Kinetic profiles and impurity transport response to 3D-field triggered ELMs in NSTX

26th IAEA Fusion Energy Conference

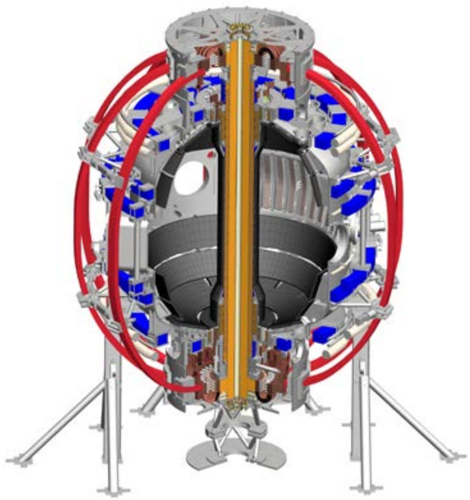
Oct.16-23, 2016 – Kyoto, Japan

F. Scotti, [1]W. Guttenfelder, V.A. Soukhanovskii,
[1]R.E. Bell, [3]G.P. Canal, [2]J.M. Canik, [1]A. Diallo, [1]B.P. LeBlanc, [1]S.P. Gerhardt, [1]M. Podesta'
LLNL, [1]PPPL, [2]ORNL, [3]GA

Lawrence Livermore National Laboratory

Fusion Energy Sciences

NSTX Upgrade



LLNL-PRES-663423

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences.. Lawrence Livermore National Security, LLC

PPPL

U.S. DEPARTMENT OF ENERGY | Office of Science

Summary/Outline

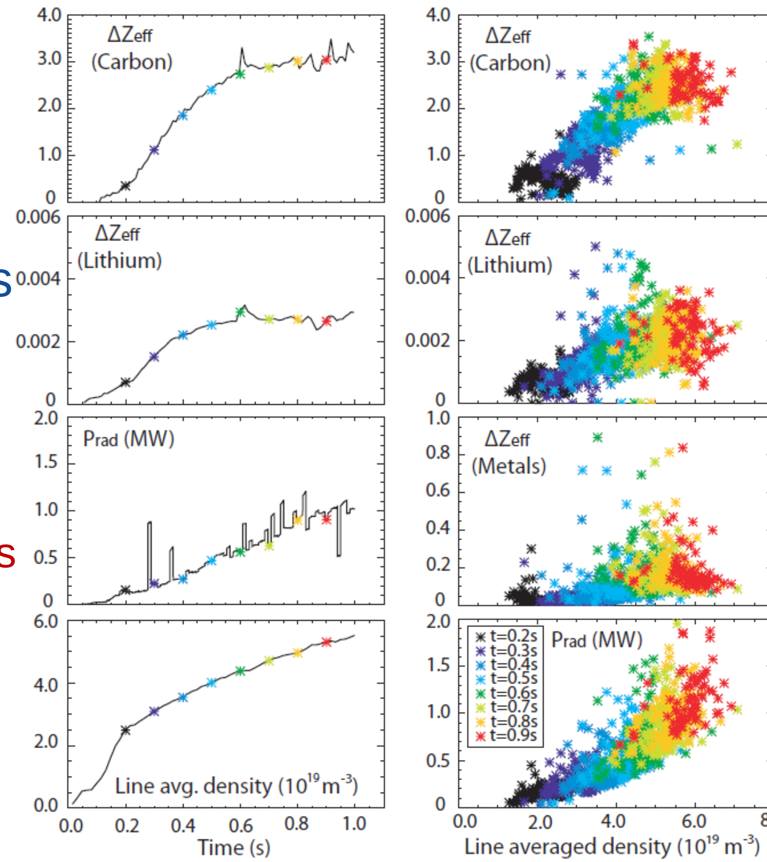
- NSTX H-mode discharges characterized by limited density control
- Lithium-conditioning + paced ELMs candidate scenario for particle control in NSTX-U
- Increase in RMP-triggered ELM frequency (0-60 Hz) leads to a progressive reduction in n_C at the pedestal top
- T_i profiles changes due to paced ELMs led to changes in carbon neoclassical coefficients
  - opposite to those observed in the transition from ELMy boronized discharges to ELM-free lithiated discharges
- Agreement of inter-ELM carbon transport with neoclassical estimates improved with the increase in paced ELM frequency
- Quasi-linear fluxes from hybrid KBMs of similar magnitude (opposite direction) of anomalous neoclassical fluxes in ELM-free discharges

This work was supported by U.S. DOE Contracts: DE-AC02-09CH11466, DE-AC52-07NA27344, DE-AC05-00OR22725, DE-SC0012706.

NSTX H-mode discharges characterized by limited density control

- Limited density control in NSTX H-mode discharges
  - Uncontrolled D inventory w/ boronized PFCs
    - — Type I/mixed Type I-Type V ELMs
  - Uncontrolled C inventory w/ lithiated PFCs
    - — ELM-free
- Baseline scenarios in NSTX-U:
  - D control via cryopump w/ boronized PFCs
  - Impurity mitigation w/ lithiated PFCs
- Impurity control techniques based on:
  - Enhanced core impurity transport
    - — Triggered ELMs via RMPs or impurity granules
    - — Optimized lithium dose (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.

RMP-triggered ELMs applied on NSTX to mitigate impurity accumulation

- Resonant magnetic perturbations produced via external midplane coils (4 ms, 3 kA, $n=3$) [1]
- ELM-pacing up to 62.5 Hz achieved [2,3]
- Large ELMs induced by magnetic perturbations [3]
  - $\Delta W/W$~15% at f_{ELM} = 10 Hz
  - $\Delta W/W$ ~ 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.

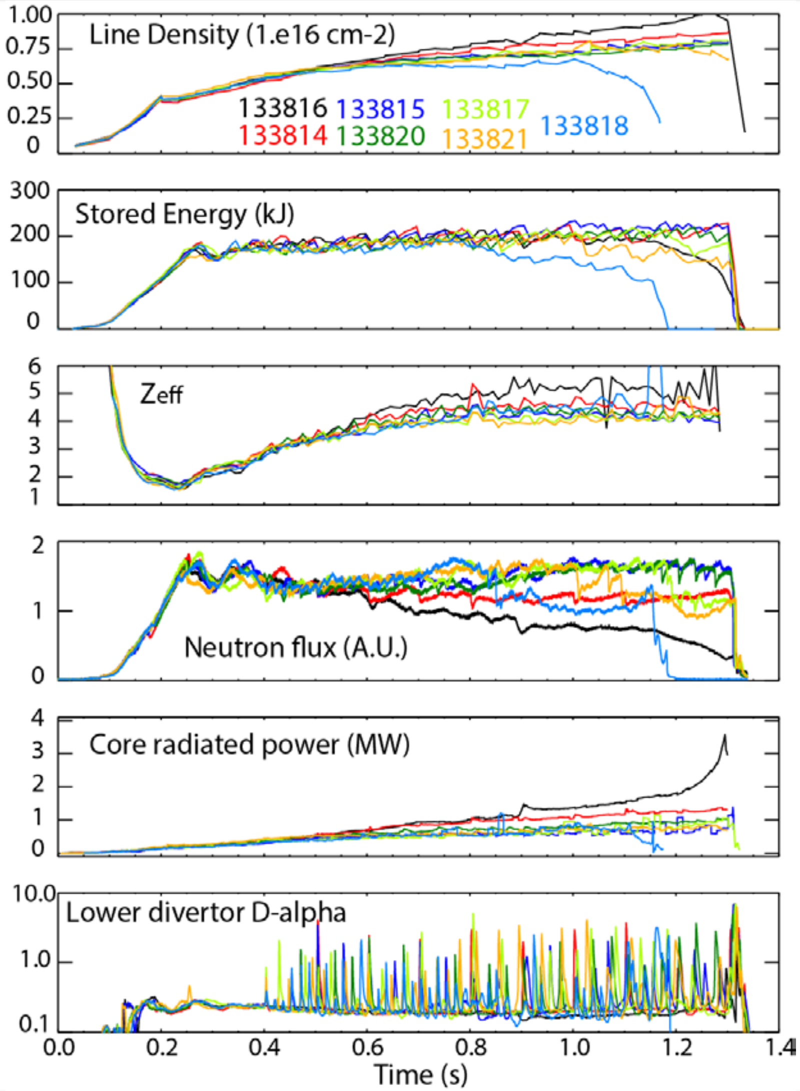
Reduction in Z_{eff}, core P_{rad} and n_e ramp rate with increase in ELM frequency

- Increasing paced-ELMs frequency 0→60Hz:
  - Reduced 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

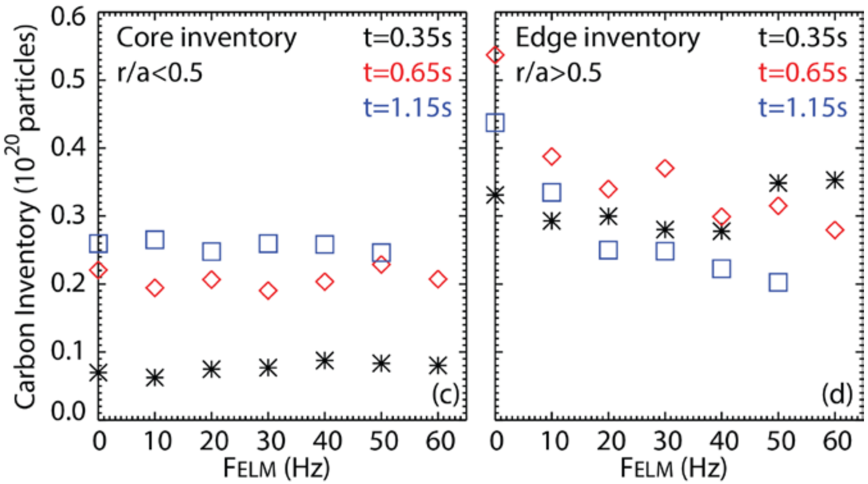
Lithium evaporative coatings: 250 mg
Lower biased double null $\delta_{r\text{-}sep}$ ~ 5-6 mm
I_p = 800 kA, P_{NBI} = 6MW
Strong shaping κ~2.4, δ~0.8
Naturally ELM-free discharges

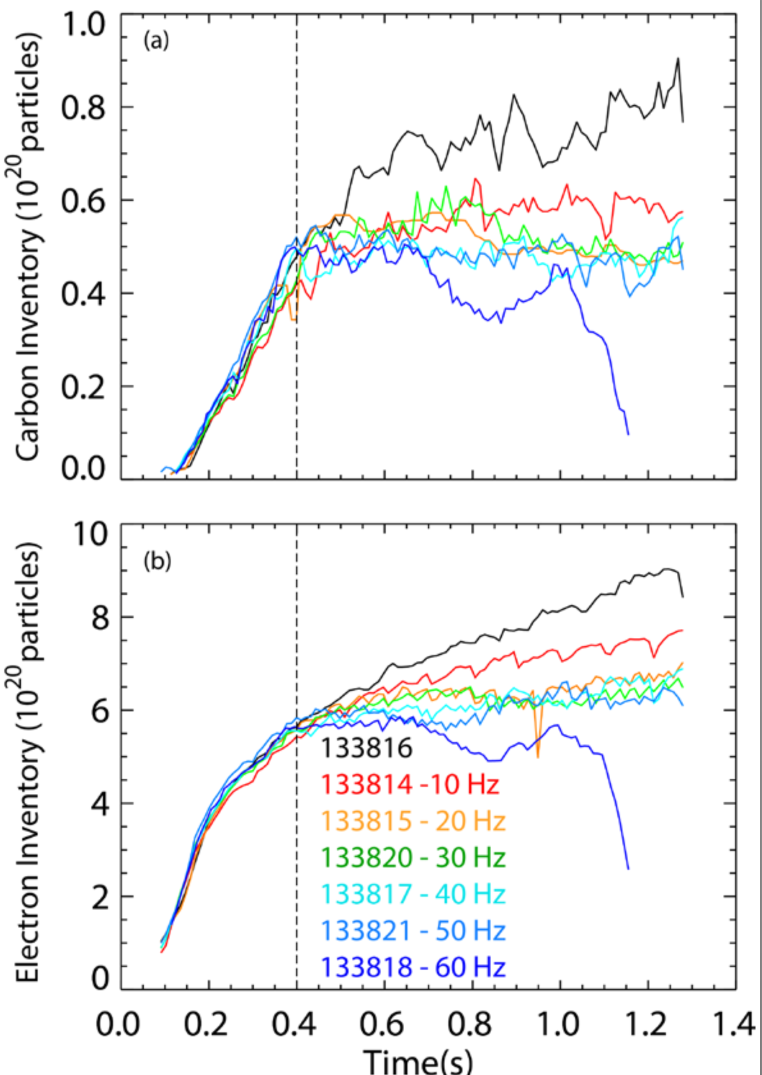
Ref., 10 Hz, 20 Hz, 30 Hz, 40 Hz, 50 Hz, 60 Hz



Total particle inventories controlled through reduction of edge inventories and unaffected core

- With RMP-triggered ELMs:
  - Progressive reduction in C and e inventories
  - ~ stationary inventories achieved at highest f_{ELM}
- D inventory controlled via lithium pumping
- Inventory reduction due to reduction in particle content in the edge (x2) with core impurity content unaffected
  - Changes in C transport beyond ELM-flushing
  - Motivates analysis of profile changes and impurity transport induced by ELMs

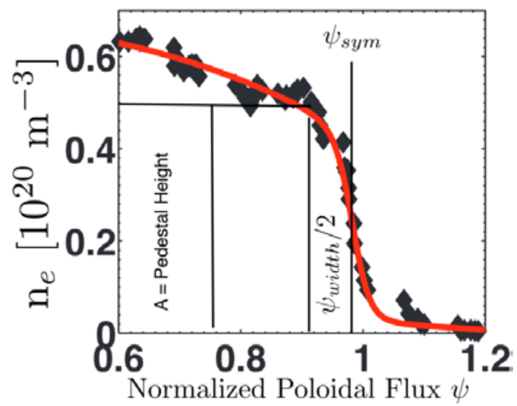




Conditional averaging applied to fit kinetic profiles during ELM cycle

- Conditional averaging over paced 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
- Kinetic EFITs via Osborne python tools



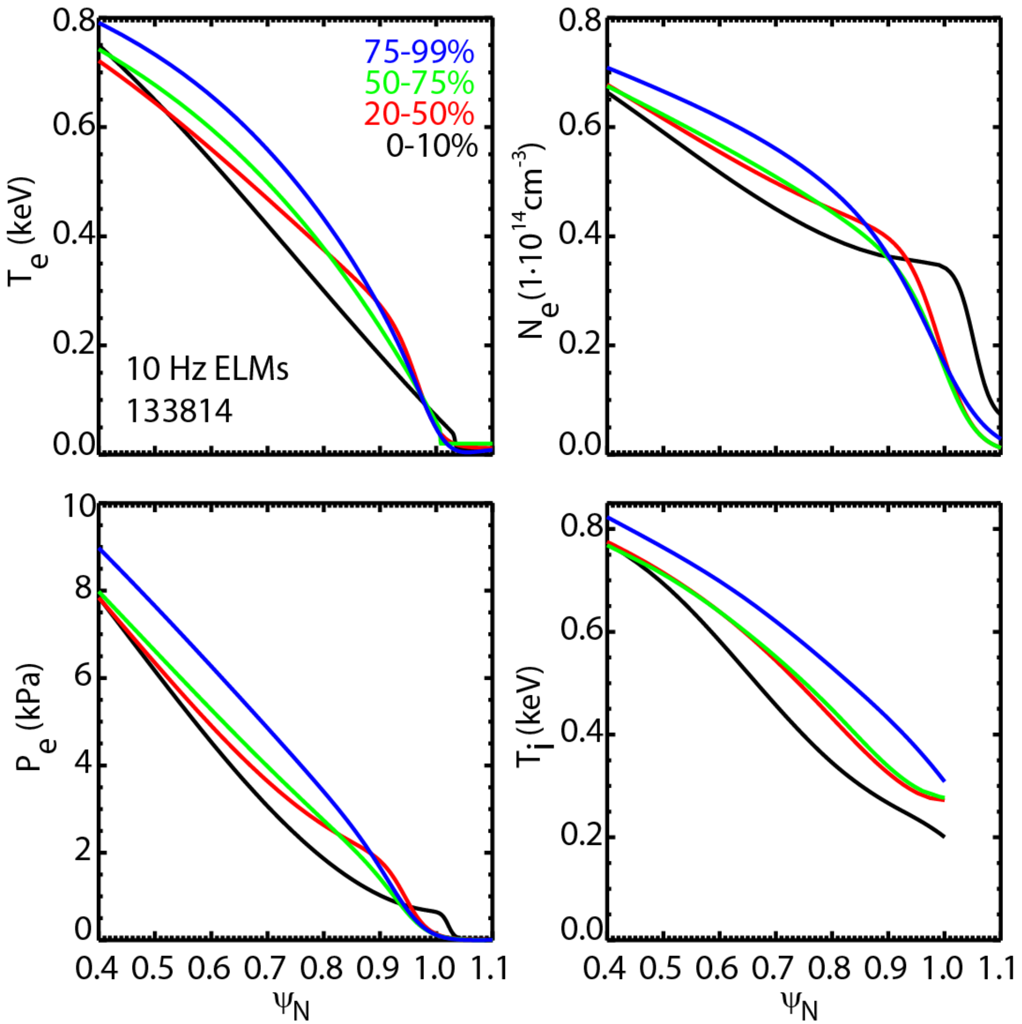
A. Diallo, Invited APS-DPP 2011.

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

R. Groebner and T. Osborne PoP (1998)

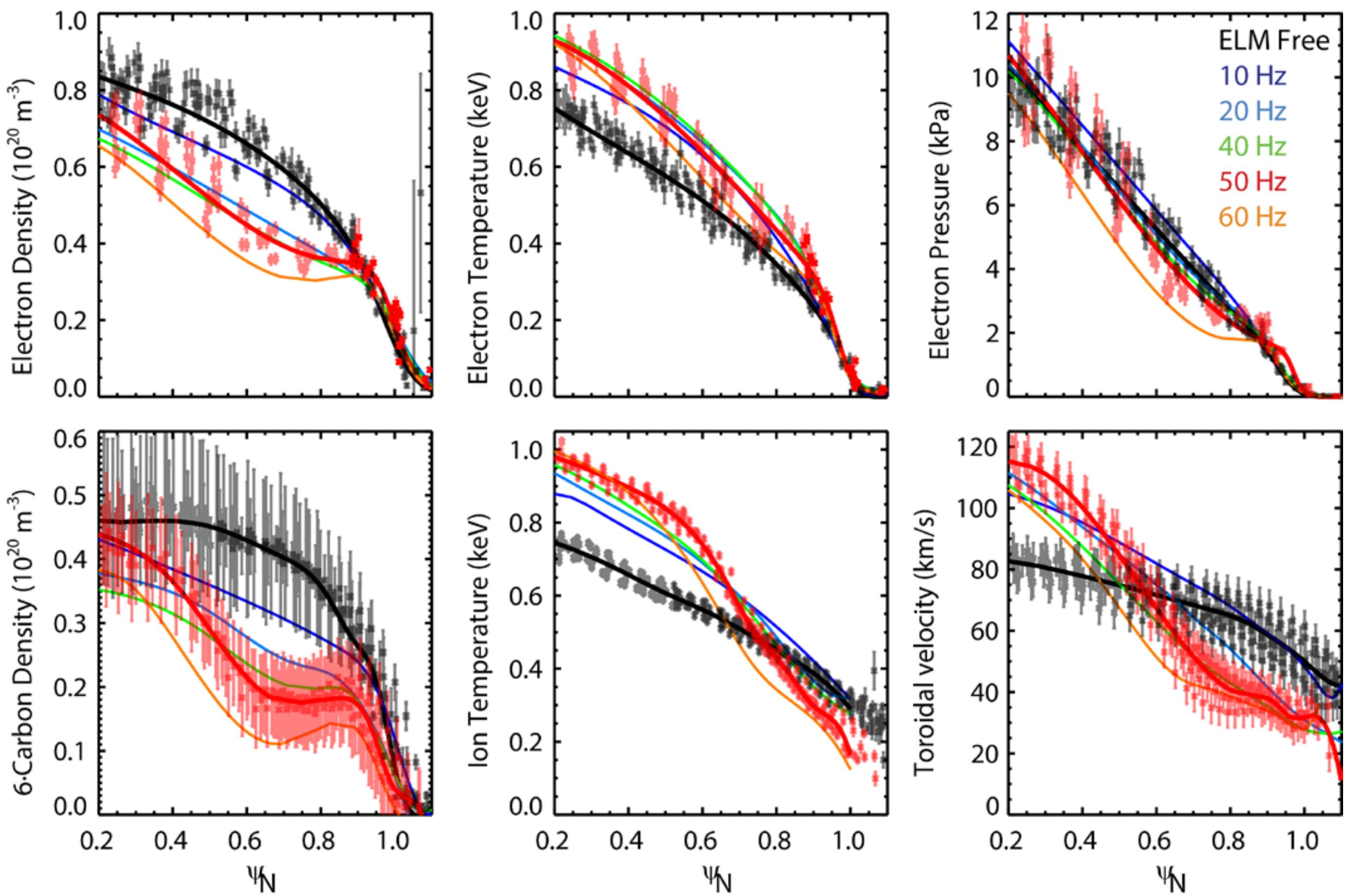
Reduction in pedestal T_e, T_i, P_e, n_e following 10Hz ELMs crash

- T_e, n_e, p_e, T_i profile crash due to triggered ELM
- Profile recovers to ELM-free values within 100 ms
- Quick recovery of steep gradient region, slower recovery of pedestal top
- Increase in f_{ELM} led to progressively smaller effects on pedestal profiles



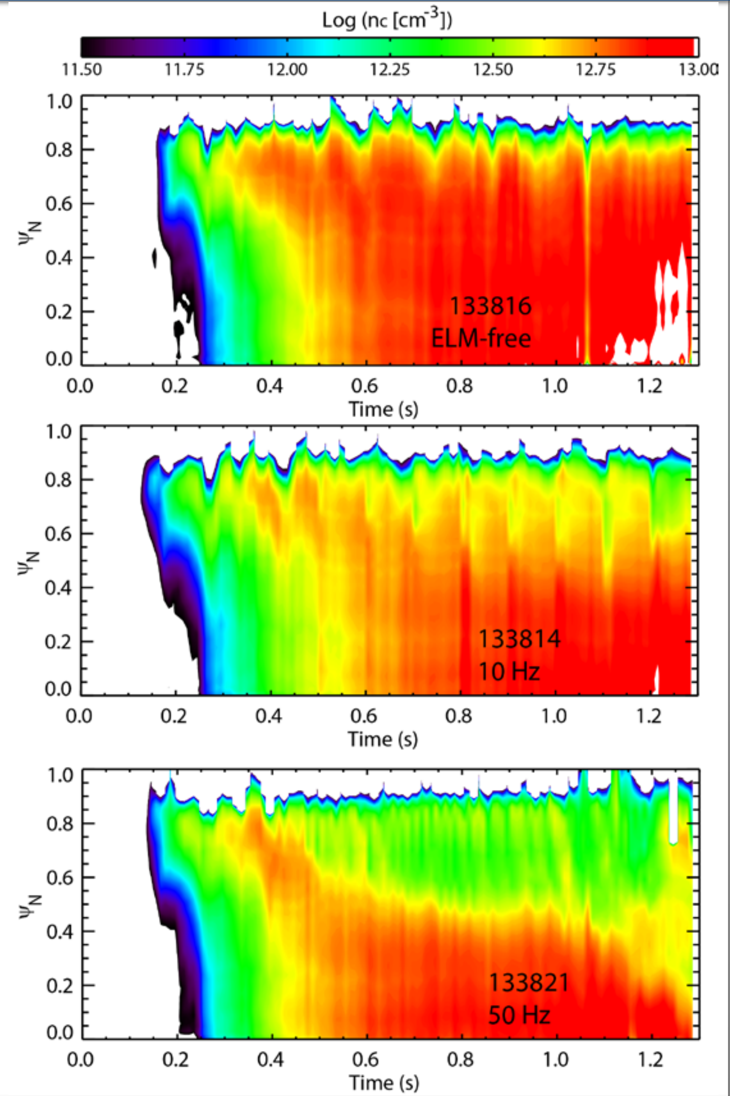
Large changes in n_e, P_e, T_i saturated profiles with increase in ELM frequency

- "Saturated" profiles from last 25% of paced ELM cycle
- Electron profiles clamped near separatrix
- Progressive reduction in n_C, n_e at pedestal top
- Different behavior for T_i, v_t profiles
  - 3-4X increase in gradient at ψ_N=0.6-0.7
  - Effect on edge collisionality and neoclassical drivers



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

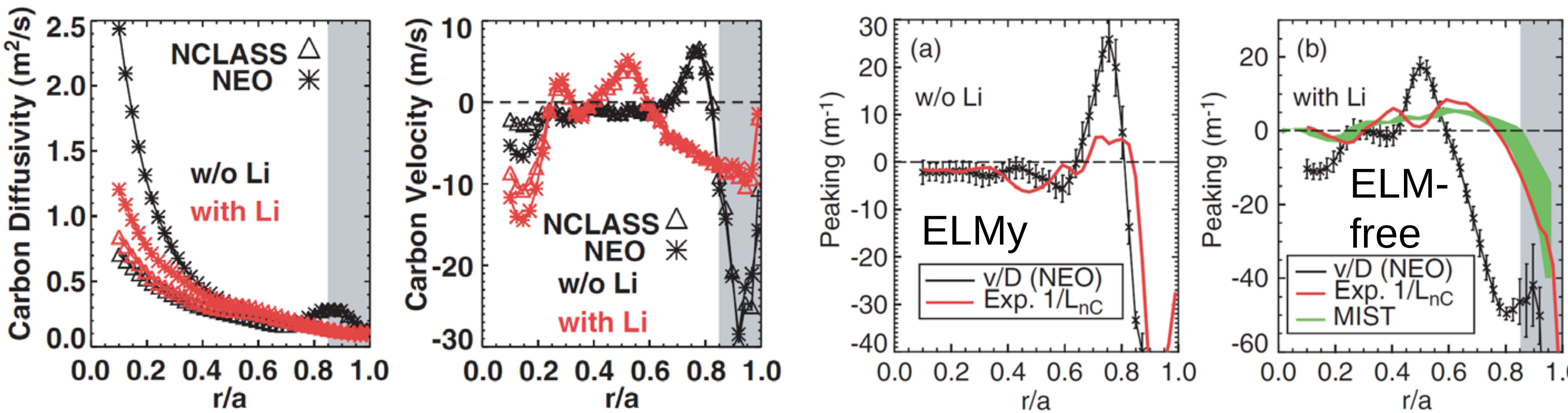
- For 10Hz ELMs n_c recovers to ELM-free profile towards the end of ELM-cycle
- Increase in f_{ELM} flushes carbon at smaller radii
  - Edge n_c halved outside ψ_N=0.4
- Changes in density profiles indicate change in impurity transport for ψ_N=0.4-0.8
  - Beyond the simple ELM-flushing
  - Motivates carbon transport analysis



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

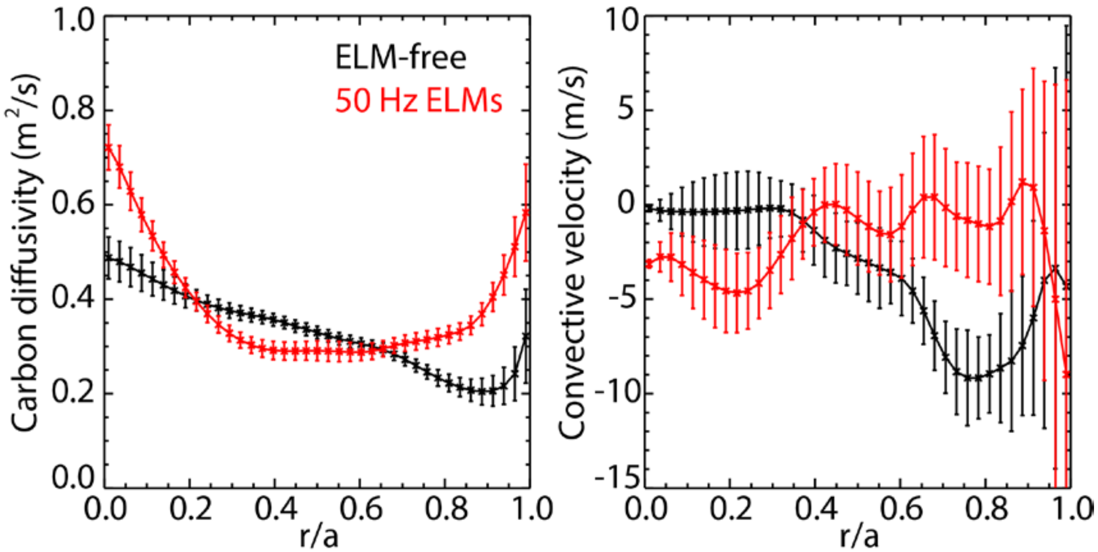
- In NSTX ion transport close to neoclassical levels [Kaye, NF 2008]
- Impurity transport close to neoclassical
  - Deviations in lithiated discharges [Scotti NF 2013]
- Changes in main ion profiles due application of lithium lead to changes in carbon neoclassical convection (NCLASS, NEO)
- Disagreement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

F. Scotti NF 2013



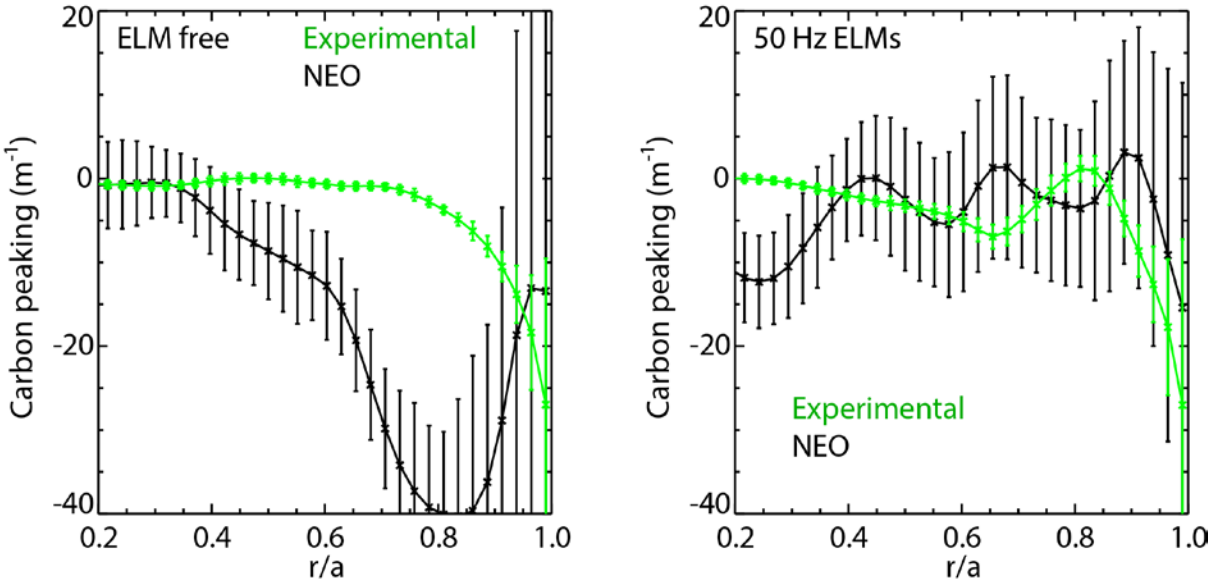
Carbon neoclassical transport modified due to changes in main ion profiles with ELMs

- δf neoclassical code NEO used to estimate carbon neoclassical transport
  - NEO run on 100 different profiles based on experimental error [Belli, PPCF 2008]
  - Scan in n_C scale length for D, v determination from radial fluxes [Belli, PPCF 2009]
  - Classical component included via NCLASS simulations
  - Rotation effects included but negligible (in/out asymmetry~10%, D enhancement~30%)
- T_i, n_D changes due to triggered ELMs modify neoclassical C coefficients
  - Changes in convective velocity at pedestal top: inward to outward (due to ∇ Ti)
  - Comparable and opposite to changes observed after lithium introduction



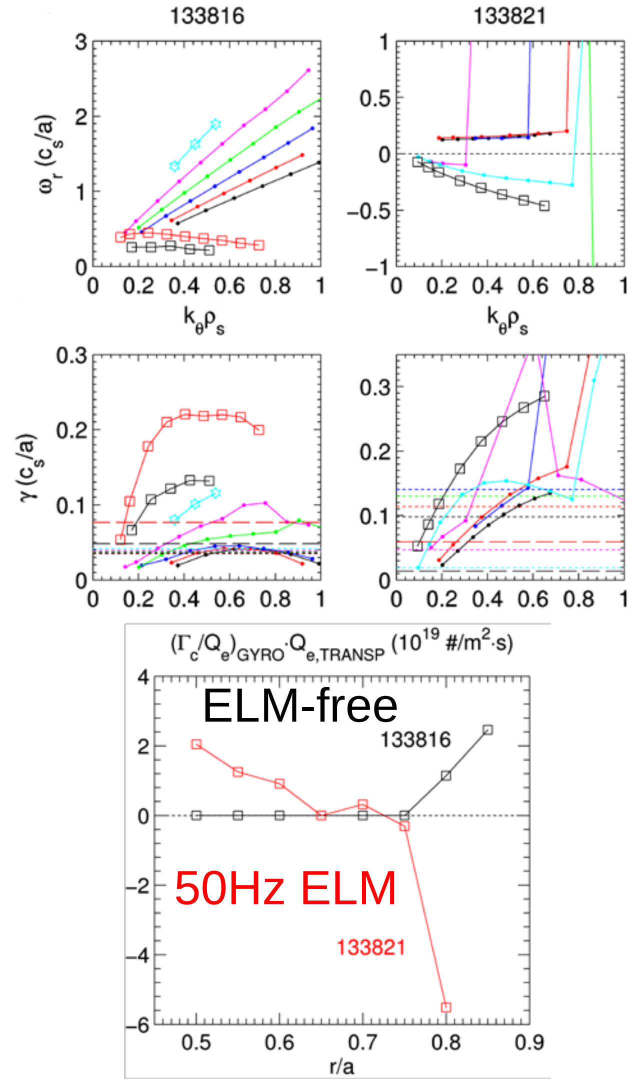
Deviations from neoclassical carbon transport reduced with triggered ELMs

- Comparison of neoclassical peaking v/D and steady state n_C normalized gradient
- Both cases agree in the steep gradient region
- Carbon density profiles in ELM-free discharges deviate from neoclassical transport
  - Weaker edge peaking than predicted by NEO
- Better agreement with NEO predictions with triggered ELMs
  - Similar to naturally ELMy discharges with comparable changes in Ti



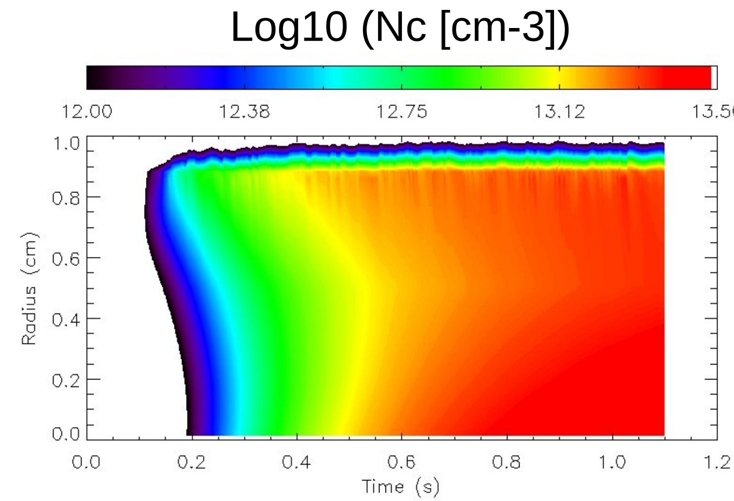
KBM quasi-linear fluxes comparable and in opposite direction to anomalous neoclassical fluxes in ELM-free discharges

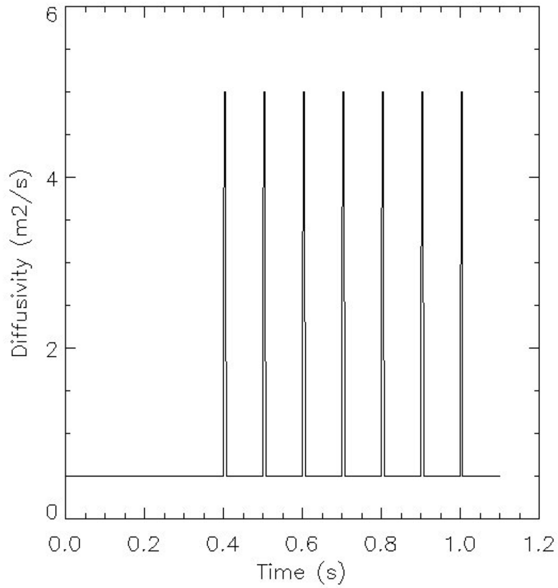
- Linear gyrokinetic GYRO simulations to assess anomalous contributions
  - Kinetic D, C, e, collisional and full em effects
- ELM-free:
  - Hybrid KBM at r/a=0.8, MT at 0.5-0.75 ($k_\theta \rho_s$ <1)
- 50 Hz ELMy:
  - No MT, mixed ballooning activity
- Carbon fluxes from quasi-linear fluxes scaling electron fluxes to experimental TRANP Q_e ($k_\theta \rho_s$ <1)
  - In ELM-free discharges KBM modes at r/a=0.8-0.85 provide outward particle flux
  - Similar to the anomalous neoclassical carbon flux (up to 3-6x10^{19} /m^2/s, extending between r/a 0.65-0.9)

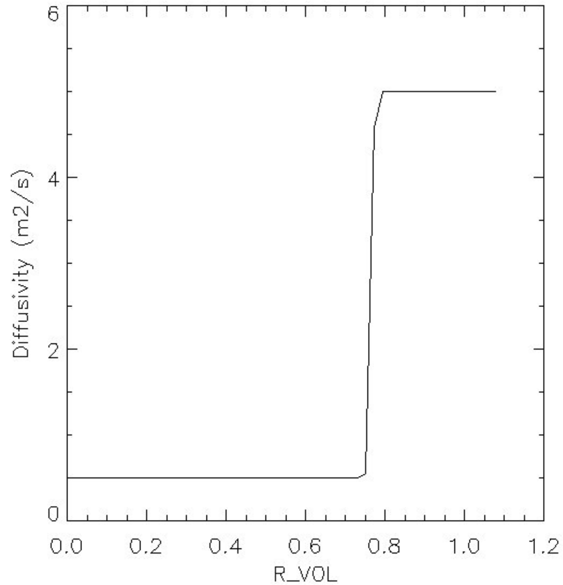


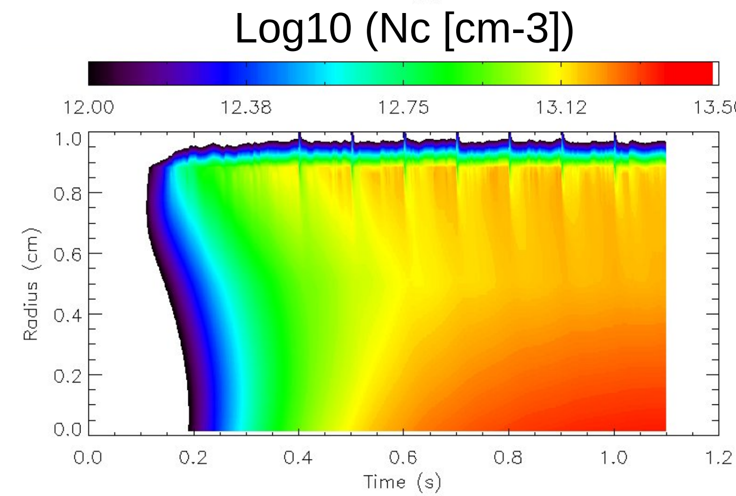
MIST used to simulate n_C profile recovery following 10 Hz triggering

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









R.Hulse, 1983 Nucl. Technol. Fusion

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

- Method:
  - v/D from steady state profiles, D neoclassical
  - Perturbation to match first CHERS frame after ELM
  - Profile recovery using steady state v, D
- 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 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 changing during the profile recovery, consistent with previous observations