Progress and Plans for Pedestal Physics and Control

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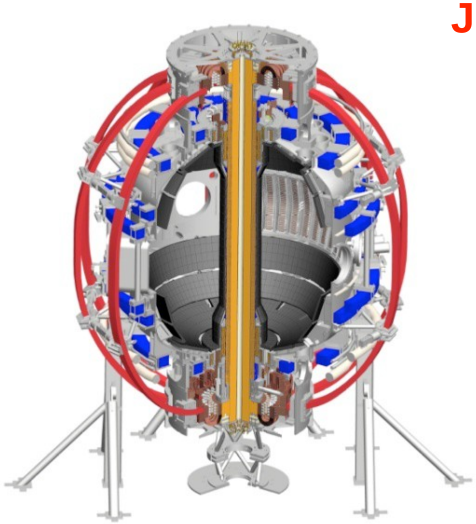

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NSTX-Upgrade with enhanced capabilities will substantially extend H-mode pedestal studies

Research milestones involving pedestal physics

- R(15-1): Assess H-mode energy confinement, pedestal, and scrape off layer characteristics with higher B_T, I_P and NBI heating power
- IR(15-1): Develop and assess the snowflake divertor configuration and edge properties in NSTX-U
- R(16-1): Assess scaling and mitigation of steady-state and transient heat-fluxes with advanced divertor operation at high power density

NSTX-Upgrade with enhanced capabilities will substantially extend H-mode pedestal studies

Characterization

- FY15: Characterize the H-Mode pedestal structure at increased B_T, I_p, and NBI heating power
  - Compare with results from NSTX, and emphasize on pedestal width dependence on pedestal poloidal β
  - Build a pedestal database for testing EPED model on STs
  - Assess the pedestal stability in both standard and snowflake configurations
- FY15: Identify the underlying mechanisms controlling the pedestal structure
  - Leverage the high spatial resolution edge diagnostics (e.g., BES, ME-SXR, bolometer)

Control

- FY16: Experiments will be performed to control the impurity accumulation in the pedestal using these tools:
  - Lithium granule injection (LGI)
  - 3D magnetic perturbations for ELM pacing

  } **this talk**

  - Upward evaporator
  - Supersonic gas injection (SGI) for ELM triggering and fueling
  - Attempt to strengthen Edge Harmonic Oscillation (EHO)
  - Snowflake to reduce divertor erosion, impurity source

  } **Backup**

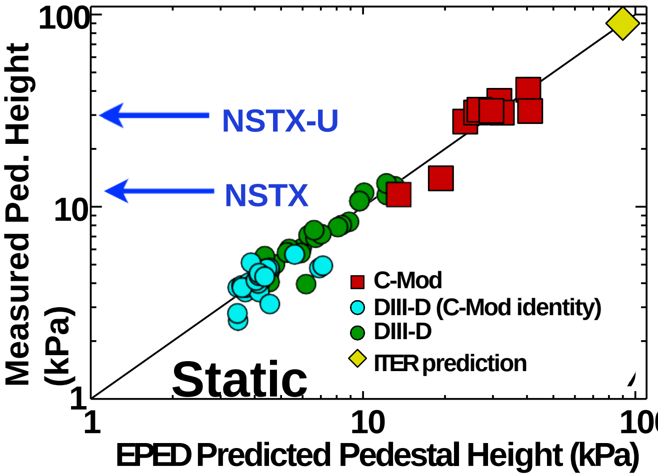
NSTX-U facilities upgrades enable access to new parameter regimes and unique capabilities for establishing the physics basis for ST-FNSF

- Pressure pedestal height scales with the square of the plasma current
  - I_p: 1.3 to 2 MA
- Higher B_T for same q_{95}, higher heating power to reach β_{ped} limit
  - B_T: 0.5 to 1 T, and P_{NBI} : 5 to 10 MW (5s) & 7.5 to 15MW (1.5s)
- Lower collisionality leading to higher bootstrap current, which in turn will result in stronger peeling instability drive
  - Reduction of collisionality by factor 2–3 during first 2 years
- High-Z plasma facing components

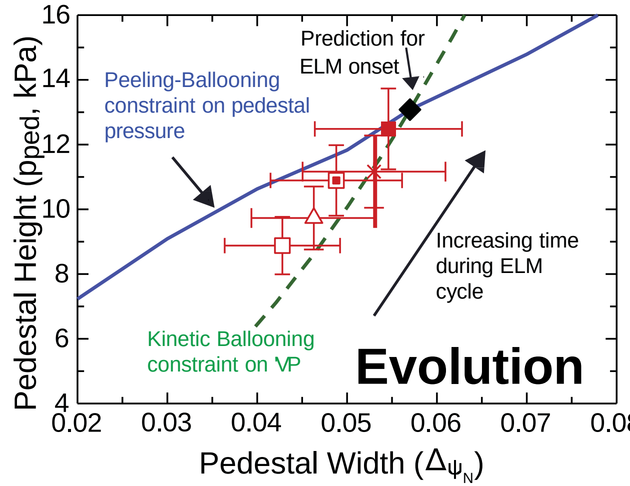
Pedestal diagnostics: high-resolution MPTS, BES, bolometers, ME-SXR

NSTX-U goal: develop predictive capability for pedestal structure and evolution for FNSF

- EPED (static mode) predicts limiting pedestal height and width on multiple high aspect ratio machines
  - EPED is only applicable to the pressure, therefore cannot distinguish individual transport channels
- NSTX parameters challenging for EPED model
  - due to high q_{95}, stability of high-n ballooning, and need to calculate n=1,2 peeling-ballooning which is challenging for ELITE
- NSTX-U will provide extensive and detailed pedestal data in FY15 & FY16 to:
  - Extend the pedestal width scaling
  - Characterize the pedestal evolution
    - density and temperature separately
    - compare with standard aspect ratio
  - Control and optimize the pedestal



EPED1 Model, DIII-D 144977 (with dynamics)



P.B. Snyder, PoP 19, 056115 (2012)

Outline

- **Recent highlights - Collaboration and NSTX**
  - **DIII-D: Pedestal recovery time scales (both density and temperature)** *and neoclassical calculations in the pedestal (in backup)*
  - *MAST: Pedestal I_p scaling and evolution (not shown here)*
  - **C-Mod: Search for kinetic ballooning modes**
  - **NSTX: Progress on pedestal edge simulations, ELM type characterizations, and on “Enhanced Pedestal” H-mode analysis**

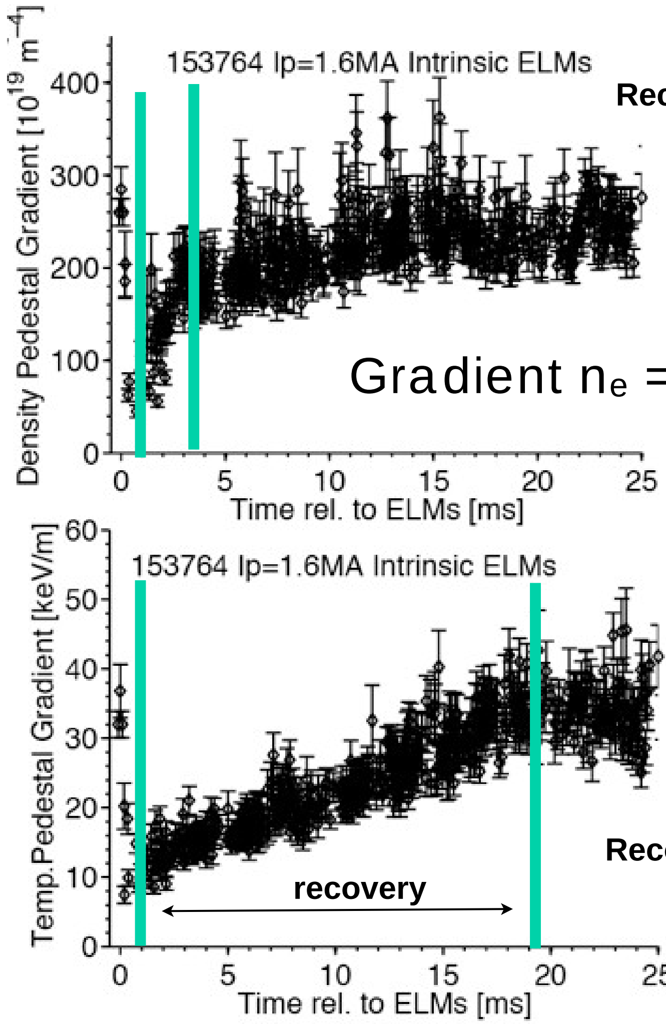
- **NSTX-U plans for FY15 & FY16**

- **Summary**

Early recovery for density and temperature are significantly different

DIII-D NATIONAL FUSION FACILITY

- First detailed measurements of the pedestal recovery dynamics after an ELM
- Clearly the density and temperature gradient recovery are decoupled
  - Suggesting heat transport is the dominant mechanism in saturating the edge pedestal



Recovery ~ first 10% of an ELM cycle

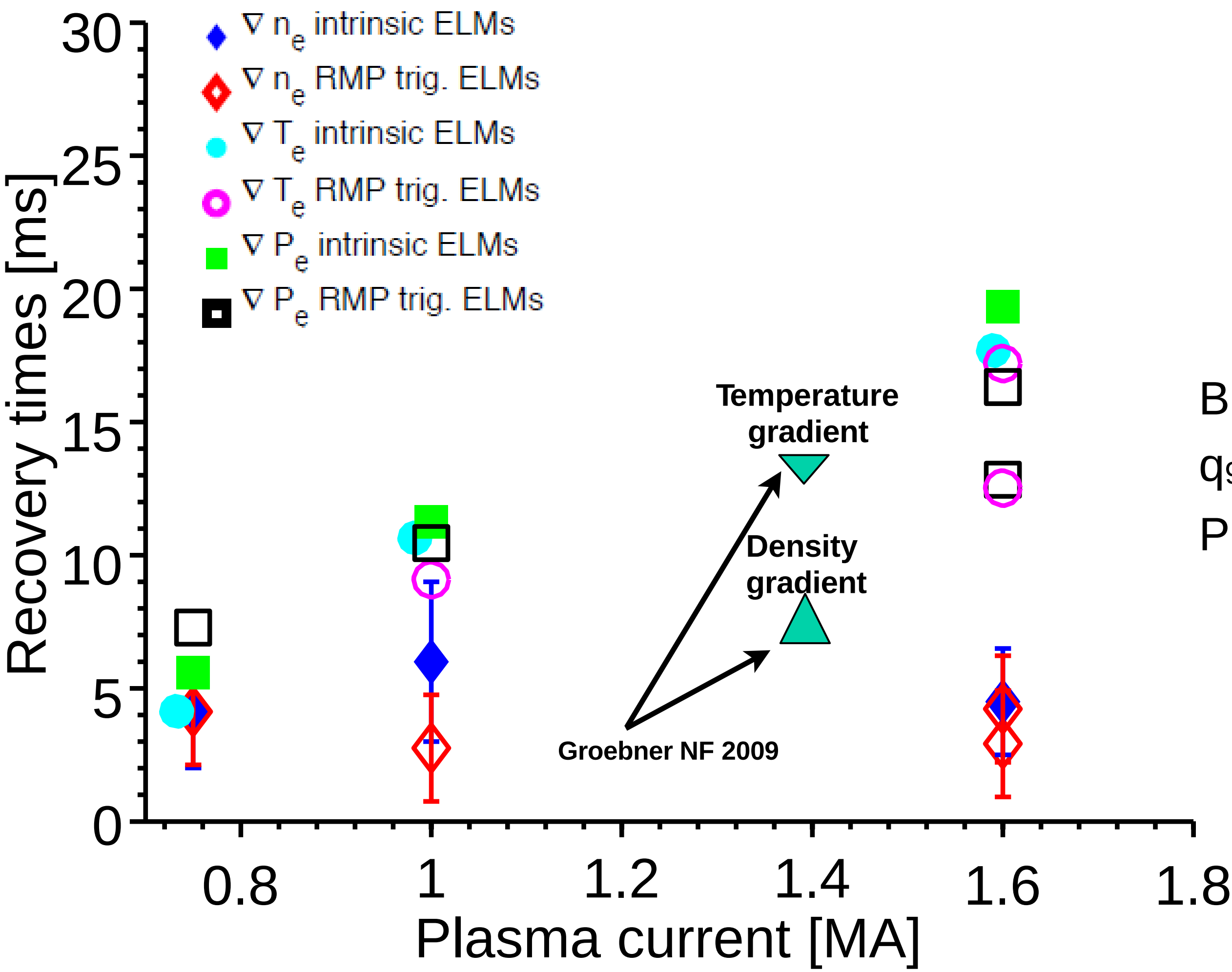
Gradient $n_e = n_e^{PED} / n_e^{Width}$

Recovery ~ first 50% of an ELM cycle

Gradient $T_e = T_e^{PED} / T_e^{Width}$

First systematic measurements of the pedestal recovery vs I_P for both intrinsic and paced ELMs

Decoupling of the temperature and density gradients at higher plasma current



B = 1.9 T

q_{95} = 2.67 ~ 6.2

P_{NBI} average - 3 - 4 MW

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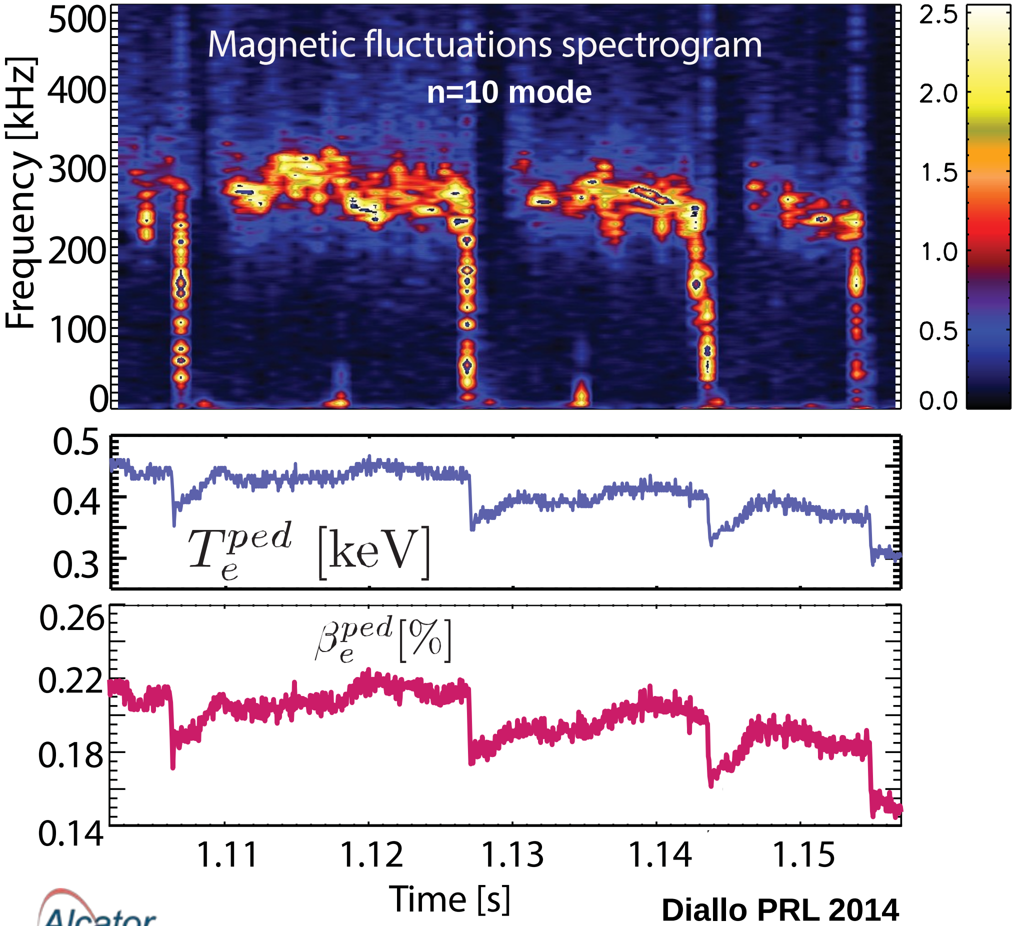
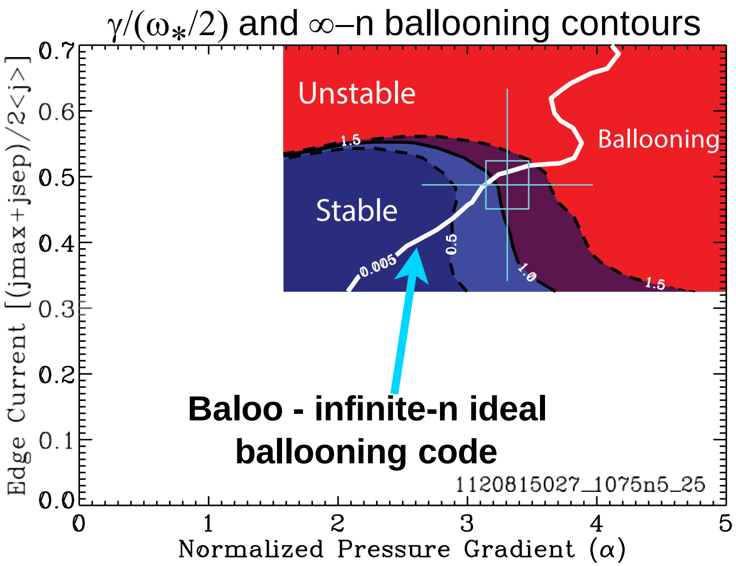
C-Mod finds coherent magnetic fluctuations consistent with kinetic ballooning mode (KBM) and EPED/ELITE models

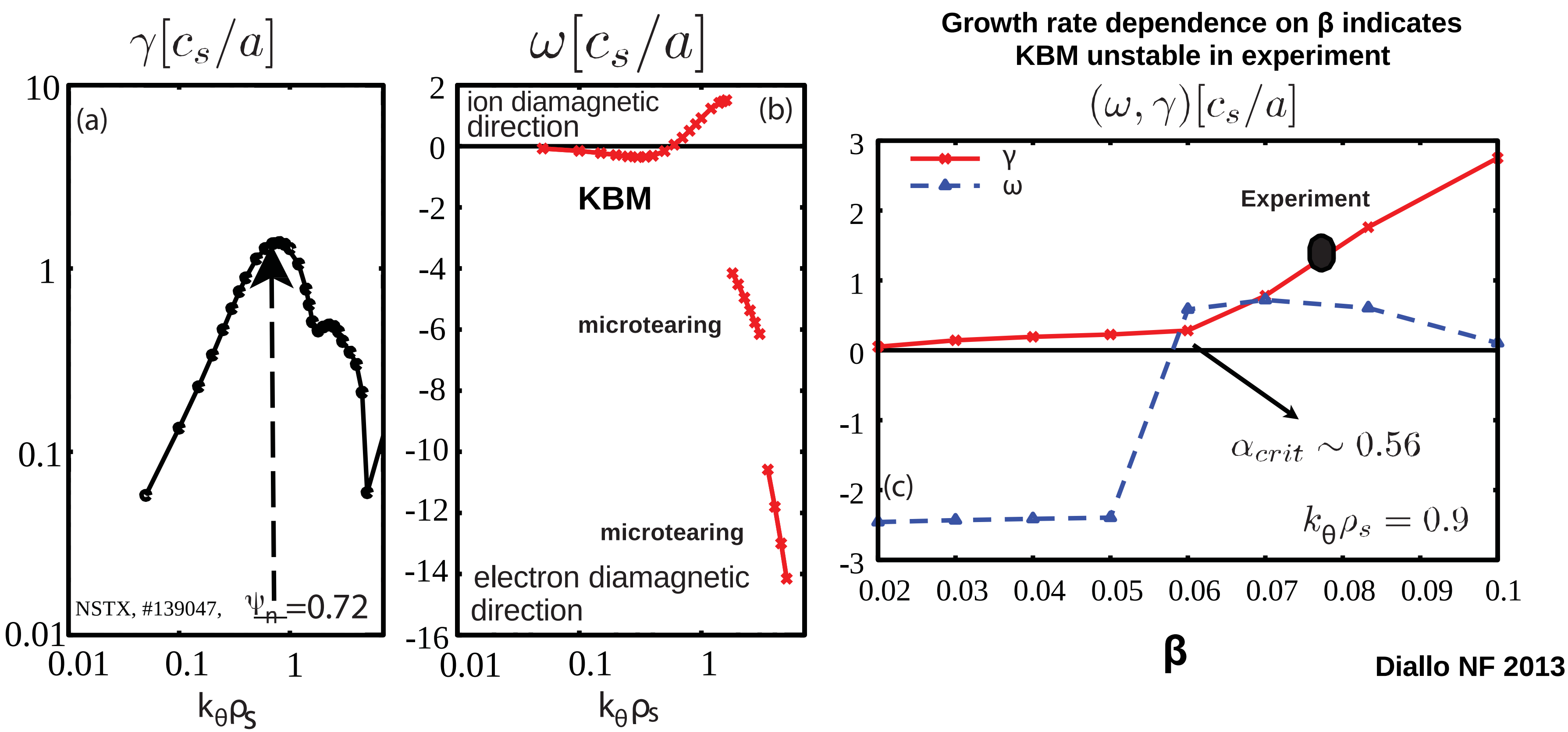




- Measured field-aligned electromagnetic mode and pedestal localized that clamp pedestal ∇T_e

- No clear evidence of such instability limiting the pedestal on NSTX

Linear simulations using GENE find NSTX pedestal top is unstable to KBM and micro-tearing



Diallo NF 2013

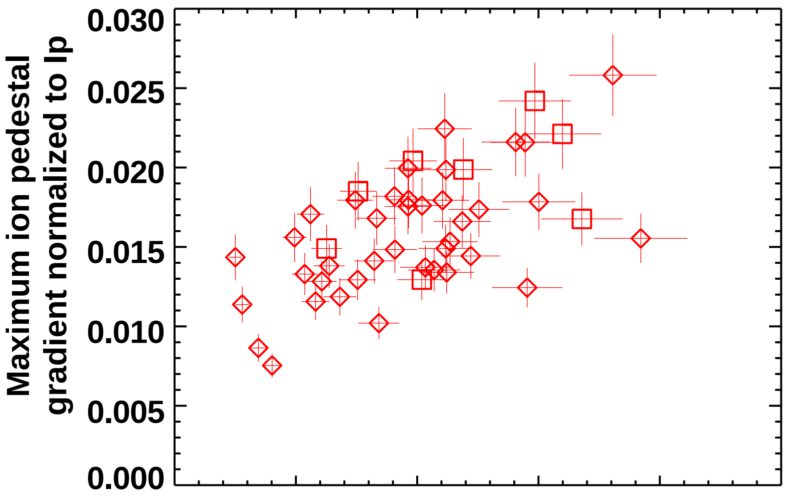
- GENE calculations with electromagnetic contribution are performed where BES measurements are localized
  - edge pedestal is unstable to KBM in agreement with calculations using GS2 by Canik (NSTX) and Dickinson (MAST)

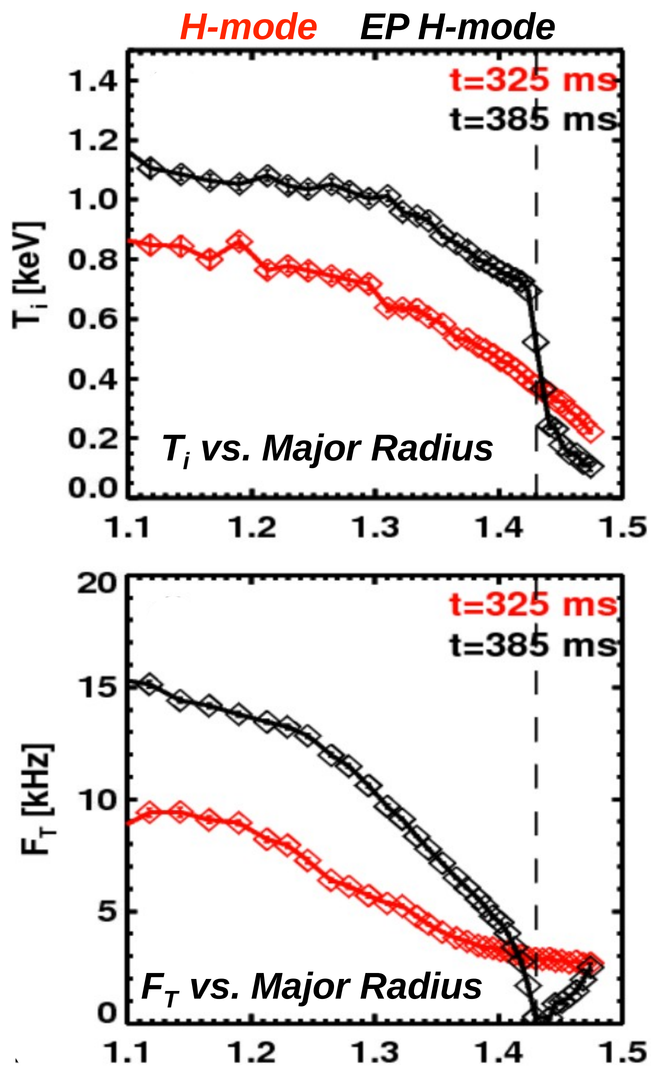
NSTX led the2013 FES multi-machine joint research target (JRT)

- Evaluate stationary enhanced confinement regimes without large Edge Localized Modes (ELMs)
- Identify correlations between edge fluctuations and transport
- The research aimed to strengthen the basis for extrapolation of stationary regimes which combine high energy confinement with good particle and impurity control
- NSTX-U will assess EPH as a leading candidate scenario for accessing very high energy confinement

EPH is a promising confinement regime with high H_{98} ~ 1.5-1.6 and higher than standard H-mode ion pedestals

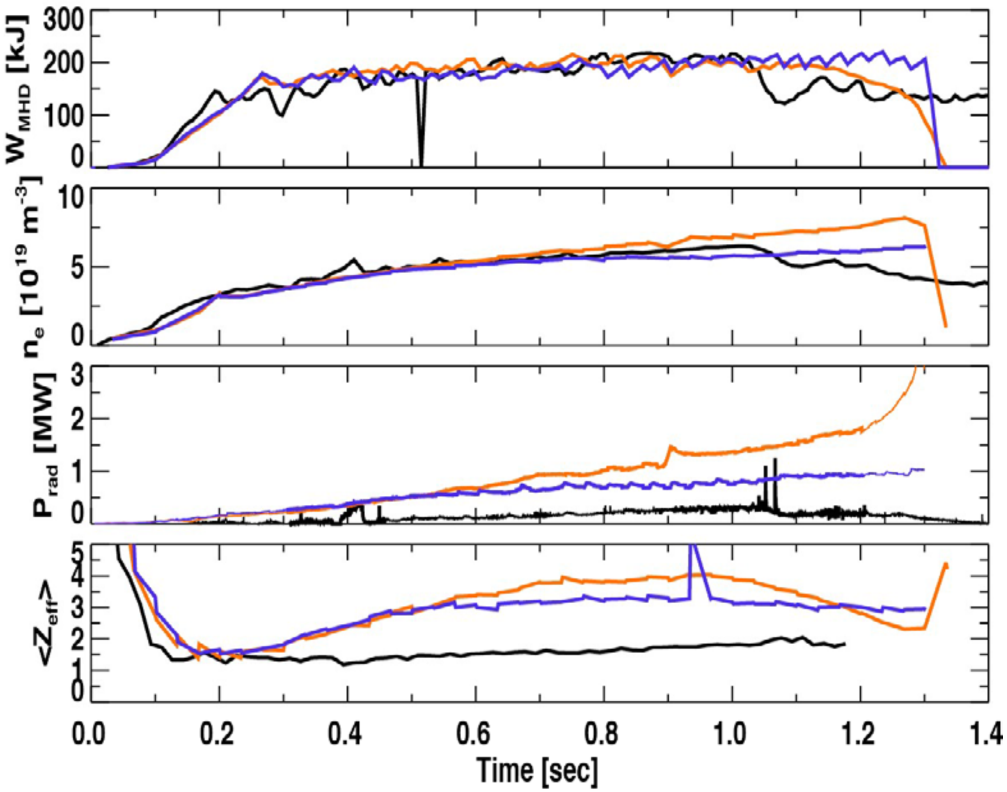
- JRT efforts enabled an extensive characterization of EPH discharges
- Ion temperature gradient is much steeper than in H-mode.
- Develops a strong toroidal flow shear, and often a very narrow minima in the flow

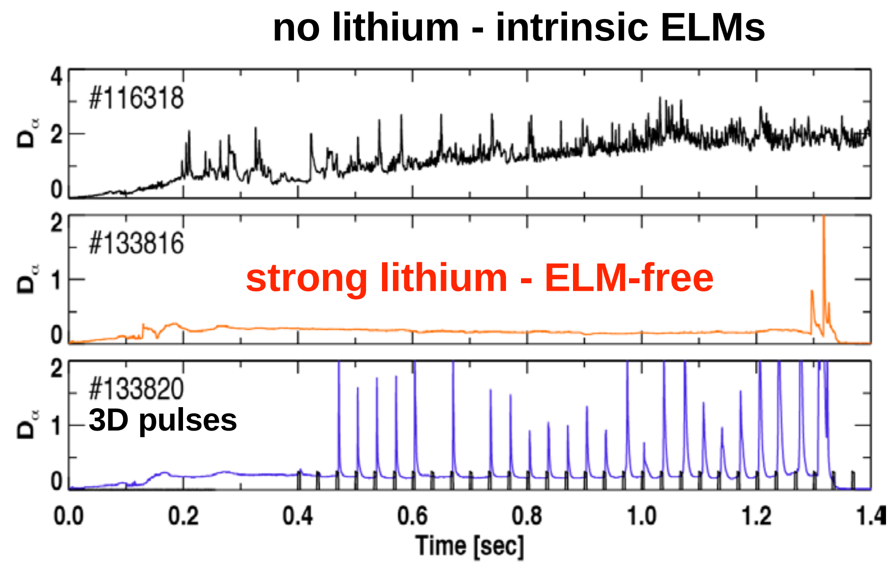




Gerhardt NF at press 2014

Lithium wall conditioning leads to elimination of ELMs and subsequent impurity accumulation



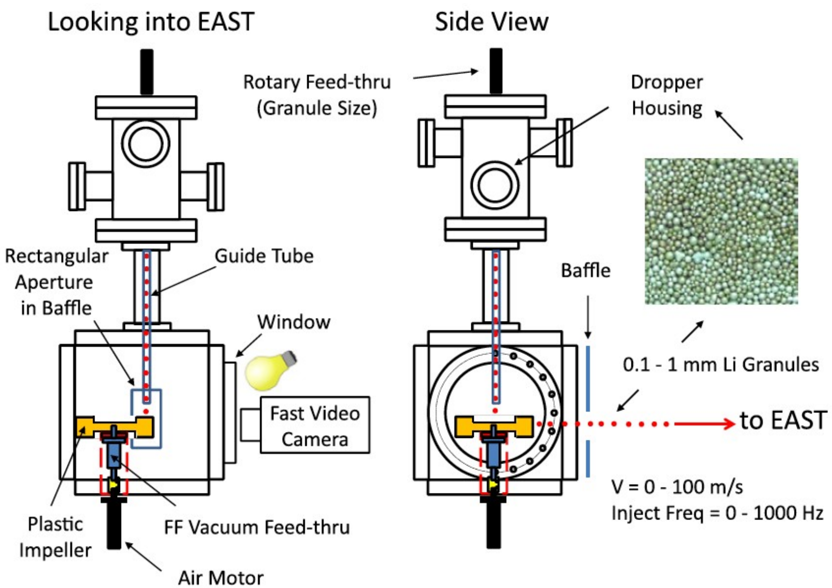


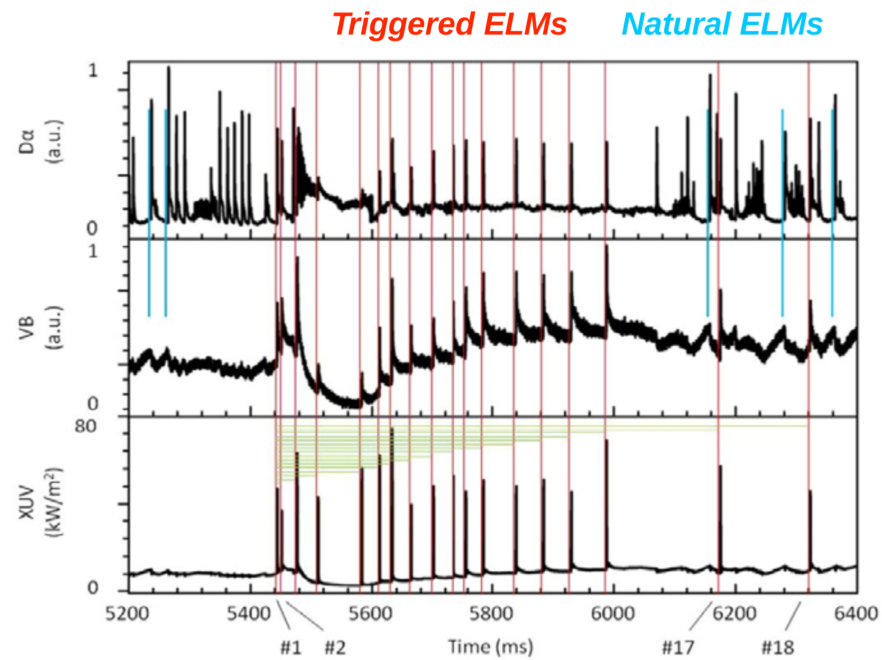
lithium + 3D RMP ELM pacing

What are the steps taken to reduce the carbon accumulation on NSTX-U?

- 3D RMP (shown above)
- EHO (see backup)
- Lithium granule injection

Lithium Granule Injector (LGI) will be tested on NSTX-U to pace ELMs with goal of flushing impurities





Mansfield Nucl. Fusion (2013)

- LGI has been successfully applied on EAST to trigger ELMs at 25 Hz
- LGI will be tested on NSTX-U to control the impurity accumulation
  - Reduce Z_{eff} to 2 - 2.5 in the pedestal
  - Investigate the effects of the injection frequency, granule velocity, size on triggering efficiency and impurity control
  - Extend the injection rate to 1kHz
- Recent collaborations with DIII-D using lithium dropper:
  - Lithium dropper resulted in ELM-free periods up to ~400ms with T_e^{ped} > 1 keV and H_{98} < 2
  - P_e^{ped} almost tripled; no sign of P_{rad} secular increase (see backup)

Pedestal Research plans for FY15

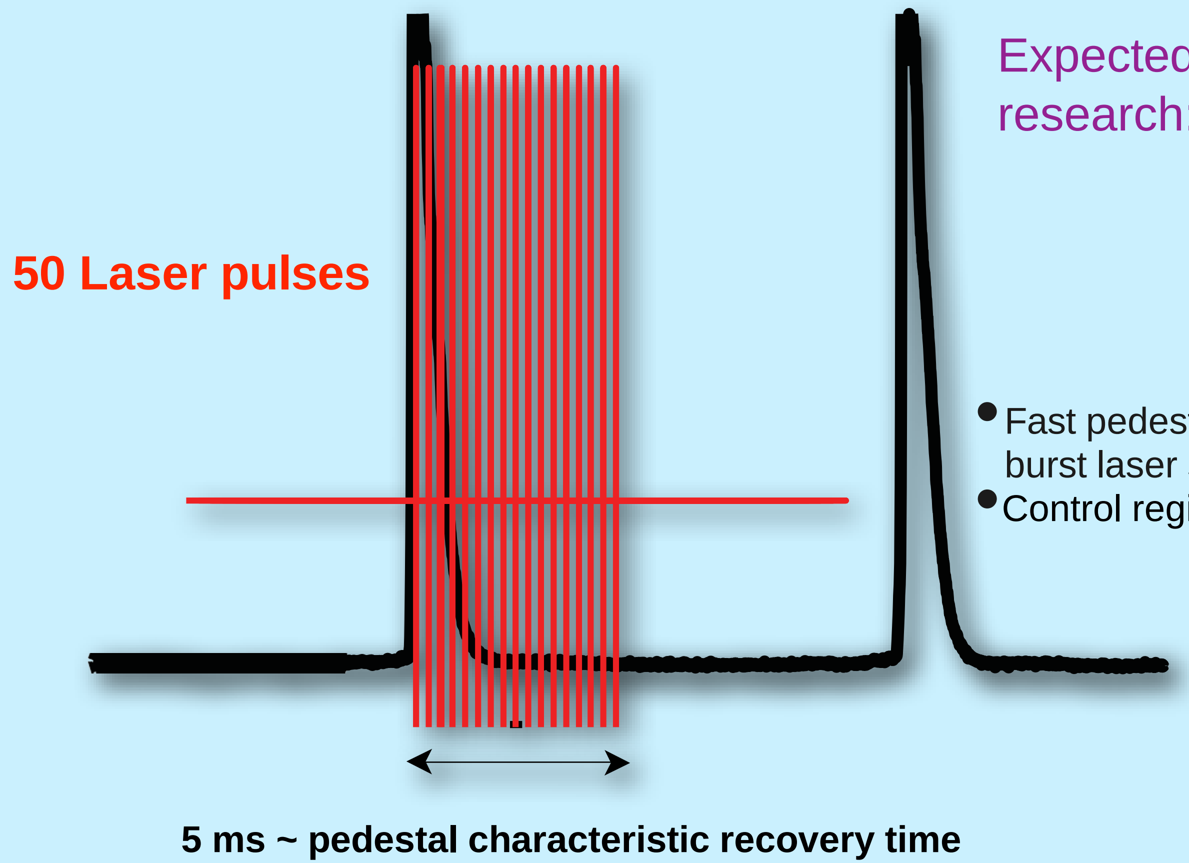
- Characterize the H-Mode pedestal structure at increased B_T, I_p, and NBI heating power, shaping, lower collisionality
  - Experiments to measure the pedestal structure dynamics
    - Compare to results from NSTX, emphasizing pedestal width dependence on pedestal β-poloidal
    - Build and extend the pedestal database for testing EPED model on STs
  - Identify common characteristics in the phenomenology of different types of ELMs
  - Access the low collisionality regime and assess its impact of the pedestal stability
    - Lower collisionality will lead to higher bootstrap current
  - Establish the EP-H regimes and further investigate (in a larger parameter space) the underlying physics mechanism leading to EPH

- Continue the investigation of the pedestal microinstabilities affecting the pedestal dynamics
  - Leverage the high spatial resolution edge diagnostics (e.g., BES, ME-SXR, bolometer)
  - Re-establish the existence of EHO and study its dependence with collisionality and rotation shear (3D midplane coils and 2nd NBI to vary rotation)

Pedestal Research plans for FY16

- Perform a range of experiments using the LGI to:
  - Trigger ELMs
  - Establish the dependence of injection rate, granule sizes with types of ELM
  - Develop a physical understanding of the triggering mechanism using nonlinear ELM codes (e.g., JOREK)
- Assess the effects of the upward evaporator on the pedestal structure and impurity content; compare with previous NSTX results
  - Determine if there is further widening of pedestal with increased lithium
- Establish the 3D magnetic perturbations for ELM pacing and compare with ELM triggered via LGI
  - Leverage the magnetic perturbation and the LGI to assess the navigability of the stability diagram
  - Supersonic gas injection (SGI) for ELM triggering and fueling
- Develop 3D triggered EPH and explore physics and impact of high edge rotation shear
- Stability: explore potential differences in pedestal fueling and/or ELM behavior from operation on high-Z vs. C tiles

Goal of measuring pedestal evolution and controlling it on ms-time scale is focus of a recent Early Career Research Proposal Award



Expected availability for physics research: during FY2016 run

- Fast pedestal measurement using pulse burst laser system (PBLS)
- Control region using actuators

see backup for more details

Summary: Pedestal research in NSTX-U will contribute to H-mode understanding and control for ITER and FNSF

- Substantial progress made on understanding of pedestal dynamics through collaborative research and in-depth analysis of NSTX data during the past year

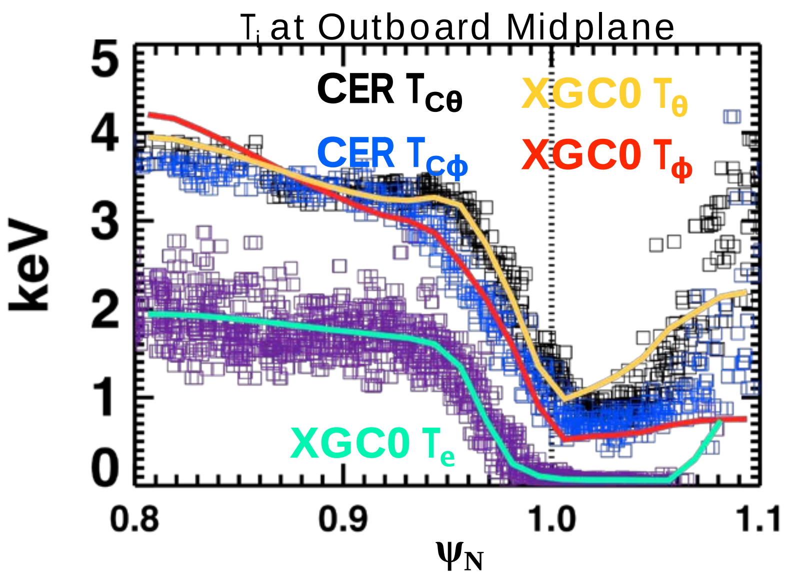
- NSTX-U will thoroughly characterize evolution during ELM cycle; Validate predictive models of pressure profile evolution
  - Will separate effects of density and temperature profiles, as needed for predictive capability and to provide control options

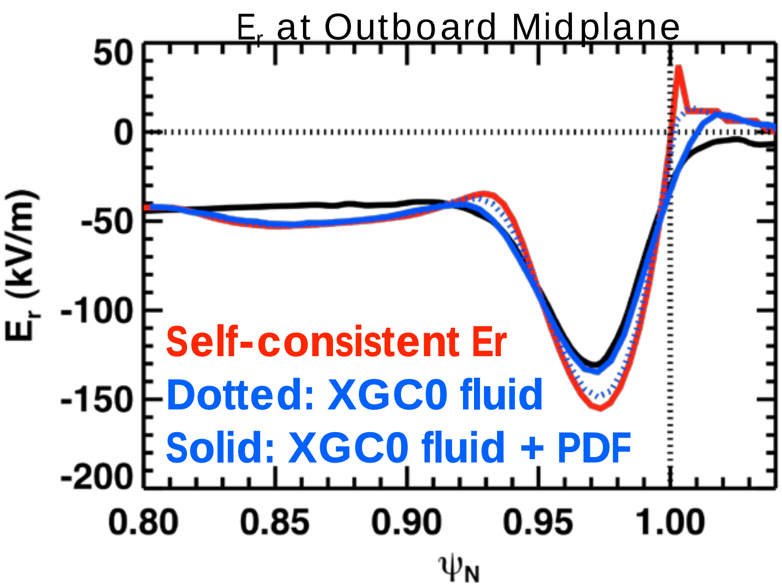
- NSTX-U will use new capabilities to effectively control the pedestal for optimum performance
  - Leverage similar control tools deployed on EAST and DIII-D

Backup

Kinetic neoclassical calculations using XGC0 captures non-Maxwellian ion distributions in DIII-D pedestal

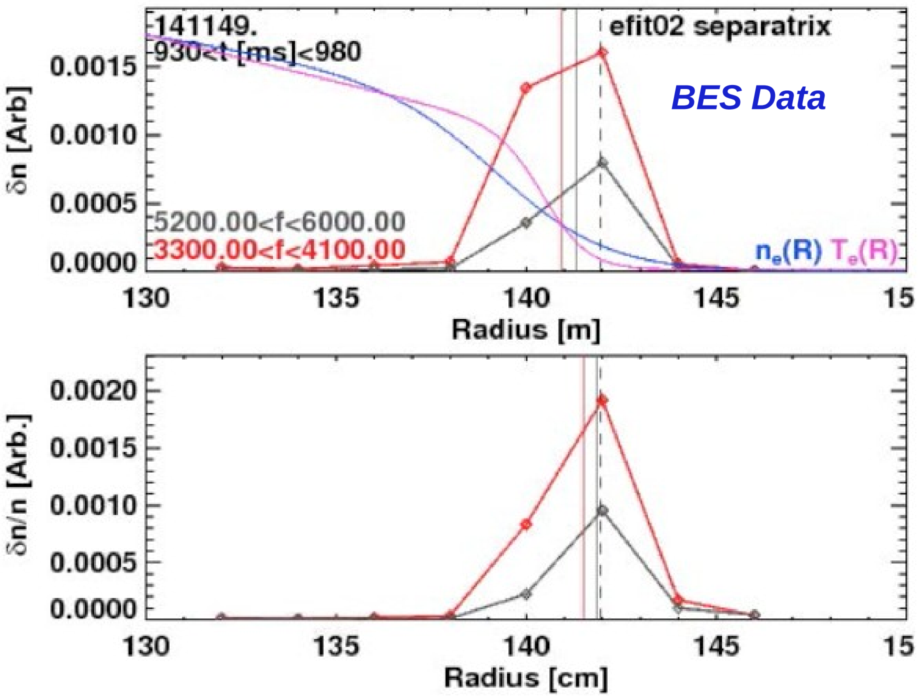
- Kinetic effects lead to non-Maxwellian ion energy distributions
  - Result: species dependent T_i anistropy and intrinsic edge flows
- E_r is the root solution that balances neoclassical ion transport
  - Balance ion orbit loss against neoclassical pinch
  - Good agreement with measured “fluid force balance” E_r when considering diagnostic and kinetic effects

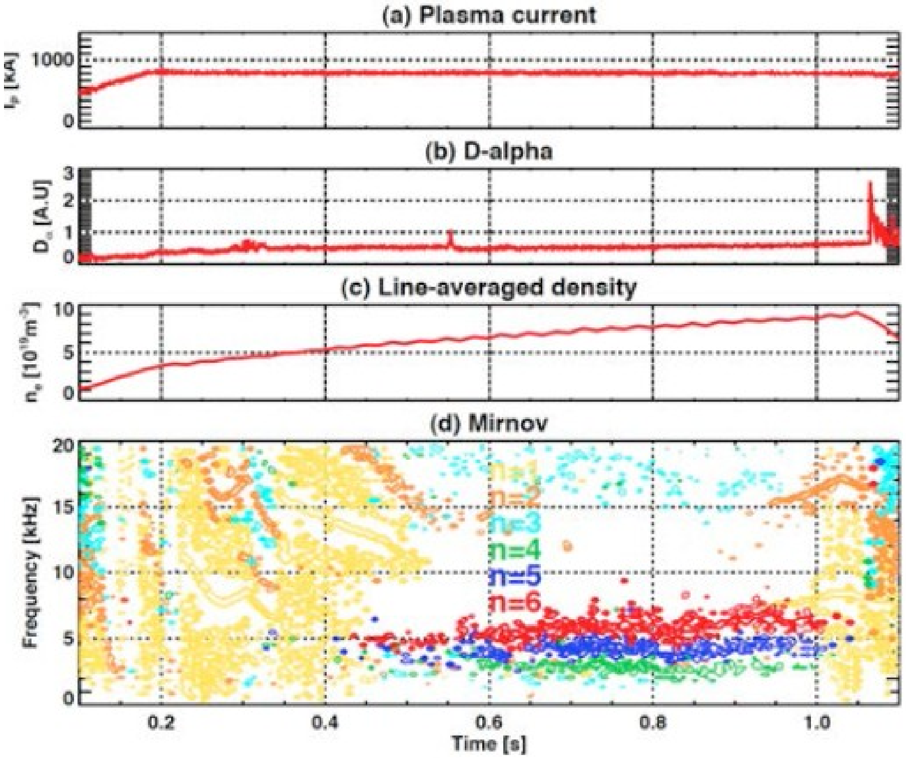




Edge Harmonic Oscillation (EHO) observed in NSTX pedestals but too weak flush out impurity

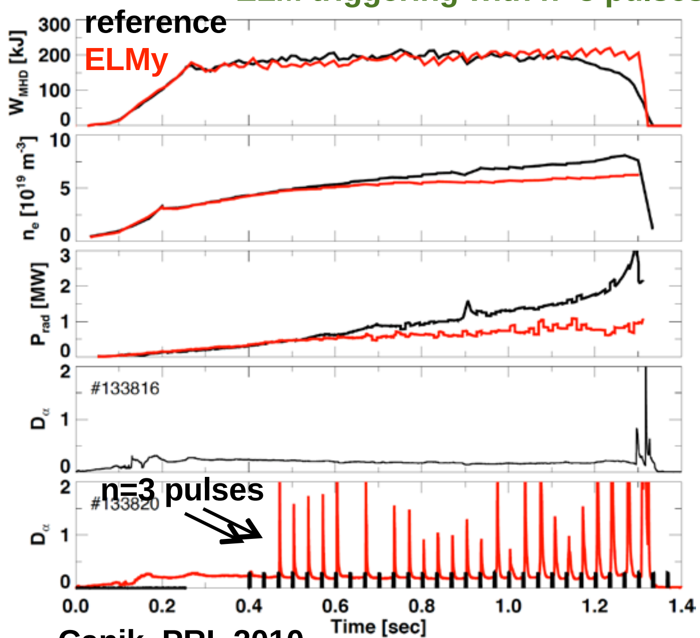
- BES and reflectometer analysis show that the modes are very edge localized
- ELITE calculations show that the pedestal resides near the peeling boundary
  - similar to EHO during QH mode in DIII-D
- NSTX-U will access low collisionality which in combination with the 2nd NBI and the midplane coils will enable variation of the edge rotation shear and potentially re-establish EHO



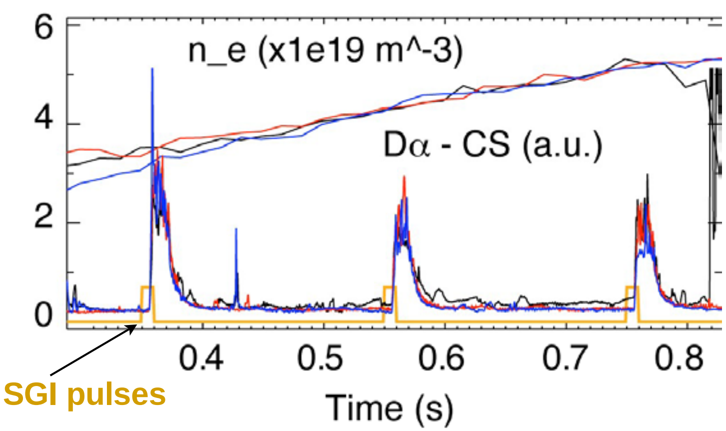


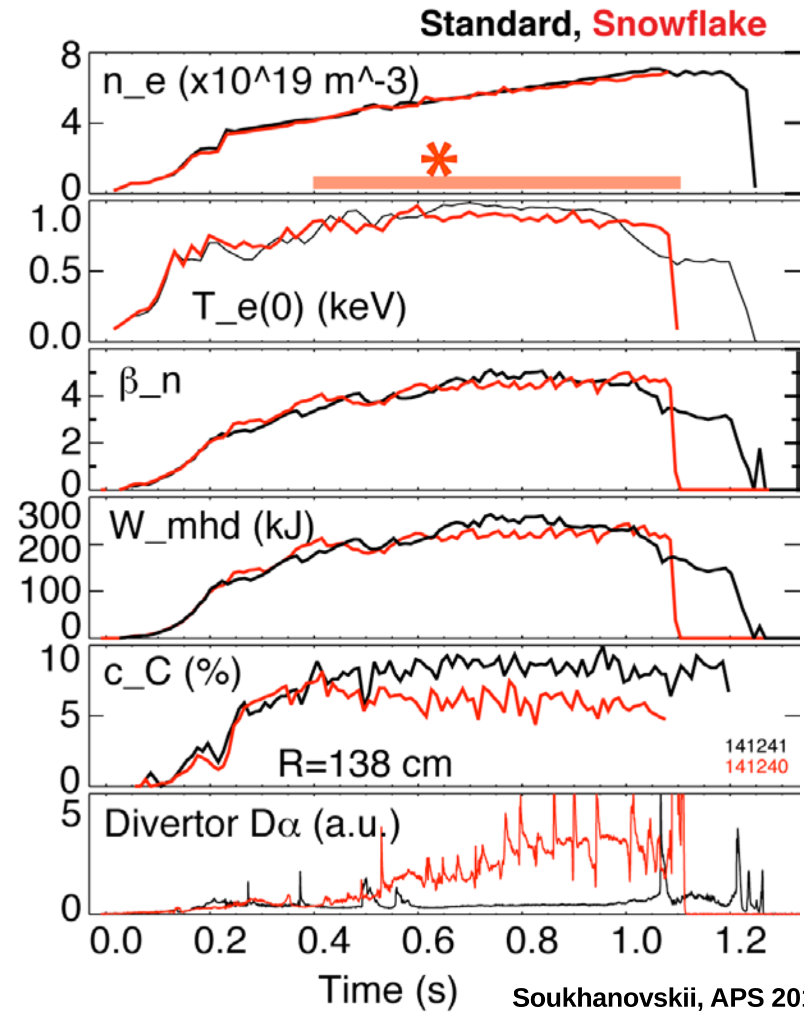
ELMs triggered with 3-D fields and SGI successful and snowflake configuration reduces edge carbon

ELM triggering with n=3 pulses



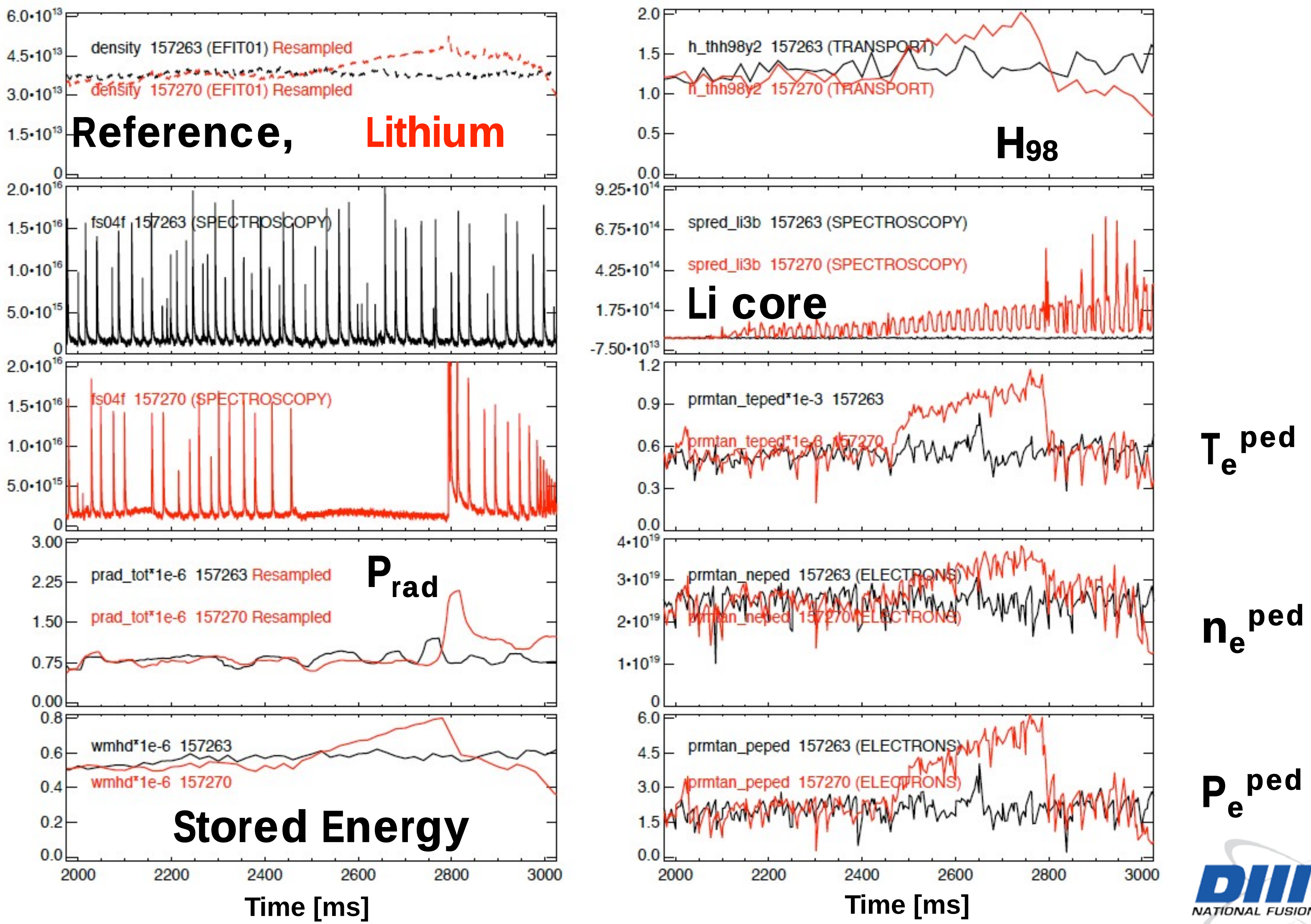
Canik, PRL 2010





Soukhanovskii, APS 2010

ELM-free periods up to ~ 400 msec observed, with T_e^{ped} > 1 keV and H_{98} < 2; P_e^{ped} almost tripled; no sign of P_{rad} secular increase



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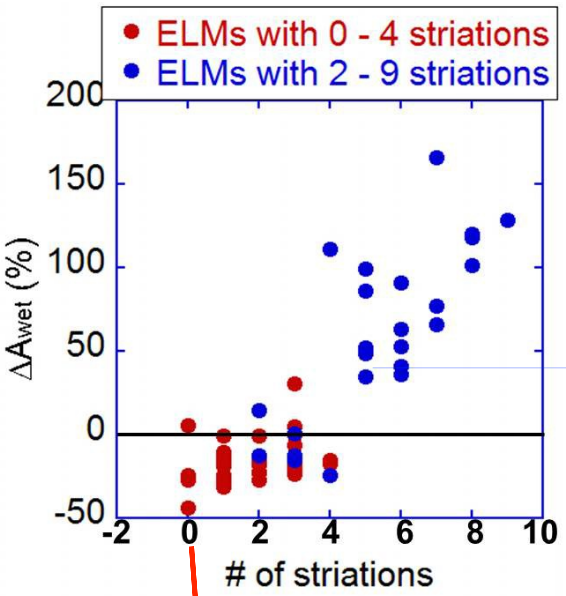
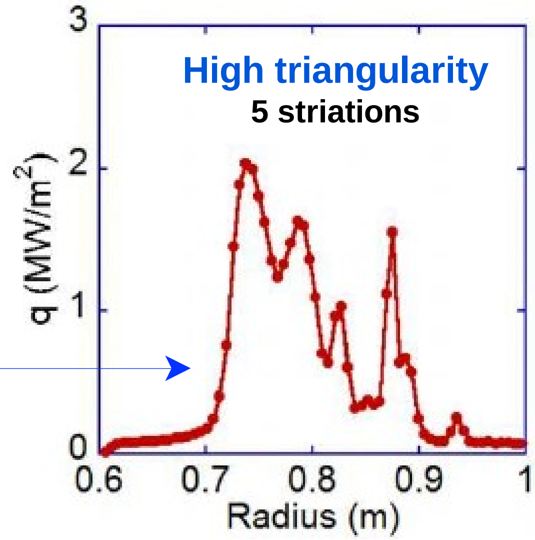
Plans to measure pedestal evolution to enable its control on ms-time scales is the focus of a recent Early Career Research Proposal Award

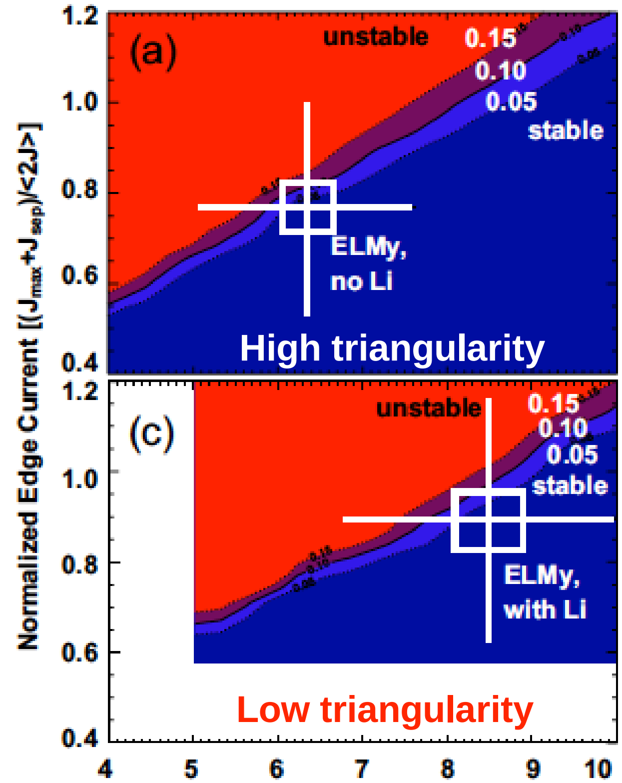
- Goals of study
  - Determine and **characterize** the fundamental mechanism at play that define the pedestal recovery, buildup until the next ELM (e.g., C-Mod, DIIID, MAST, plans for NSTX-U)
  - Develop a fast Thomson scattering system for **characterizing** the pedestal recovery with high time resolution and provide the means to **control** the pedestal
- FY2013-2014 results/progress
  - Direct evidence of coherent instability limiting the pedestal evolution
  - Characterized the time scales at play during the early recovery of the pedestal
- Thus far: procured phase I of a hybrid laser system design with PSL at UW (with 30 Hz base rep rate and 1 kHz or 10 kHz rep rate bursting phase)
  - Design review to be held in July 2014
  - Phase II can commence once the laser head is delivered (expected August 15 2014)
  - Developing real-time algorithm for computing density and temperature
- Actuators for controlling the pedestal
  - Near term candidate: LGI, and molecular cluster injector (collaboration from LTX)
  - Long term candidate: EHO antenna, ECH/EBW

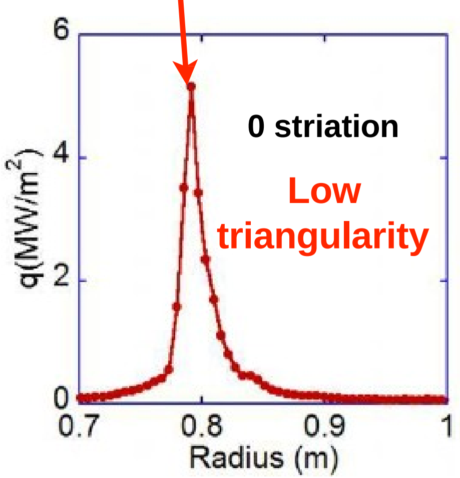
ELM heat flux footprint becomes more peaked with decreasing number of striations; related to NSTX stability on low-n current driven stability boundary





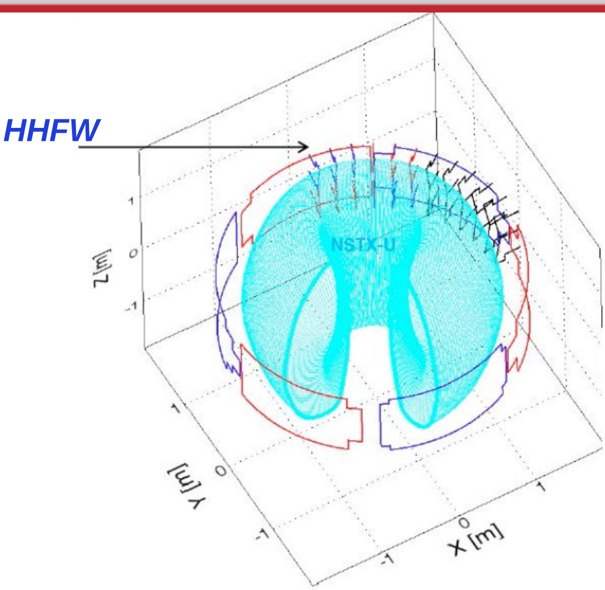
Ahn submitted PRL 2014

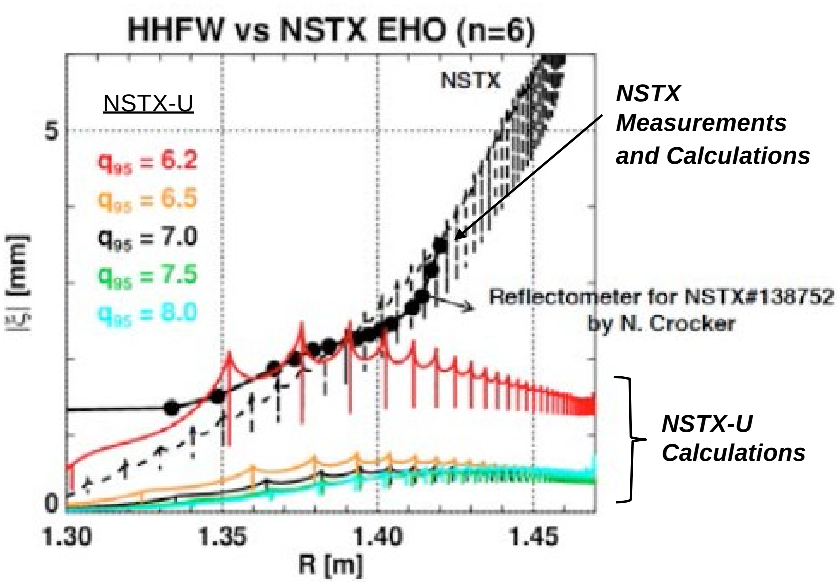




- For a given low-n (<4), the wetted area increases with number of striations
  - Shaping appears to play a role in spreading the heat
- ITER also predicted to be on low-n current driven boundary – like NSTX?

Coupling of the NSTX-U HHFW antenna to the plasma was examined as means to amplify EHO modes (expected in FY 2018)





- IPEC used to compute plasma displacements using an ideal plasma response model.
  - Calculations show that displacements with ~1 kA current in the HHFW antenna matches the observed EHO displacements.
- NSTX-U calculations indicated that comparable displacements may be achievable at lower-q_{95}
  - Need to assess the β_N dependence

HHFW field configuration not fully optimized for the best EHO coupling in NSTX-U

Leverage recently identified long pulse EP H-modes for exploration in NSTX-U

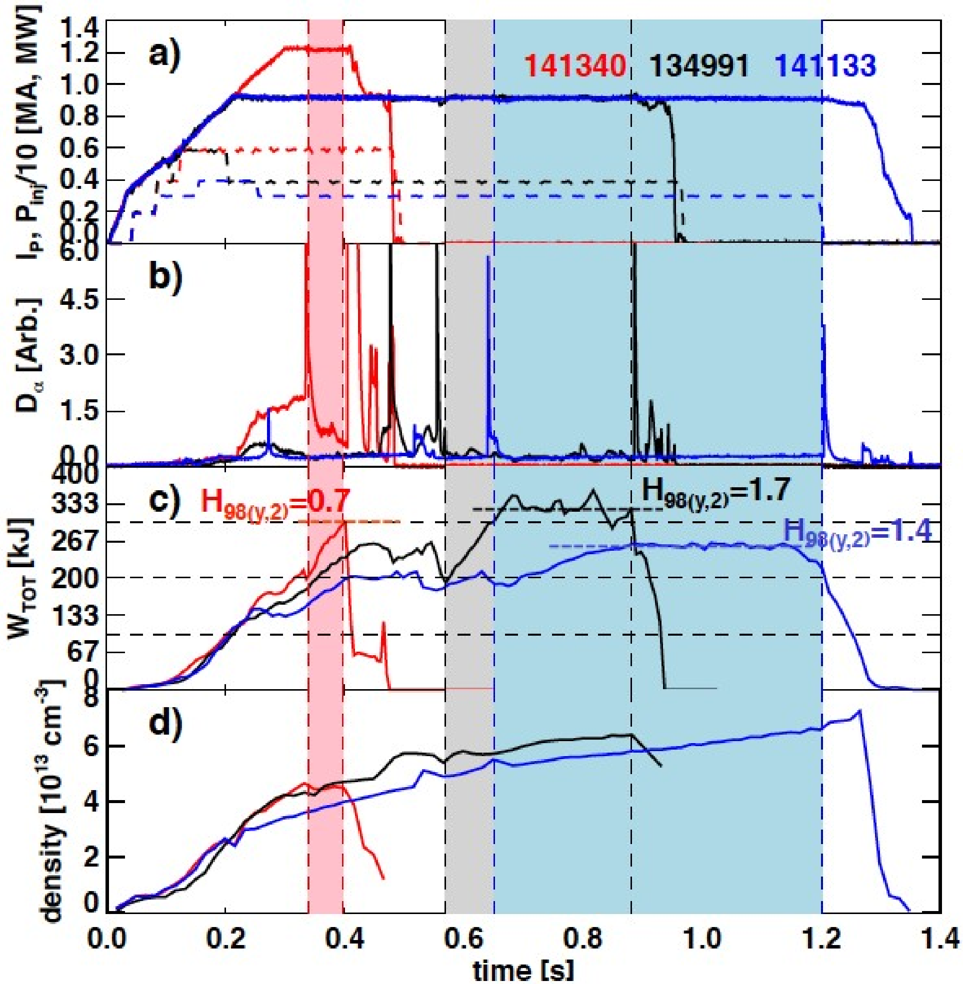
Early Examples
short-lived
[Maingi JNM 2009]

↓

First extended EP-H mode
many confinement times
[Maingi PRL 2010]

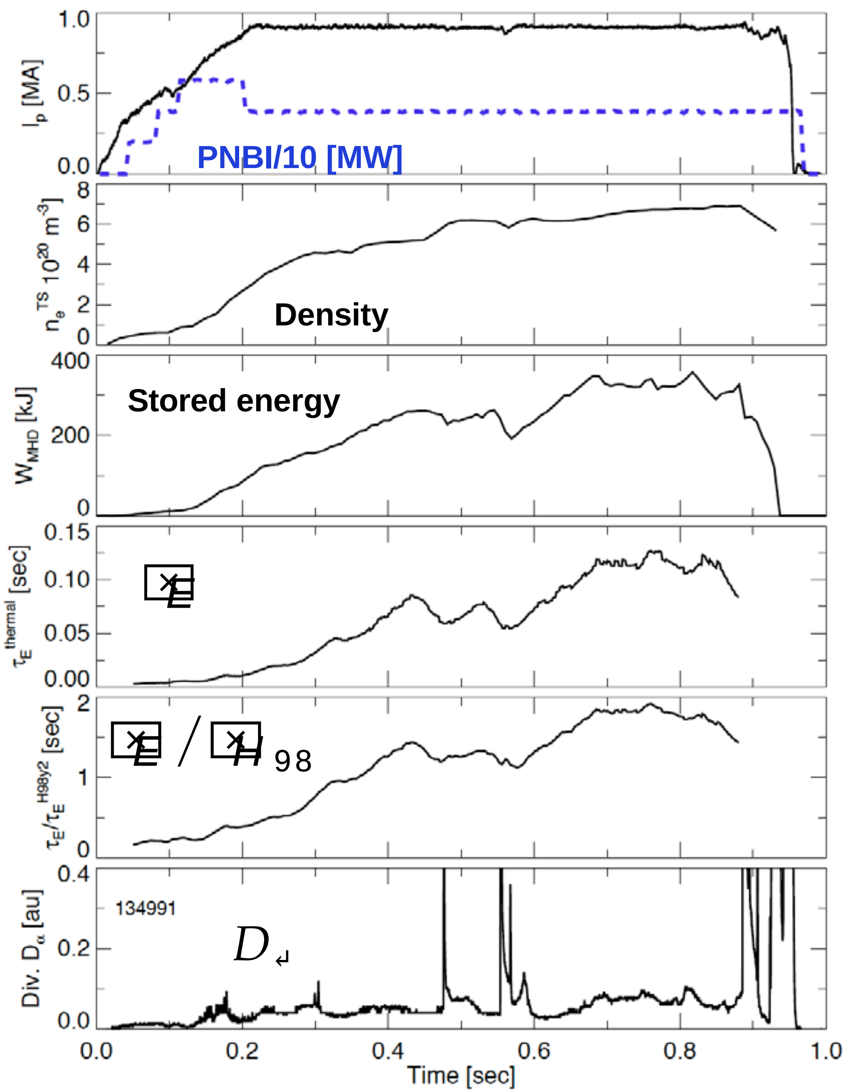
↓

Quiescent long-duration EP H-mode
maintained for NB heating and quiescent
[Gerhardt submitted to NF 2014]

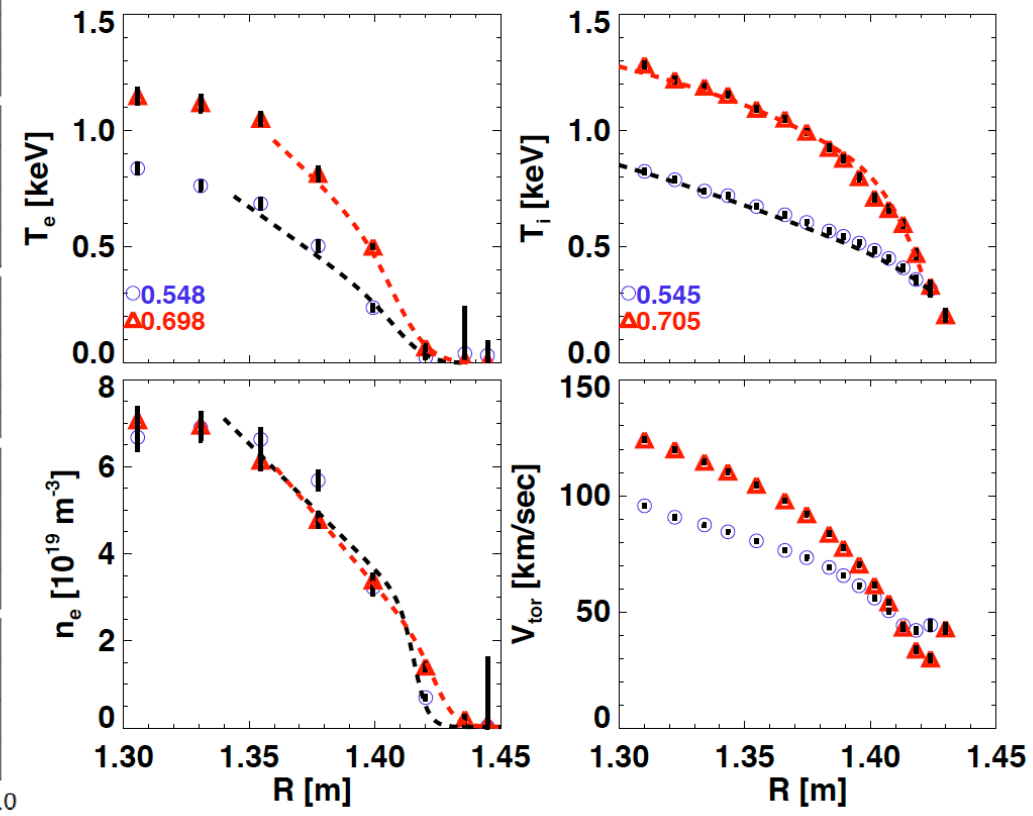


Density rise due to carbon impurity accumulations

Enhanced Pedestal H-mode (EP- H) observed with H_{98} < 1.7, higher than H-mode ion temperature pedestal



Profile characterization



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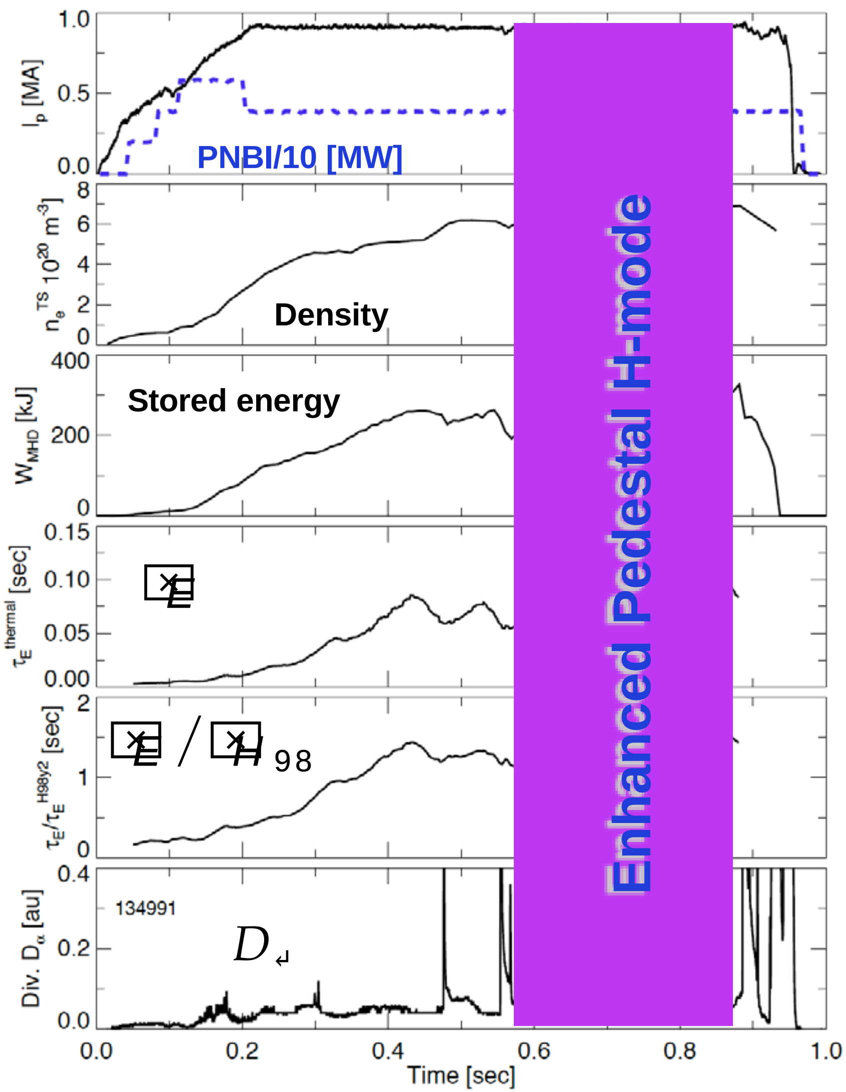

Profile characterization