observed with application of sub-threshold n=3 fields [4]

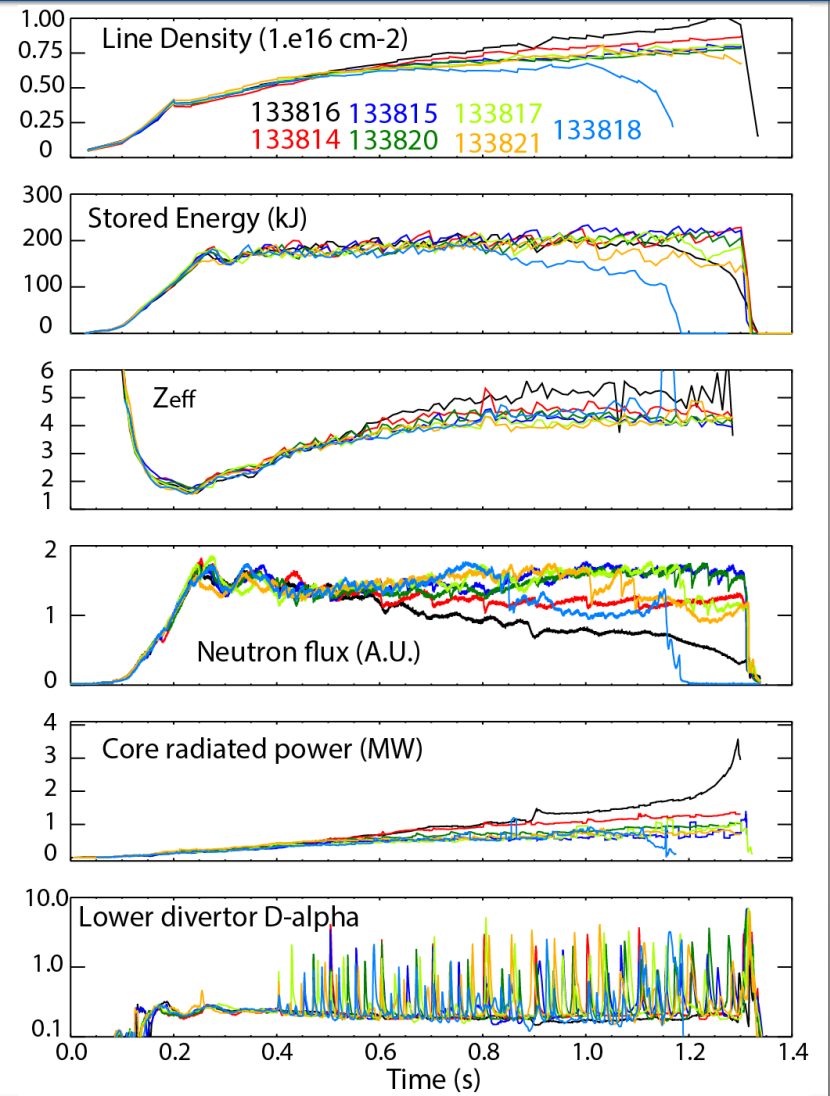
[1] J. Canik, PRL 2009.
[2] J. Canik, NF 2010 - 1.
[3] J. Canik, NF 2010 - 2.
[4] J. Lore, JNM 2013.

Reduction in Z_{eff}, core P_{rad} and n_e ramp rate with increase in ELM frequency

Lithium evaporative coatings: 250 mg
Lower biased double null $\delta_{r\text{-}sep}$ ~ 8 mm
I_p = 800 kA, P_{NBI} = 4MW
Strong shaping κ~2.4, δ~0.7
Naturally ELM-free discharges

- Decreased n_e ramp rate
- Decrease in Z_{eff} , core P_{rad}
- Increase in neutron flux
- Confinement degraded at high f_{ELM} due to onset of MHD activity (n=1)
  - 133818 at t=0.8 s

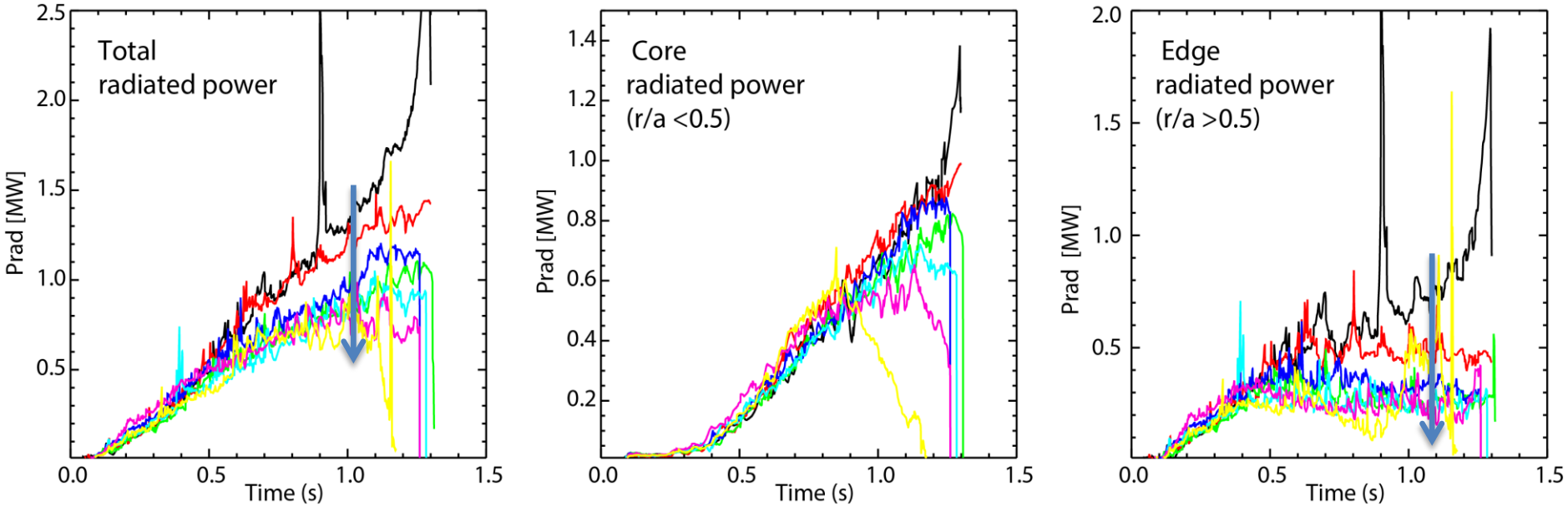
Ref., 10 Hz, 20 Hz, 30 Hz, 40 Hz, 50 Hz, 60 Hz



Radiated power controlled in outer plasma, unaffected by ELMs in the core

- Progressive reduction of total core P_{rad}
- Arrested P_{rad} ramp in outer half of plasma
- No effect on P_{rad} inside r/a=0.5, strongly peaked P_{rad} density due to metals

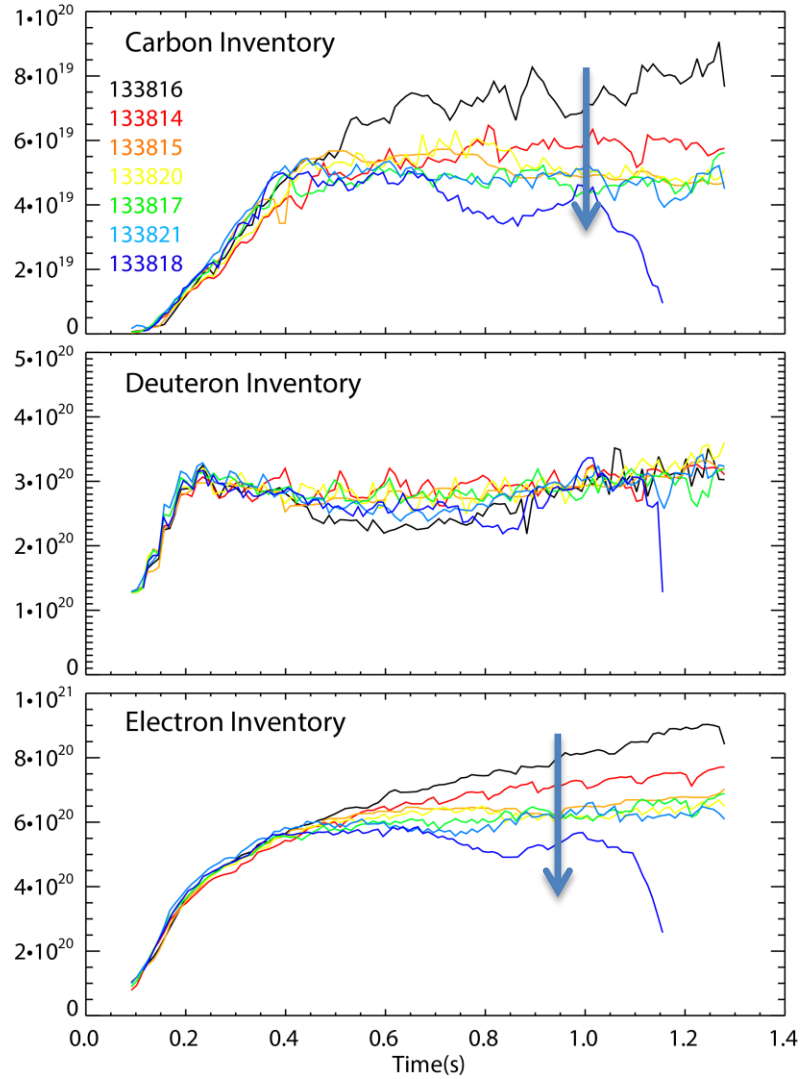
Ref., 10 Hz, 20 Hz, 30 Hz, 40 Hz, 50 Hz, 60 Hz



Carbon inventory controlled, electron inventory ramp rate slowed down

- Deuterium inventory always ~ controlled thanks to lithium conditioning
- With RMP-triggered ELMs:
  - Uncontrolled carbon inventory slowed down and stopped
  - Ramp rate of electron inventory reduced

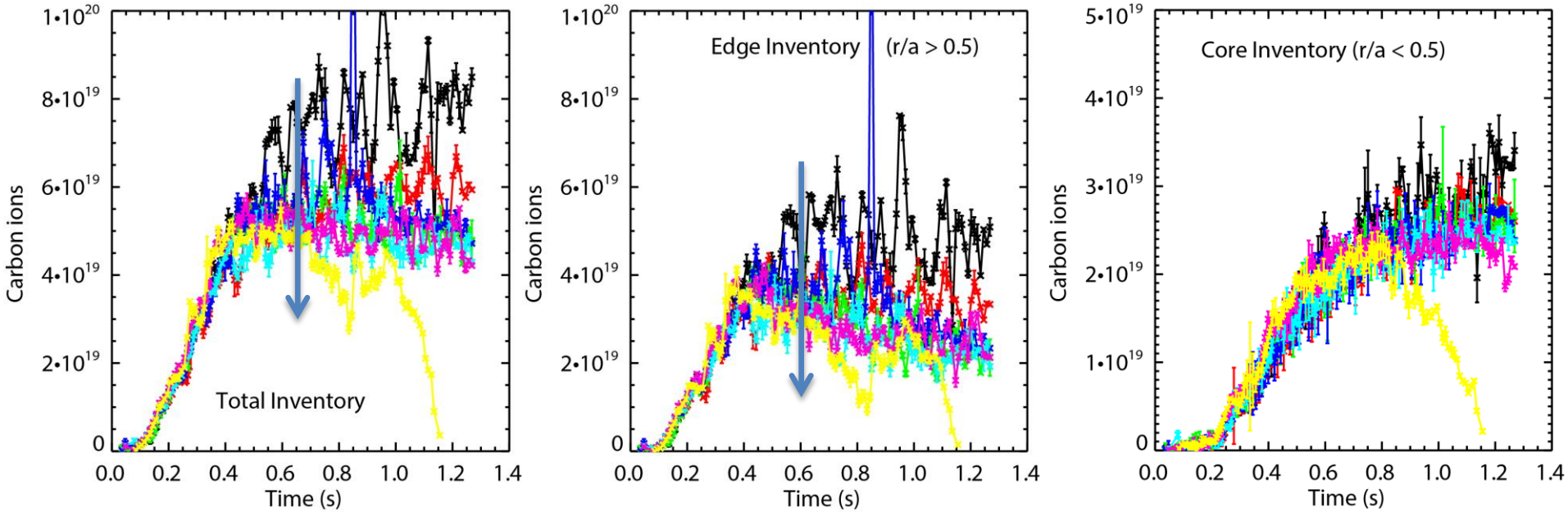
Ref.,
10 Hz, 20 Hz, 30 Hz,
40 Hz, 50 Hz, 60 Hz



Carbon edge inventory decreases with f_{ELM}, core inventory unaffected

- Progressive effect on total inventories due to flushing of edge carbon
- No effect on carbon inventories inside r/a=0.5
- Motivates analysis of profile changes and impurity transport induced by ELMs

Ref., 10 Hz, 20 Hz, 30 Hz, 40 Hz, 50 Hz, 60 Hz

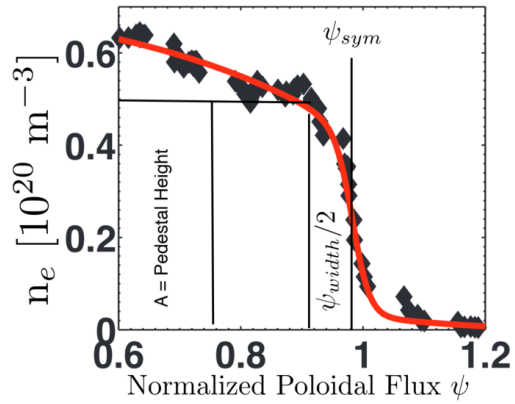


Conditional averaging applied to fit kinetic profiles during ELM cycle

- Conditional averaging over pseudo ELM cycle used to accumulate T_e, n_e, T_i, v_{tor}, n_c profiles
  - Profiles evolution recovering from RMP-ELM crash
  - Profile changes between shots at same fraction of ELM cycle

- Modified tanh function fitted to T_e, n_e, p_e profiles

- Spline fits for T_i, v_{tor}, n_c



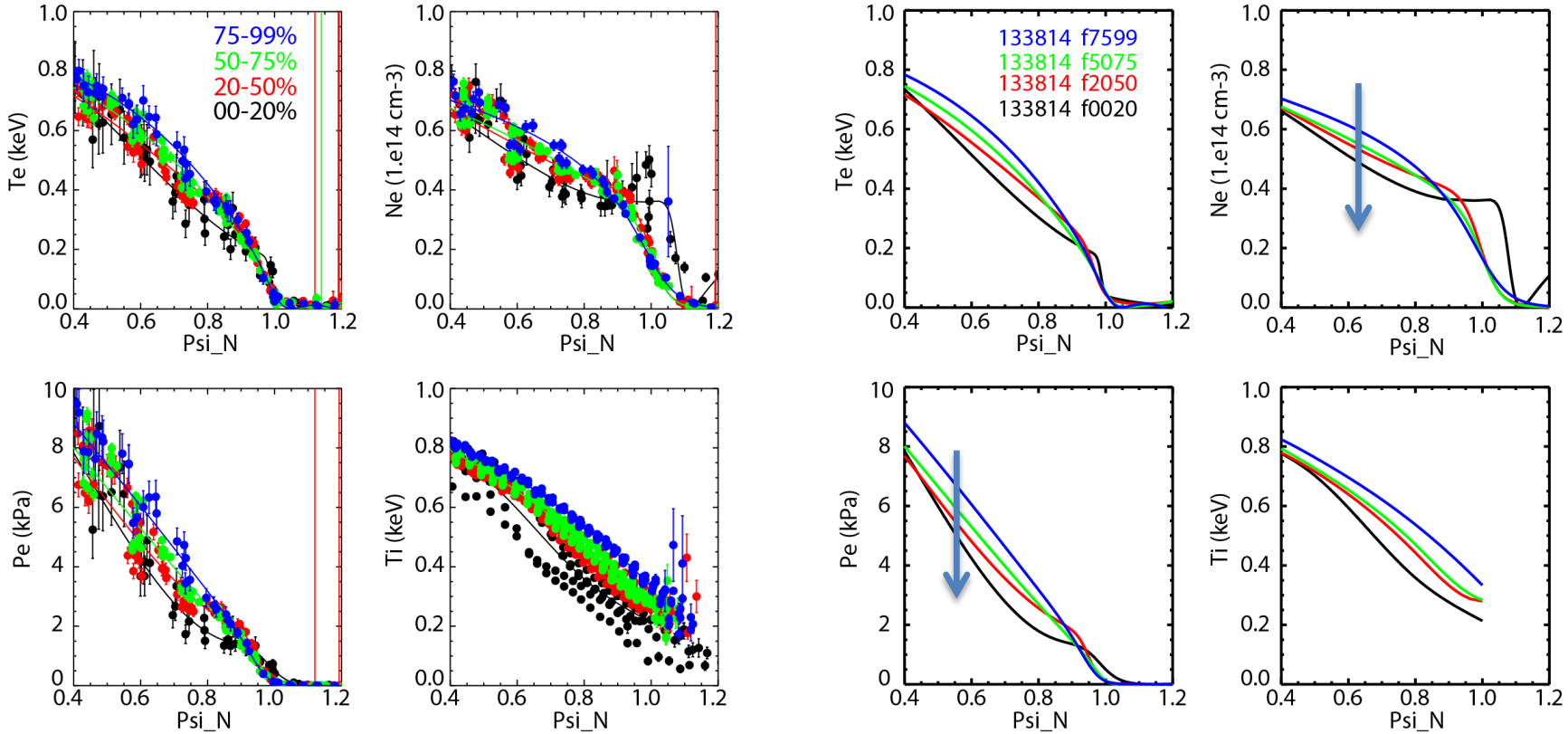
A. Diallo, Invited APS-DPP 2011.

$$N(\psi) = A \tanh\left(\frac{\psi_{sym} - \psi}{\psi_{width}}\right) + offset$$

R. Groebner and T. Osborne PoP (1998)

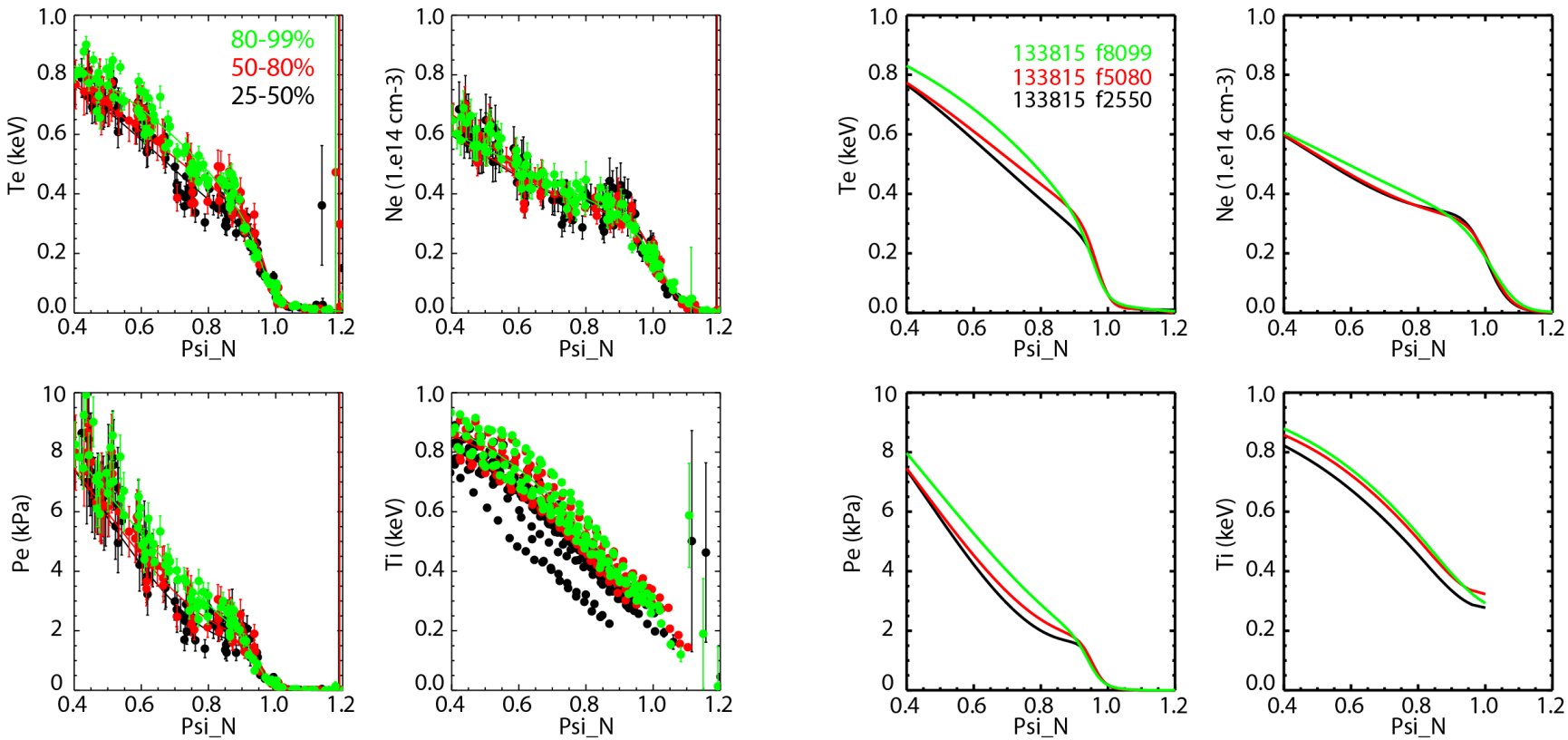
Reduction in pedestal T_e, T_i, P_e, n_e following 10Hz ELMs crash

- T_e, n_e, p_e, T_i profile crash due to triggered ELM
- Profile recovers to ELM-free values within 100 ms



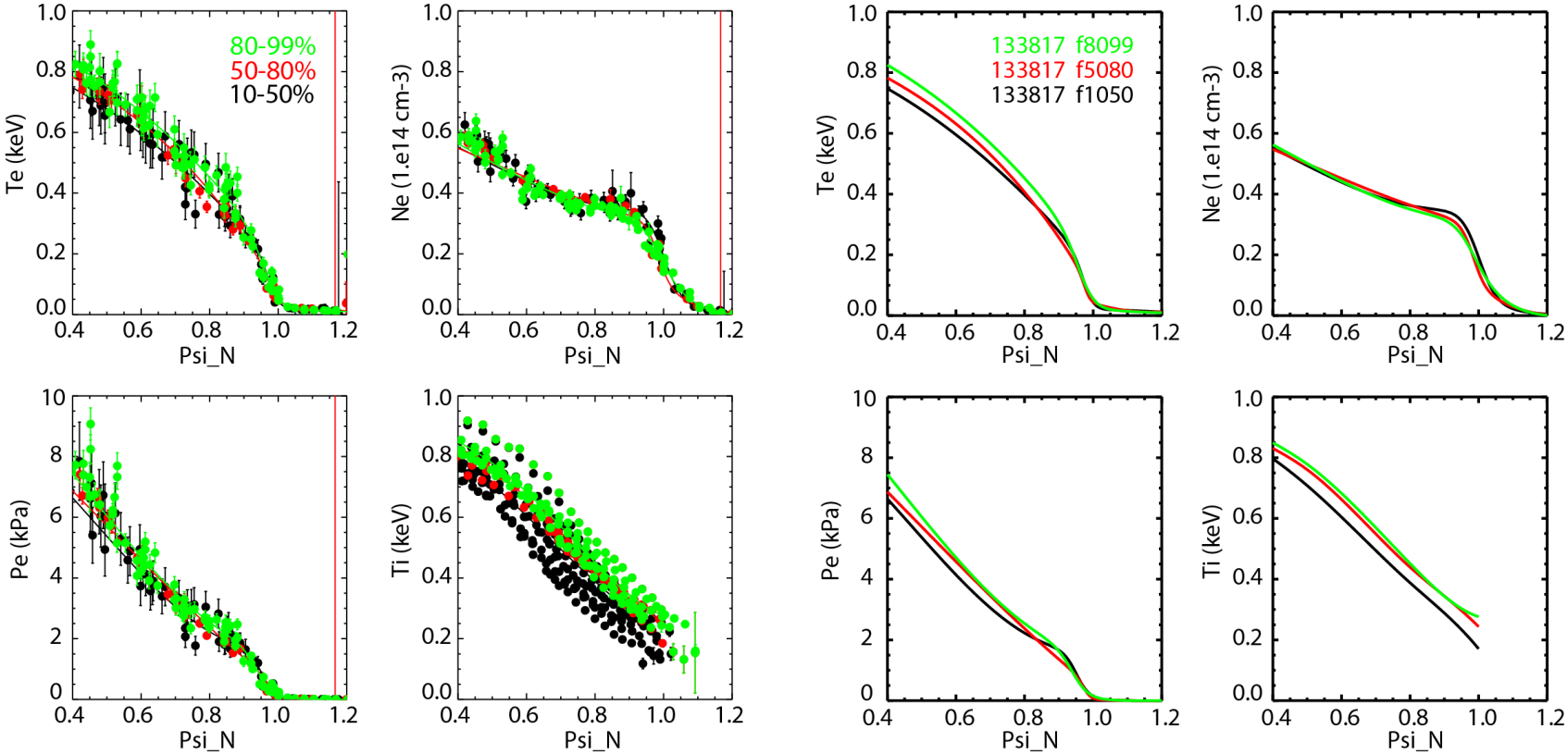
Increasing the triggering frequency reduces the size of triggered ELMs

- Smaller effect on T_e, n_e, p_e, T_i profiles at 20 Hz
- Profiles do not recover to the ELM-free values



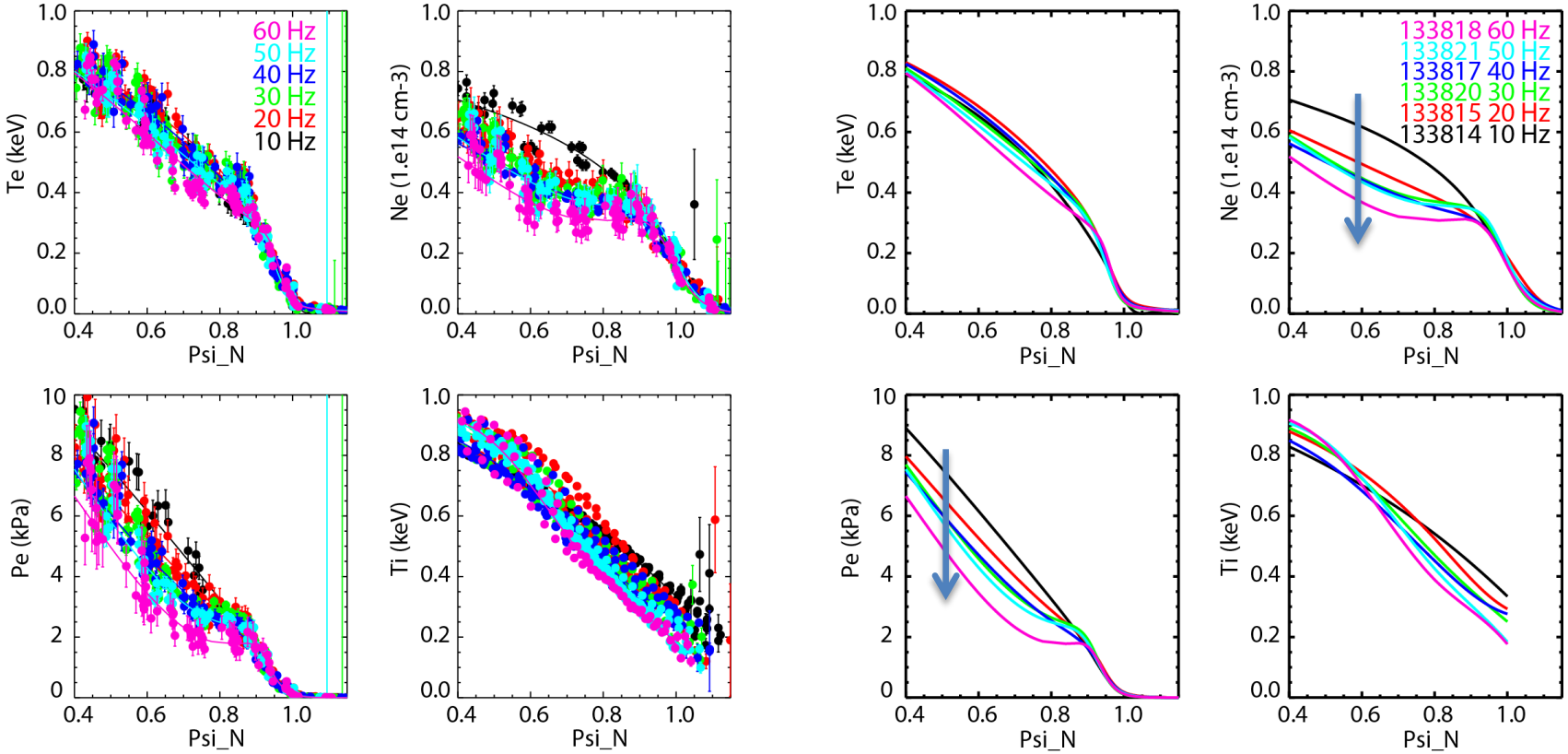
Equilibrium profiles progressively affected by higher f_{ELM}

- At 40 Hz, even smaller effect on T_e, n_e, p_e, T_i profiles
- Profiles do not recover to the ELM-free values



Large changes in n_e, P_e, T_i equilibrium profiles with increase in ELM frequency

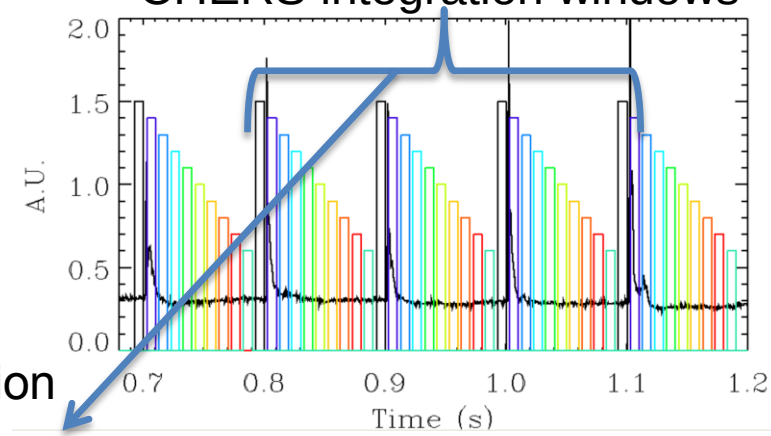
- Electron profiles clamped near separatrix
- Largest changes in n_e, p_e, T_i at Psi_N=0.7

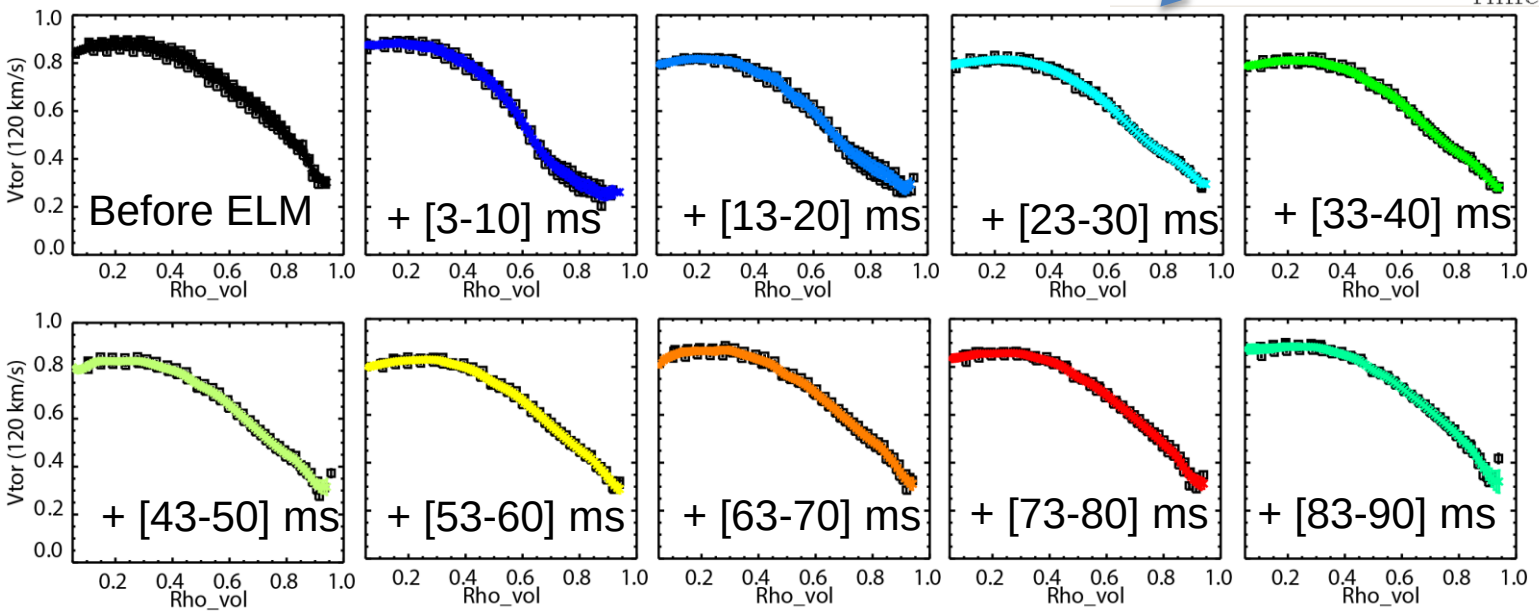


ELM-triggering synced to CHERS acquisition, profiles accumulated over ELM cycles

- ELM-triggering synced to CHERS acquisition
- Profiles accumulated over ELM cycles
- Smoothed splined profiles
- Monte Carlo method for error determination
- Can't resolve ELM crash due to CHERS integration

CHERS integration windows

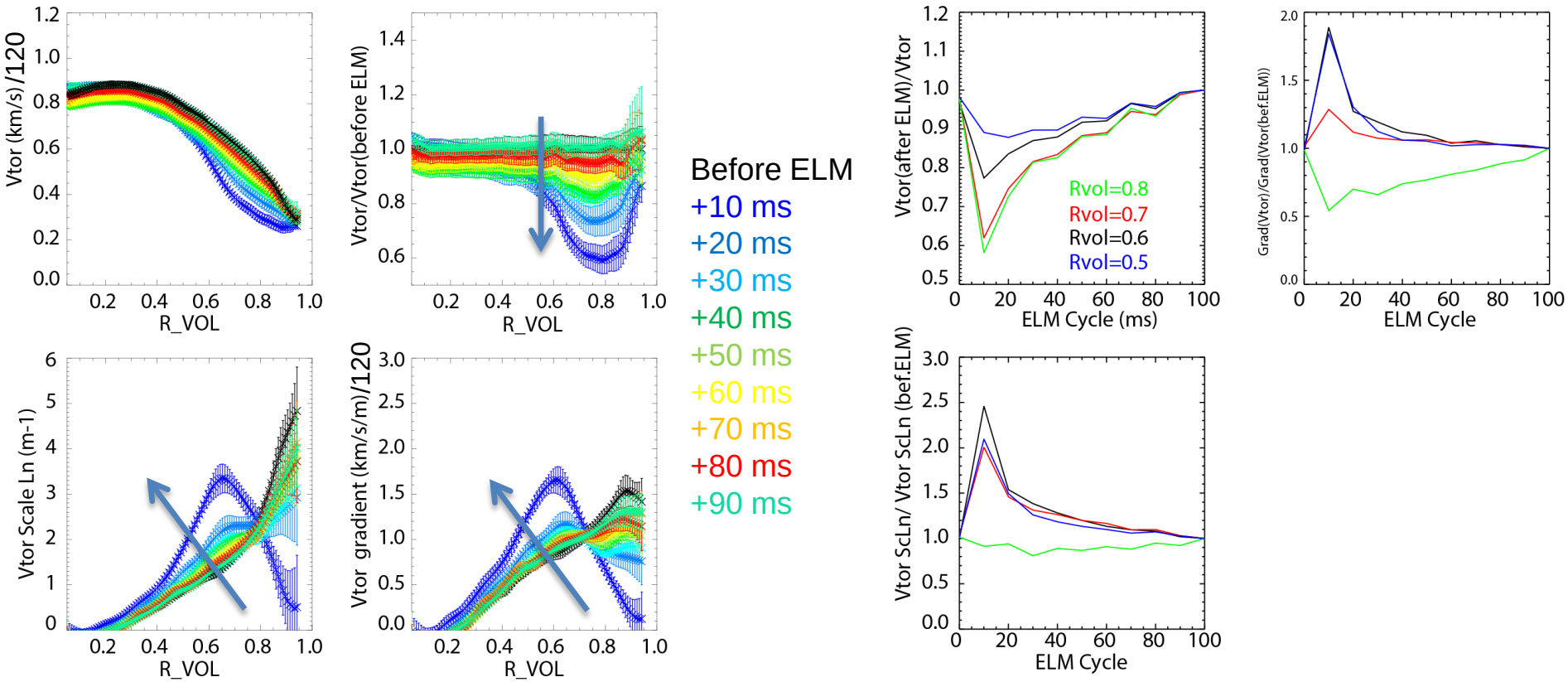




133814 Profiles from 3 ELM cycles

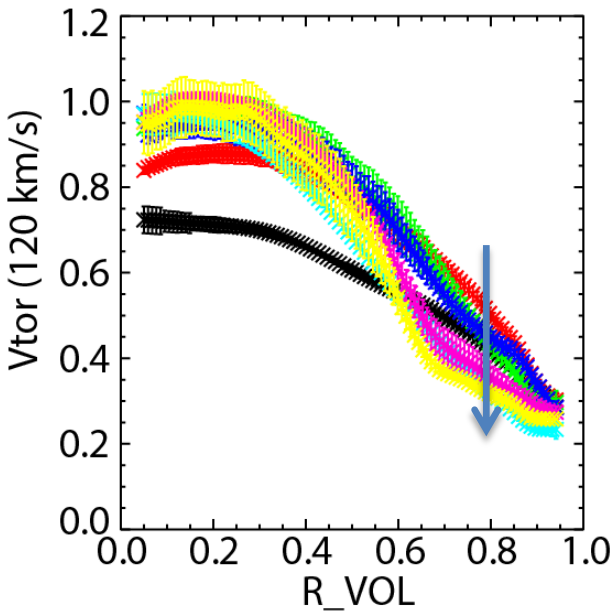
Pedestal v_{tor} drops 40% following 10Hz ELMs, recovery time 10s ms

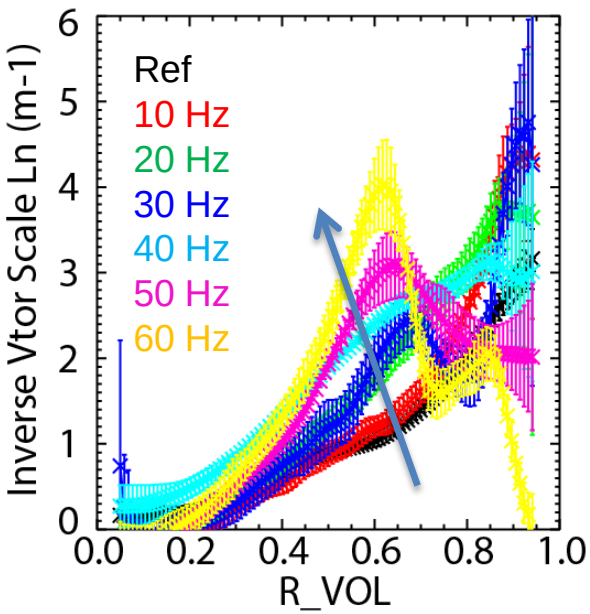
- V_{tor} profile recovers to pre-ELM values within 100 ms
- Edge v_{tor} gradient increases, moves inward

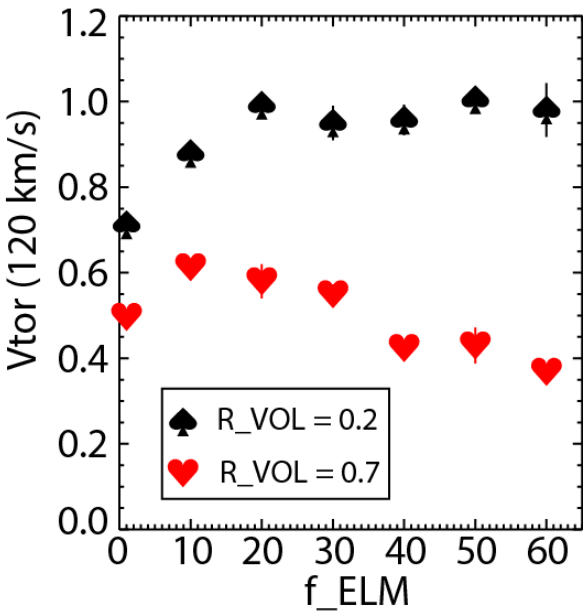


Steady state v_{tor} profiles progressively affected by increase in f_{ELM}

- V_{tor} higher in the core, lower at edge
- Steep gradient moves inward
- Profile does not recover to the ELM-free values

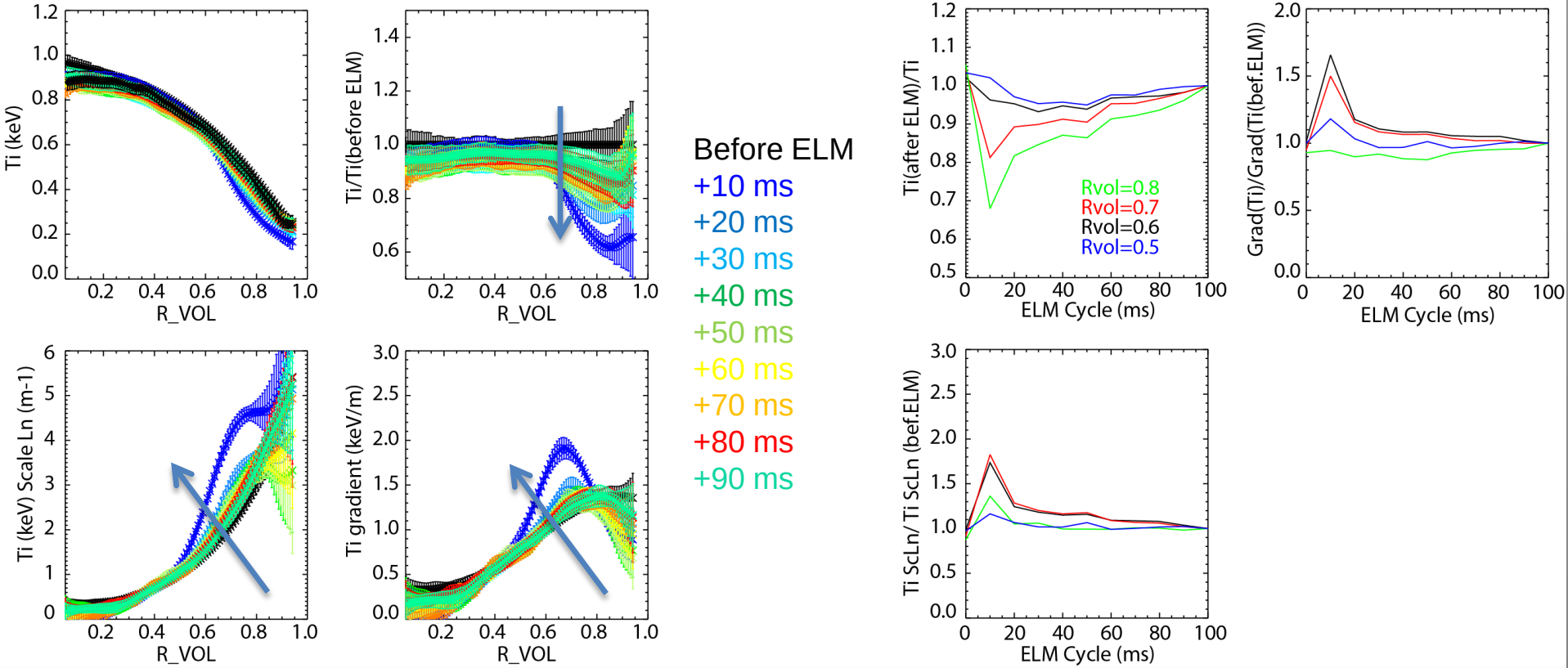






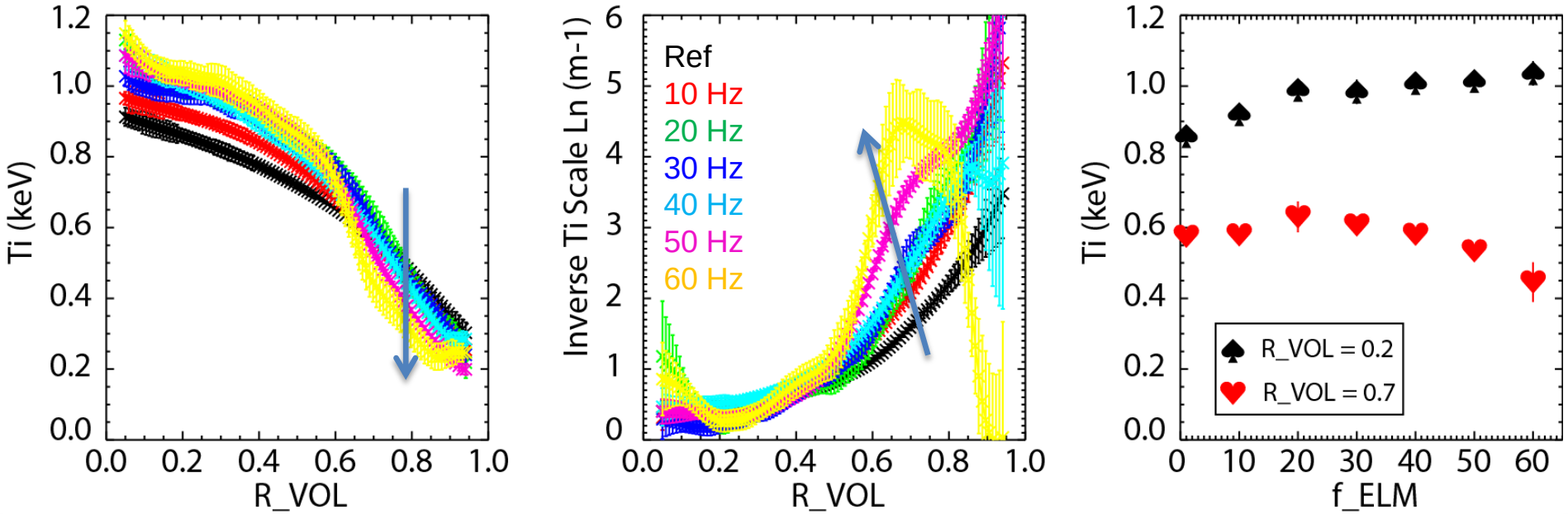
Pedestal T_i drops 40% following 10Hz ELMs, recovery time 10s ms

- T_i profile recovers to pre-ELM values within 100 ms
- Edge T_i gradient increases, moves inward



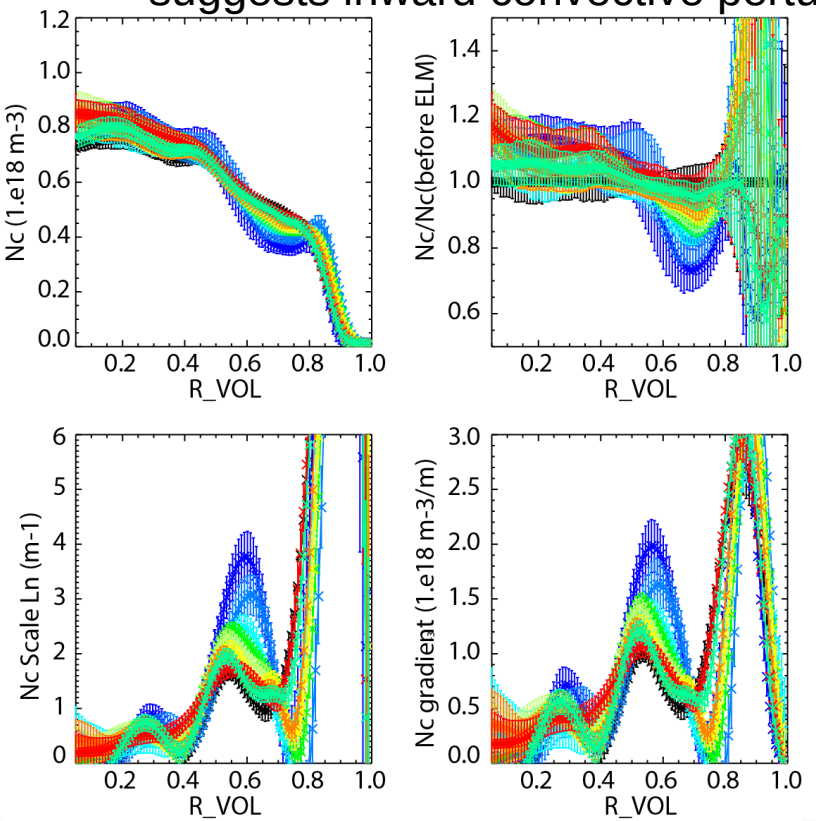
Steady state T_i profiles progressively affected by increase in f_{ELM}

- T_i higher in the core, lower at edge, steep gradient moves inward
- Changes comparable to changes in v_{tor} profiles
- Profile does not recover to the ELM-free values

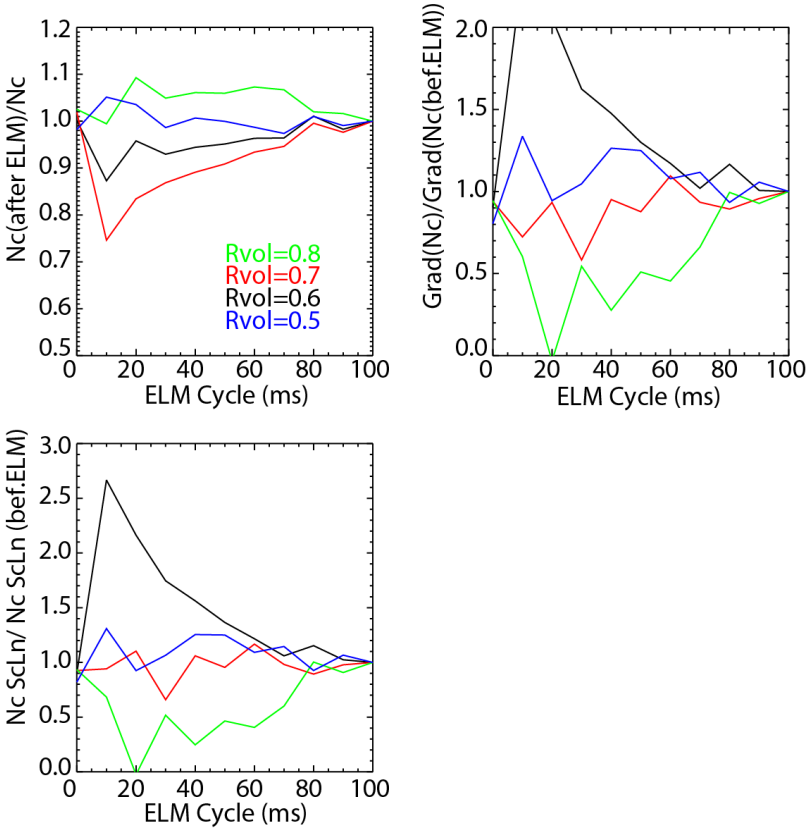


Carbon density drops up to 30% inside pedestal top as a result of 10 Hz ELMs

- n_C drops 30% inside pedestal top, flattening between R_{vol}=0.6-0.8
  - Suggests outward diffusive/convective perturbation
- n_C increases inside R_{vol} =0.5
  - suggests inward convective perturbation

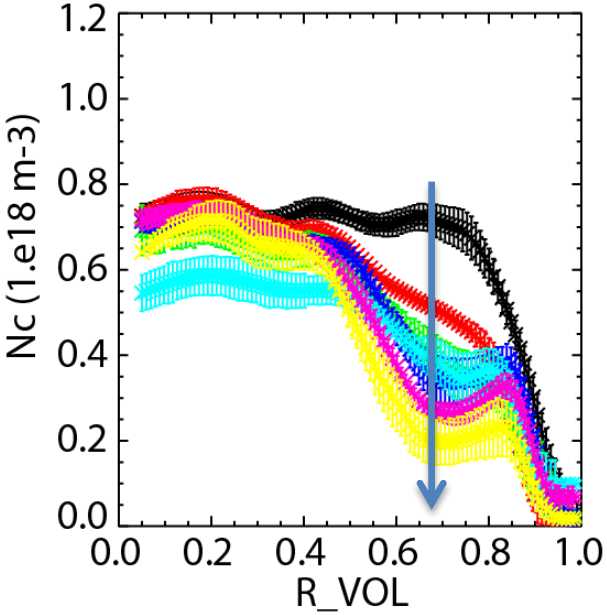


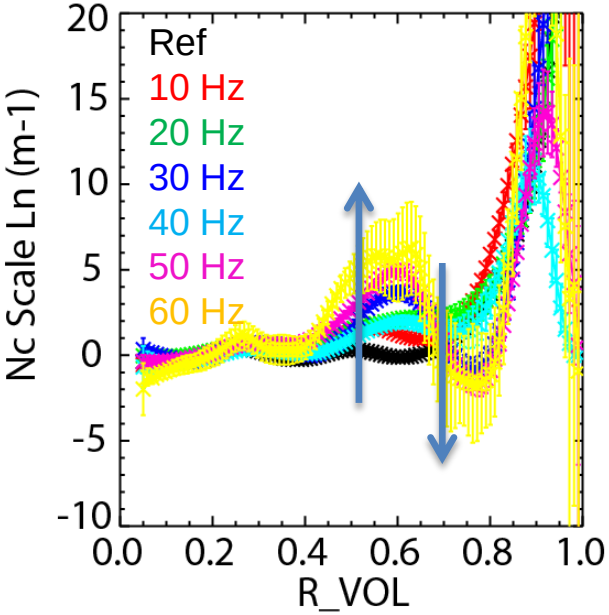
Before ELM
+10 ms
+20 ms
+30 ms
+40 ms
+50 ms
+60 ms
+70 ms
+80 ms
+90 ms

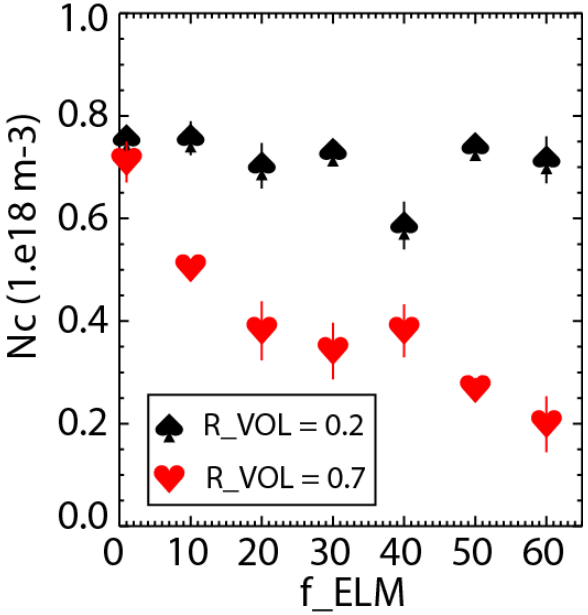


Steady state edge carbon density progressively affected by increase in f_{ELM}

- n_c progressively flushed outside R_{vol} =0.5
  - Over 3x decrease for f_{ELM}=60Hz with respect to ELM-free
- n_c unchanged in steep gradient region and in core
  - Suggest transport change for R_{vol} =0.5-0.8

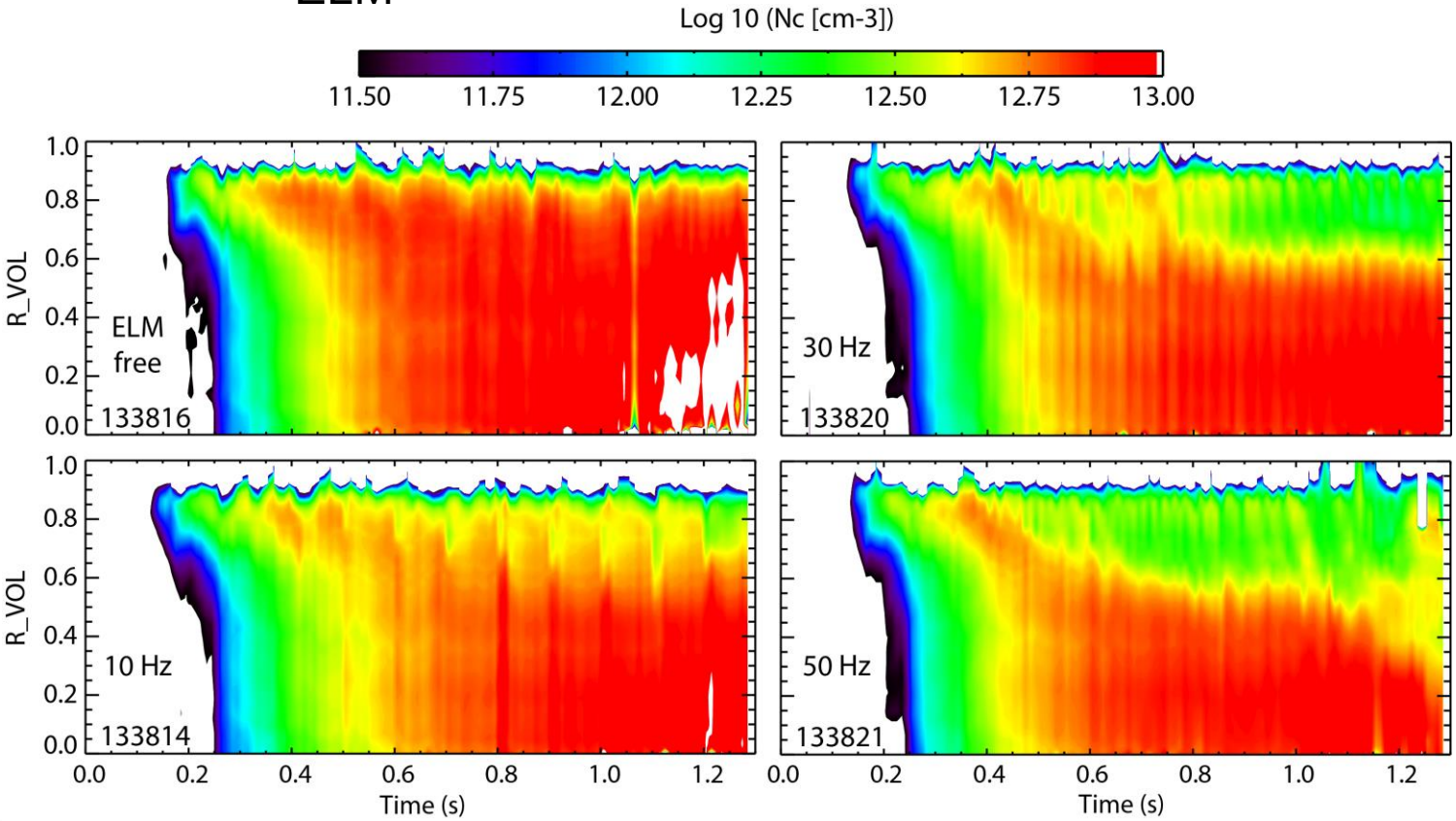






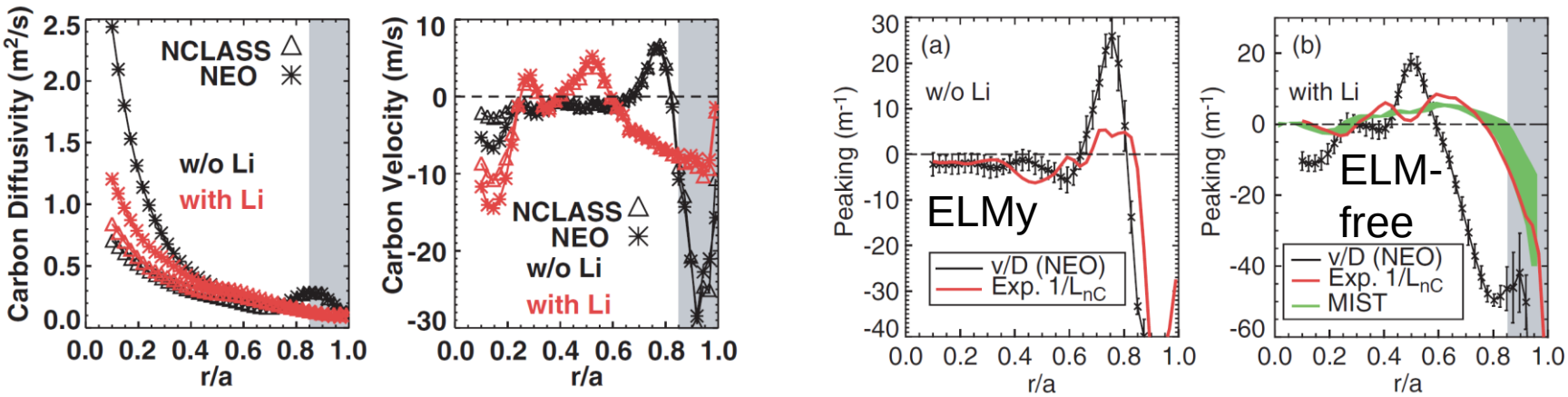
With increase in f_{ELM} carbon density at inner radii progressively flushed

- Edge n_c effectively flushed outside R_{vol} =0.5
- Increase in f_{ELM} flushes carbon at smaller radii



Deviations from neoclassical carbon transport observed in lithiated ELM-free discharges

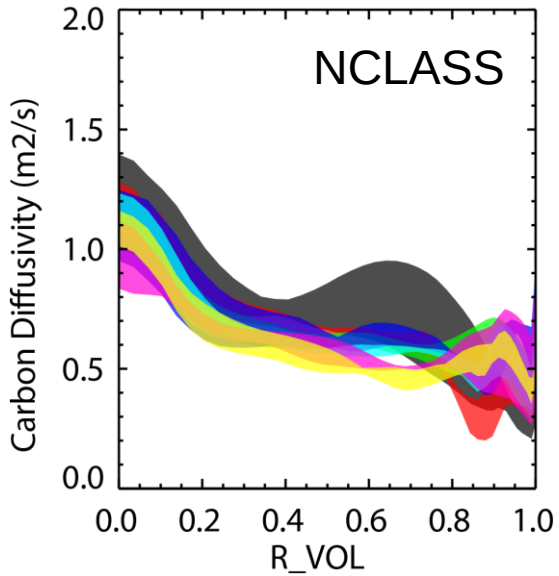
- In NSTX ion transport close to neoclassical levels [Kaye, NF 2008]
- Impurity transport close to neoclassical, deviations in lithiated discharges [Scotti NF 2013]
- Changes in main ion profiles due application of lithium lead to changes in carbon neoclassical convection (NCLASS, NEO)
- Disagreement between experimental profiles and neoclassical predictions at top of pedestal

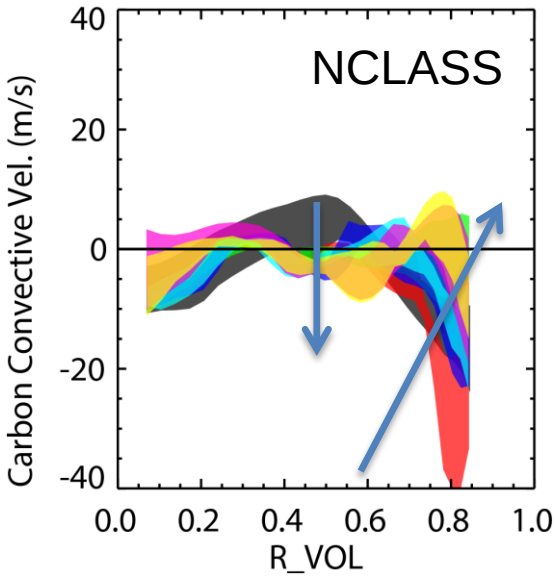


F. Scotti NF 2013

Carbon neoclassical transport modified due to changes in main ion profiles with ELMs

- Changes in main ion profiles due to triggered ELMs lead to changes in carbon neoclassical coefficients
  - Neoclassical transport parameters inferred from NCLASS
  - Changes in carbon convective velocity (due to changes in Grad(Ti))
  - Comparable and opposite to changes observed after lithium introduction





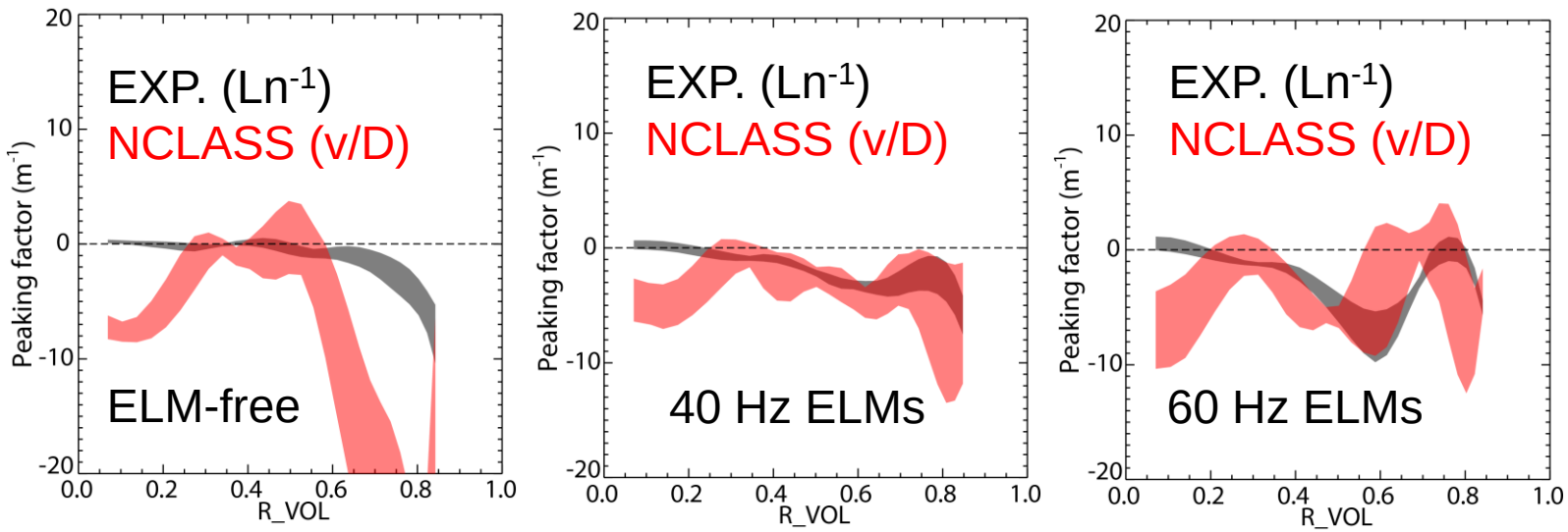
Ref, 10 Hz,20 Hz, 30 Hz, 40 Hz, 50 Hz, 60 Hz

t=[0.7-0.75]s

Deviations from neoclassical carbon transport reduced with triggered ELMs

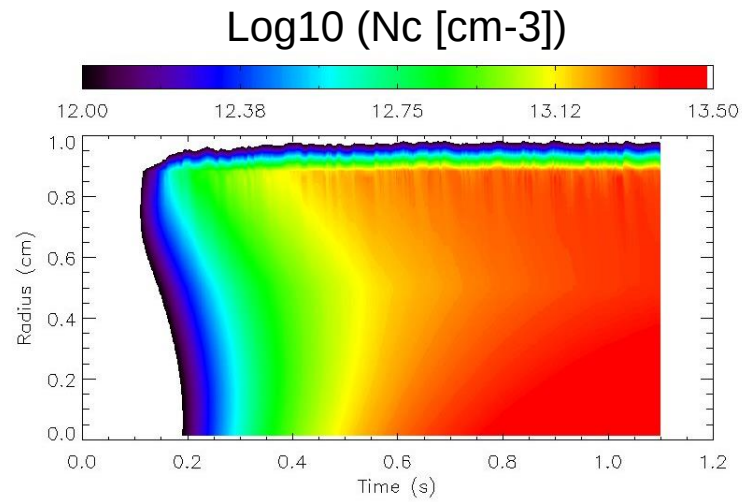
- Carbon density profiles in ELM-free discharges typically deviate from neoclassical transport
  - Weaker edge peaking than predicted from NCLASS, NEO
- Preliminary analysis indicates better agreement with neoclassical transport predictions with triggered ELMs
  - Similar to naturally ELMy discharges

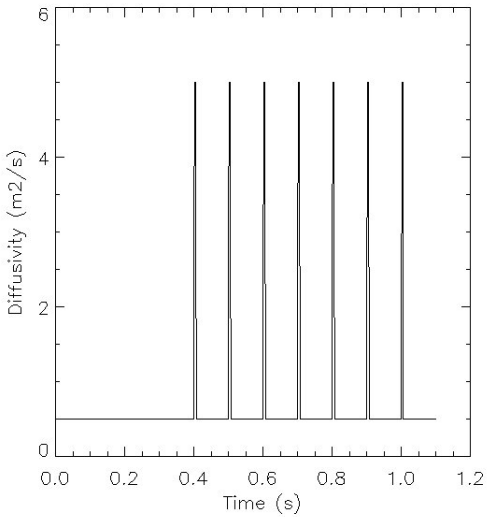
t=[0.75-0.80]s

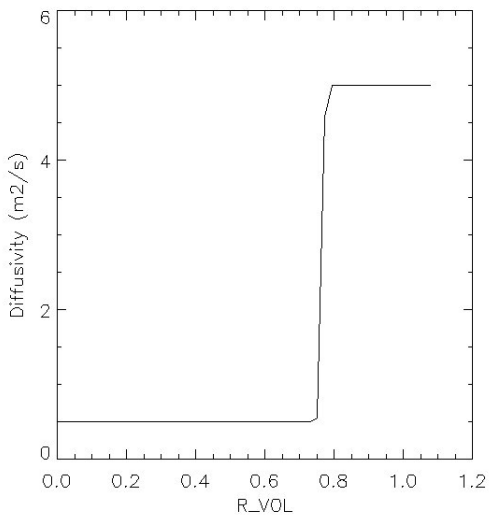


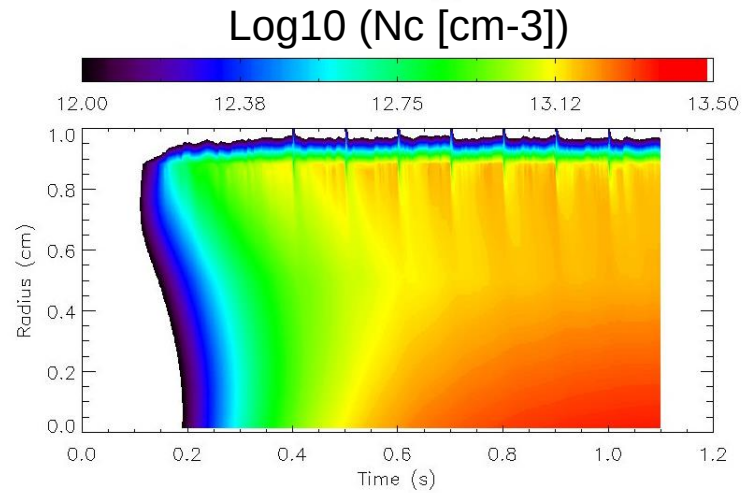
MIST impurity transport code used to study impurity transport following ELM

- MIST [1] impurity transport code used to study impurity recovery after ELM
  - Time dependent runs
  - ELM perturbation in input D, v





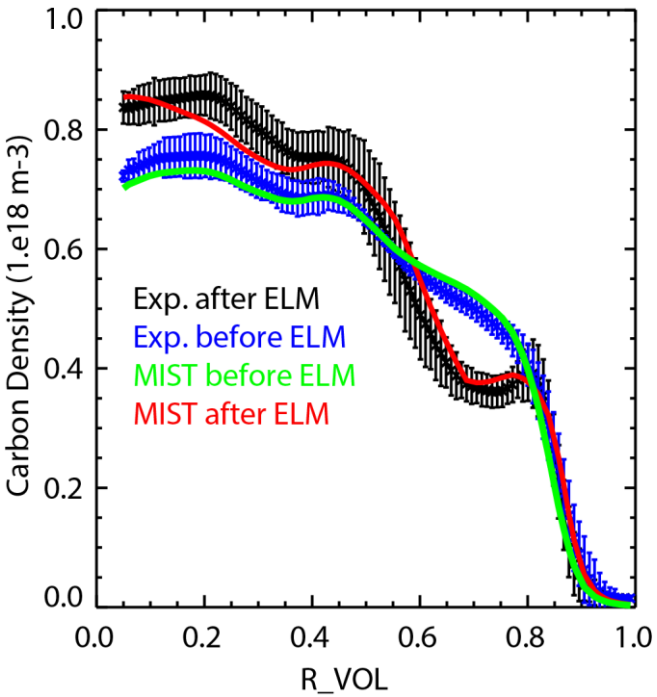




[1] R.Hulse, 1983 Nucl. Technol. Fusion

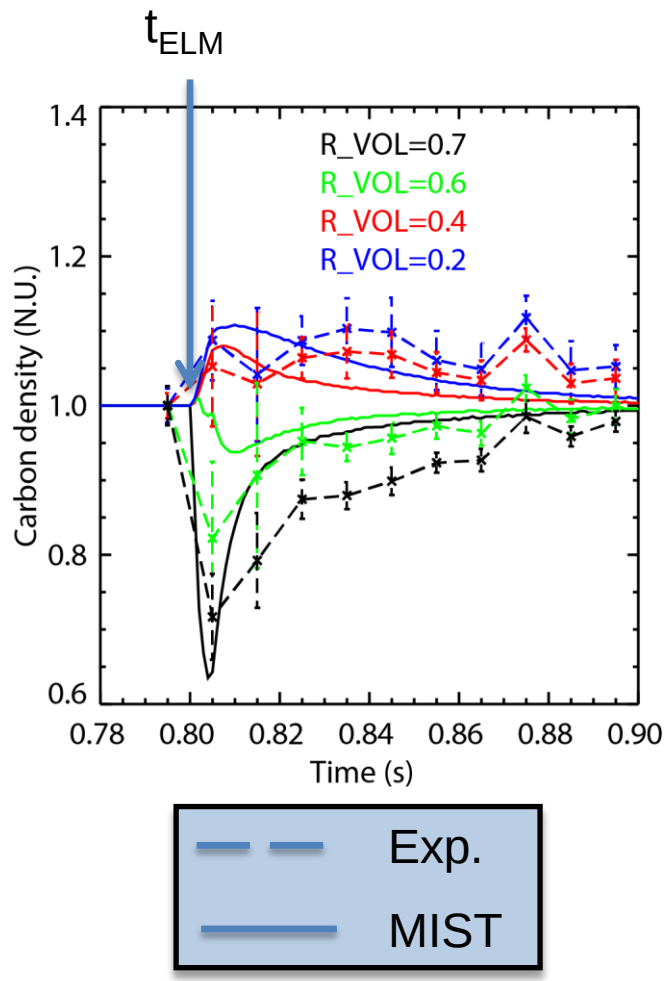
MIST used to simulate ELM flushing and profile recovery for the 10 Hz triggering

- Method:
  - v/D from steady state profiles
  - D neoclassical
  - ELM perturbation to match first CHERS frame after ELM
  - Profile recovery using steady state v, D
- Easy to match CHERS frame after ELM with:
  - outward velocity + increased diffusivity for $0.6<R_{VOL}<0.8$
  - Inward pinch for $R_{VOL}<0.5$



Profile recovery based on steady state v, D faster than observed experimentally

- Profile recovery simulated based on steady state v/D scaled to neoclassical D:
  - Recovery is too fast
  - Matching recovery keeping steady state v/D would require transport level below neoclassical
  - Suggest transport is actually changing during the profile recovery consistently with what previously observed



Future work

- Similarity in carbon neoclassical transport between naturally ELMy boronized discharges and triggered ELMy lithiated discharges not surprising given ~similar changes in main ion profiles
- Still need to understand reason for deviations from neoclassical in ELM-free discharges
  - Due to applicability of standard neoclassical?
    - But NEO typically in agreement with NCLASS
    - Non-local neoclassical code GTC-NEO will be used
  - Due to change in turbulent transport?