NSTX-U

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Progress in characterization of the pedestal structure, stability and fluctuations during ELM cycle on NSTX

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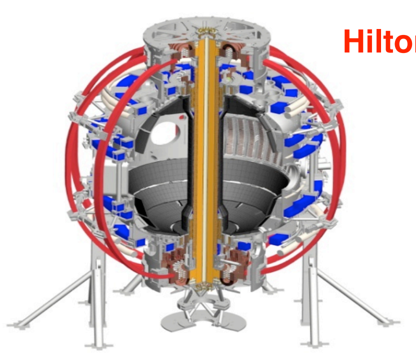
24th IAEA Fusion Energy Conference
8-13 October 2012
Hilton San Diego Bayfront Hotel



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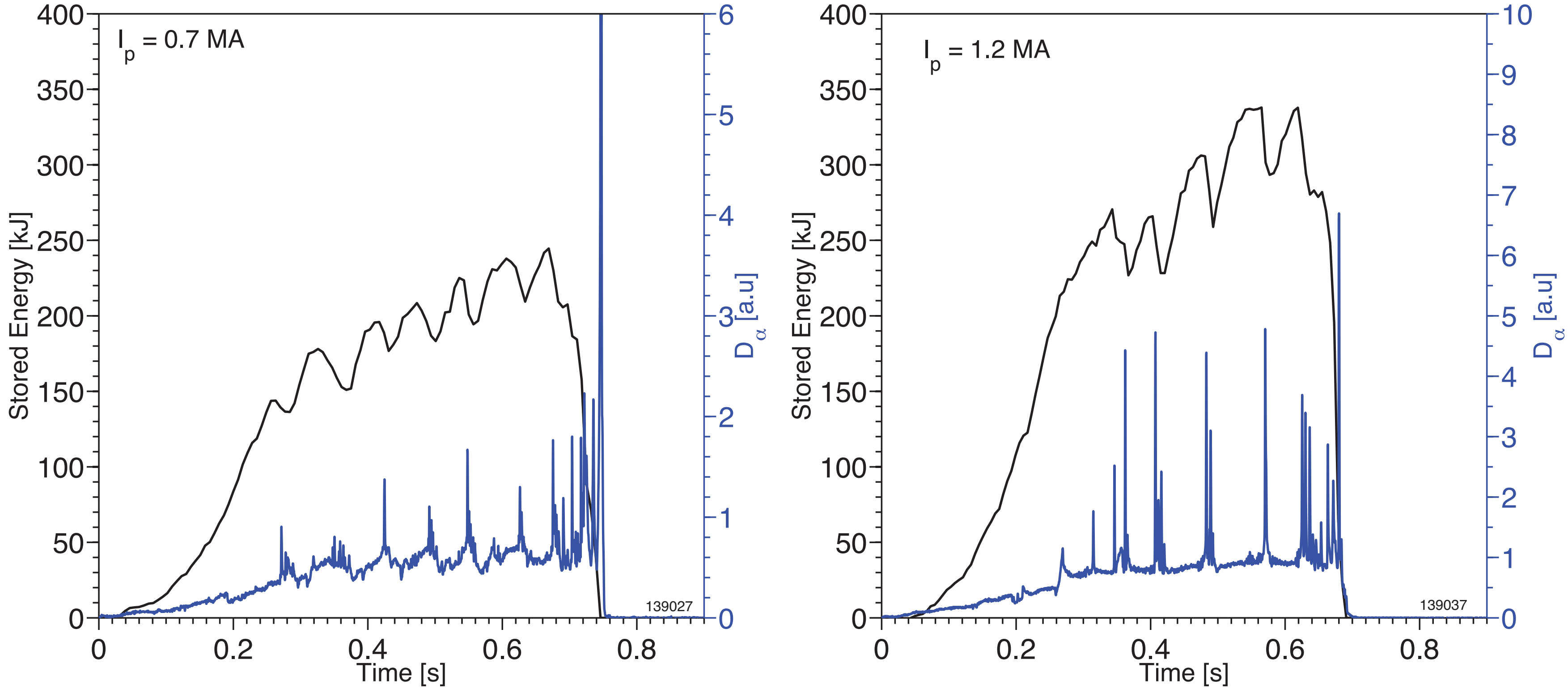
Abstract

Understanding the pedestal structure is important for achieving high performance pedestals necessary for maximum core fusion gain in ITER and future next-step devices. The stability of the pedestal is characterized in high performance discharges in National Spherical Torus Experiment (NSTX). In addition, the spatial structure of turbulence present during an ELM cycle in the pedestal region indicates spatial scales $k_\perp \rho_i^{ped}$ ranging from 0.2 to 0.7 propagating in the ion diamagnetic drift direction at the pedestal top. These propagating spatial scales are found to be poloidally elongated and consistent with ion-scale microturbulence. Linear gyrokinetic simulations using GENE indicate the presence of hybrid ITG/KBM-TEM modes at the pedestal top. Nonlinear gyrokinetic simulations -- XGC1 -- find localized fluctuations agreeing with experimental level radial and poloidal correlation lengths.

This work is supported by U.S. Dept of Energy contracts DE-AC02-09CH11466.

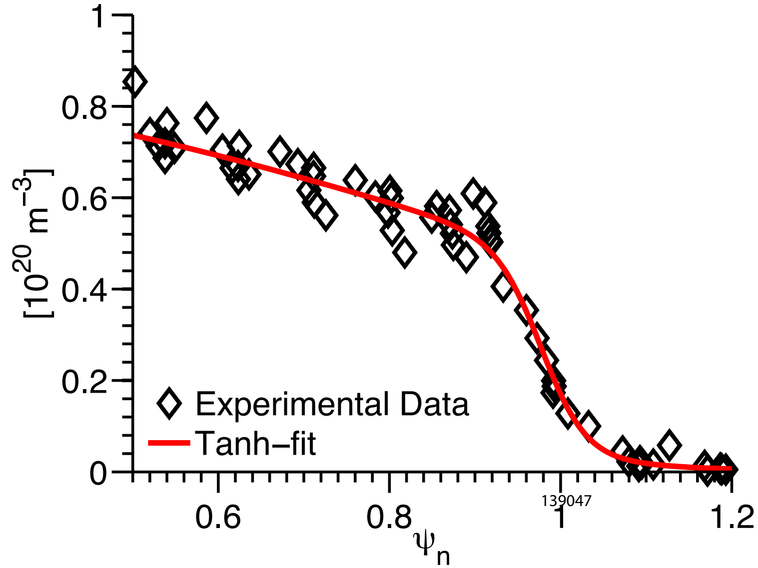
Dedicated experiments to vary the pedestal pressure height and width through I_p scans were performed on NSTX

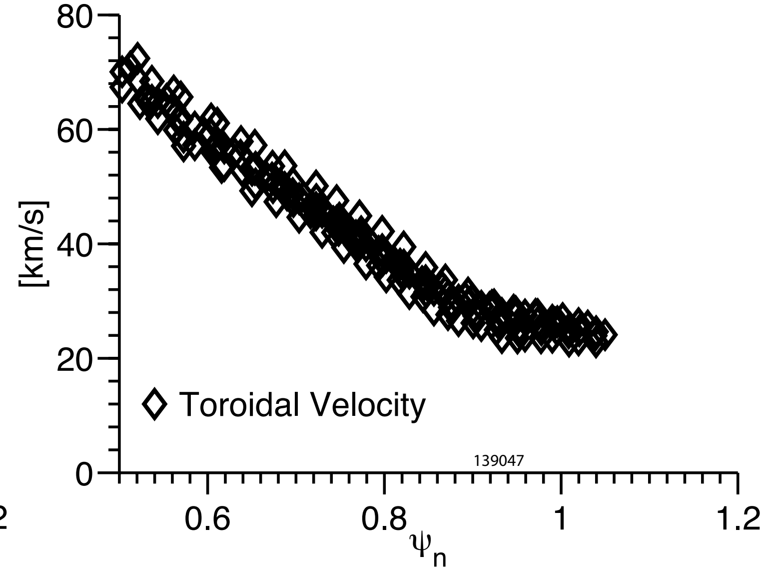
- Constant injected power (P_{NBI}) and magnetic field (B_T)
- Lower single null slightly downward and fixed high triangularity shaping.

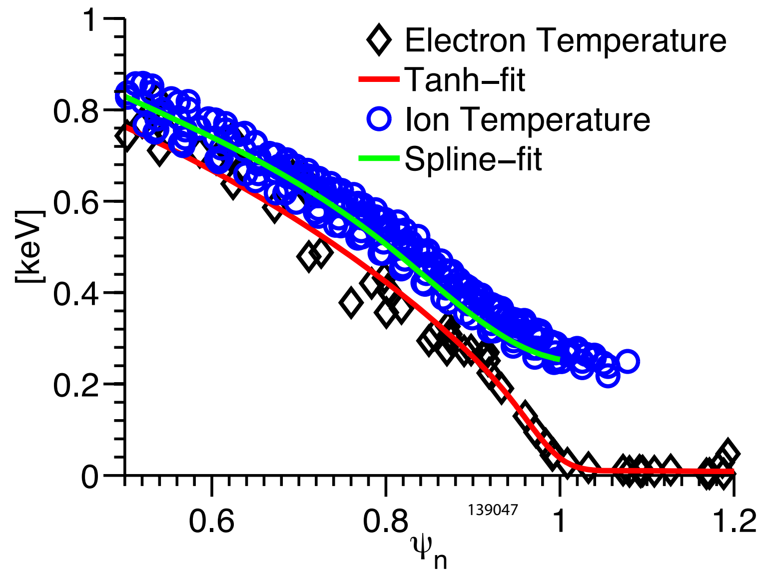


- Large drop (up to 15%) of stored energy (W_{mhd}) after each ELM crash.
  - Loss of pedestal stored energy ~ 25% - 40%
- Implicitly generating scans of the pedestal structure.

Radial profiles of density, temperature and velcity are composite of times between multiple fraction of ELMs (e.g., 50-99% ELM cycle)







- Electrons edge radial profiles are fitted using a modified tanh function

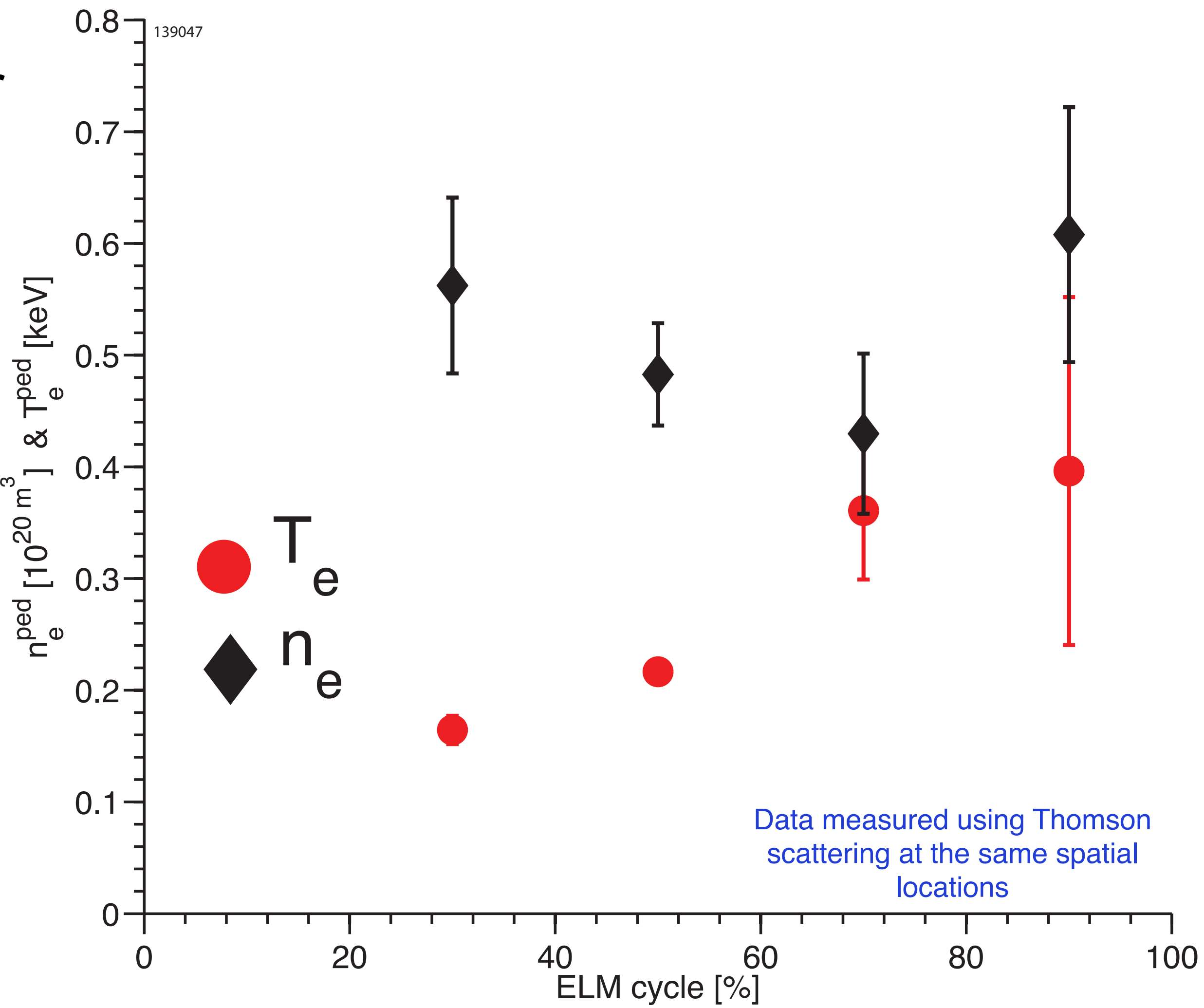
$$N(\psi) = A \tanh\left(\frac{\psi_{sym} - \psi}{\psi_{width}}\right) + offset$$

R. Groebner and T. Osborne PoP (1998)

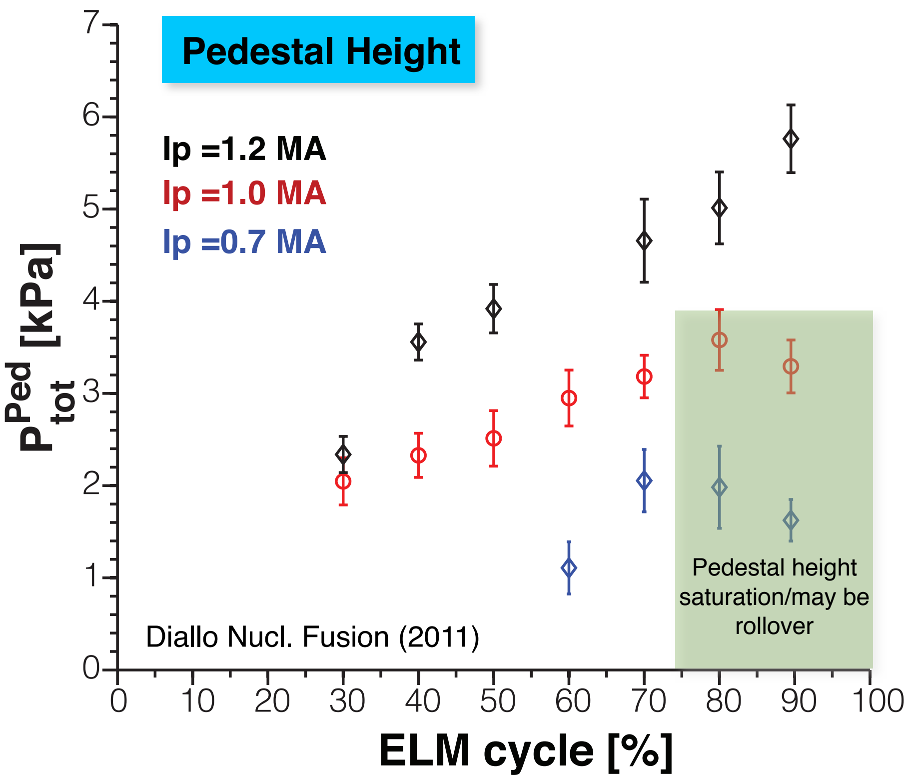
- Ion profiles are spline fitted

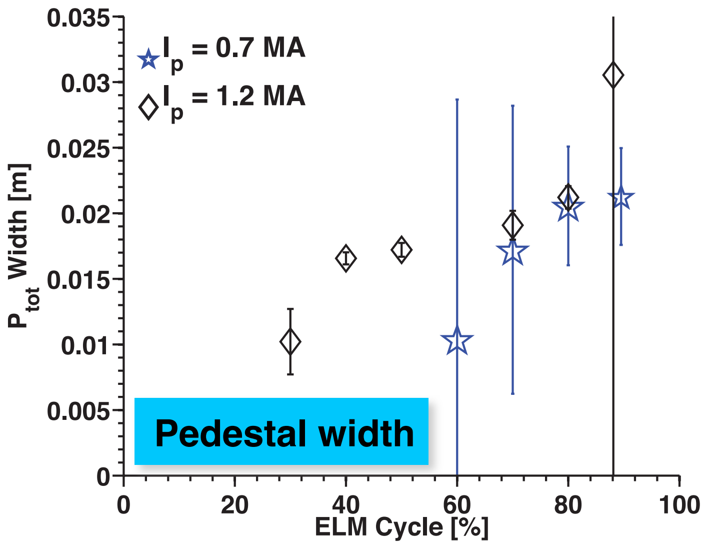
Temperature pedestal height increases during the ELM cycle while the density pedestal shows no convincing trend

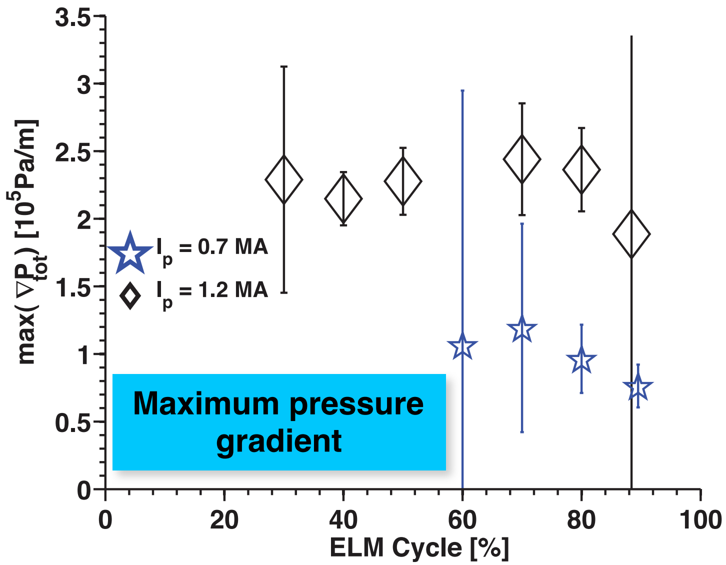
- More than a factor of two increase in pedestal temperature
- Density pedestal is much less sensitive to the ELM cycle
- Heat and particle evolutions appear to be decoupled



Pedestal width and height progressively increase during ELM cycle but the peak pressure gradient remains clamped

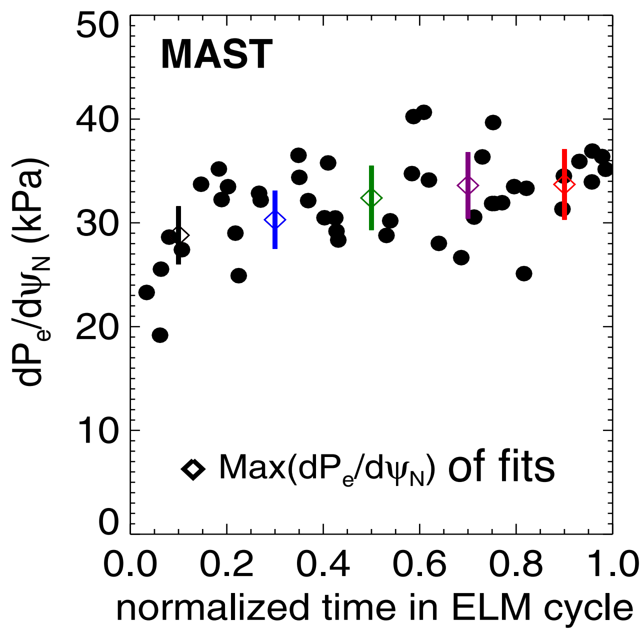


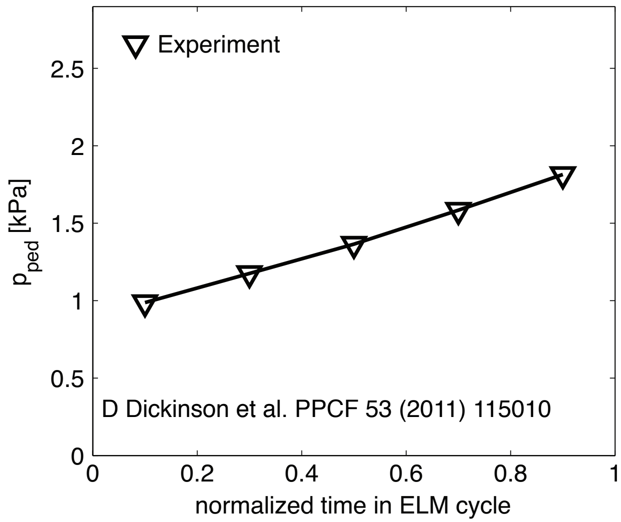


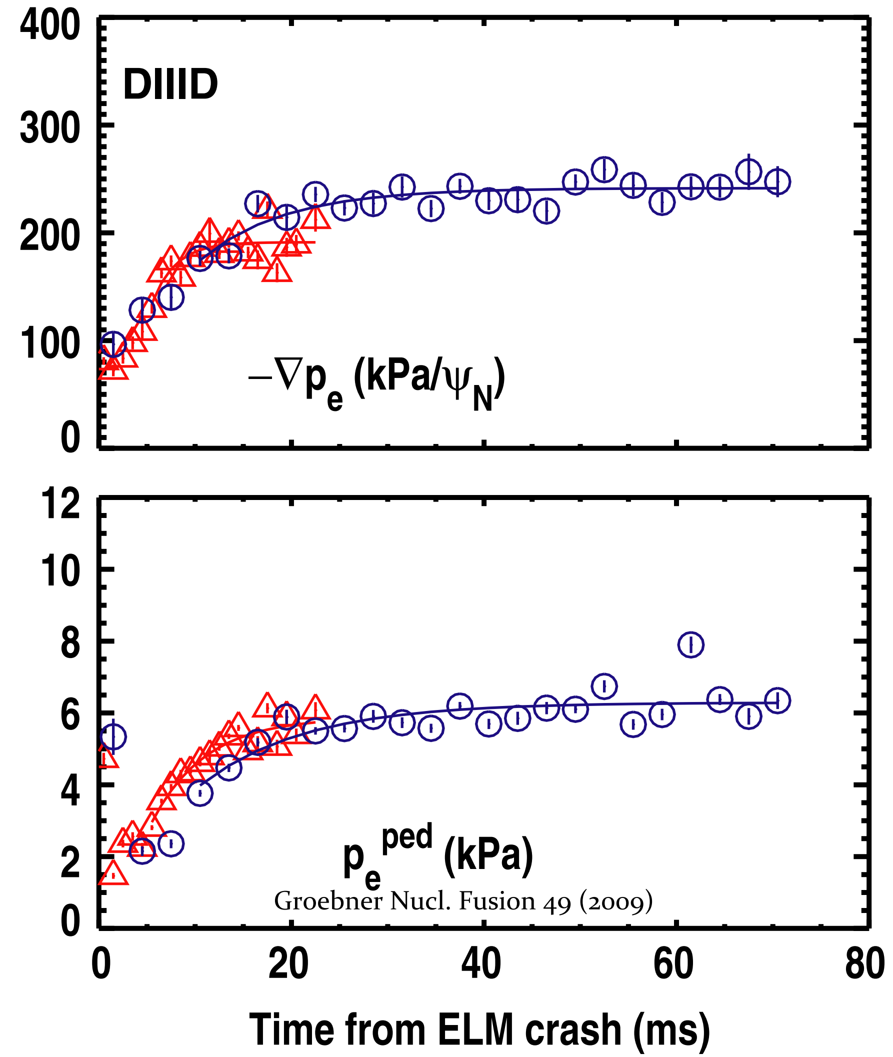


- Pedestal height increases by a factor ≤ 3
  - Height scales with I_p
- Pedestal width increases independently of I_p
- Gradient is clamped early in ELM cycle

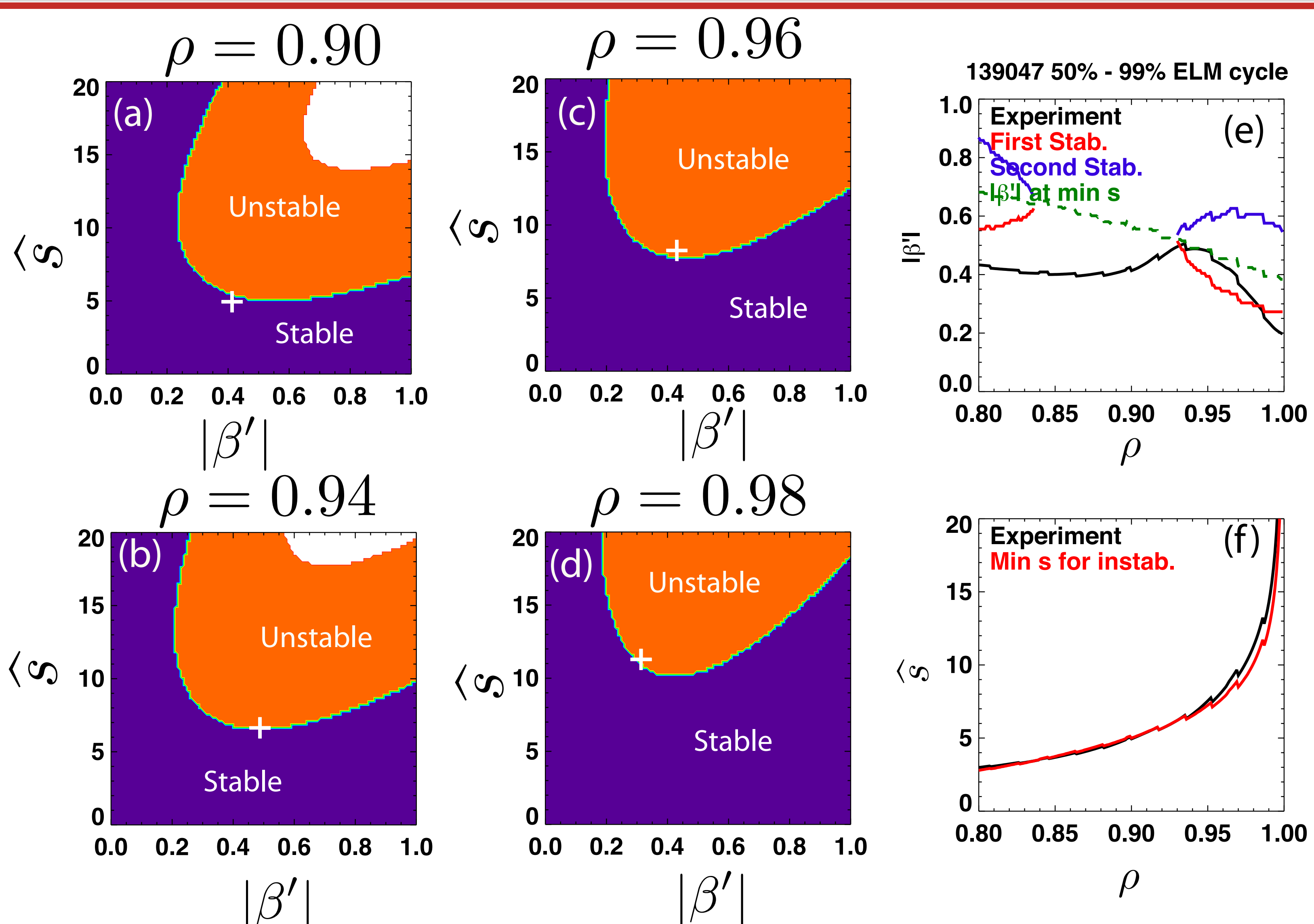
Saturation of the gradient is ubiquitous across devices, but different trends in pedestal height evolution are observed





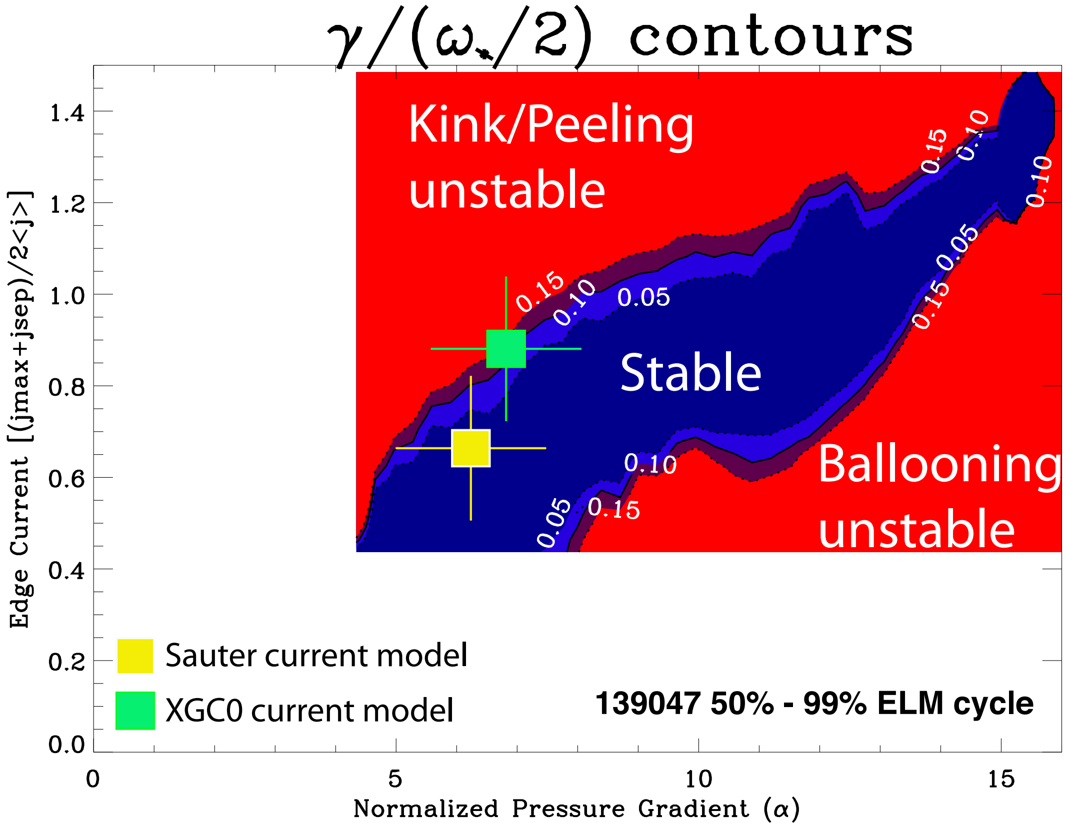


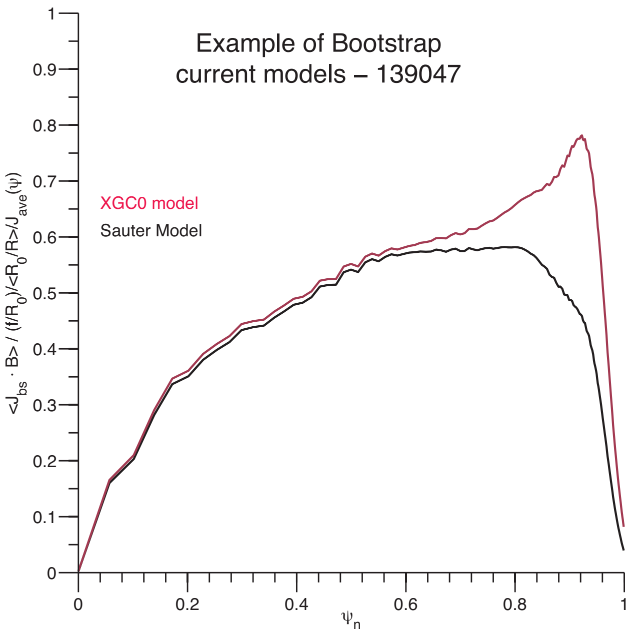
Ideal ballooning stability is performed using "ball" module of GS2 during the last 50% of ELM cycle: Pedestal top is found to be ballooning unstable



See Canik - this meeting

ELITE Peeling-ballooning mode stability diagram confirms that NSTX pedestal is kink-peeling unstable



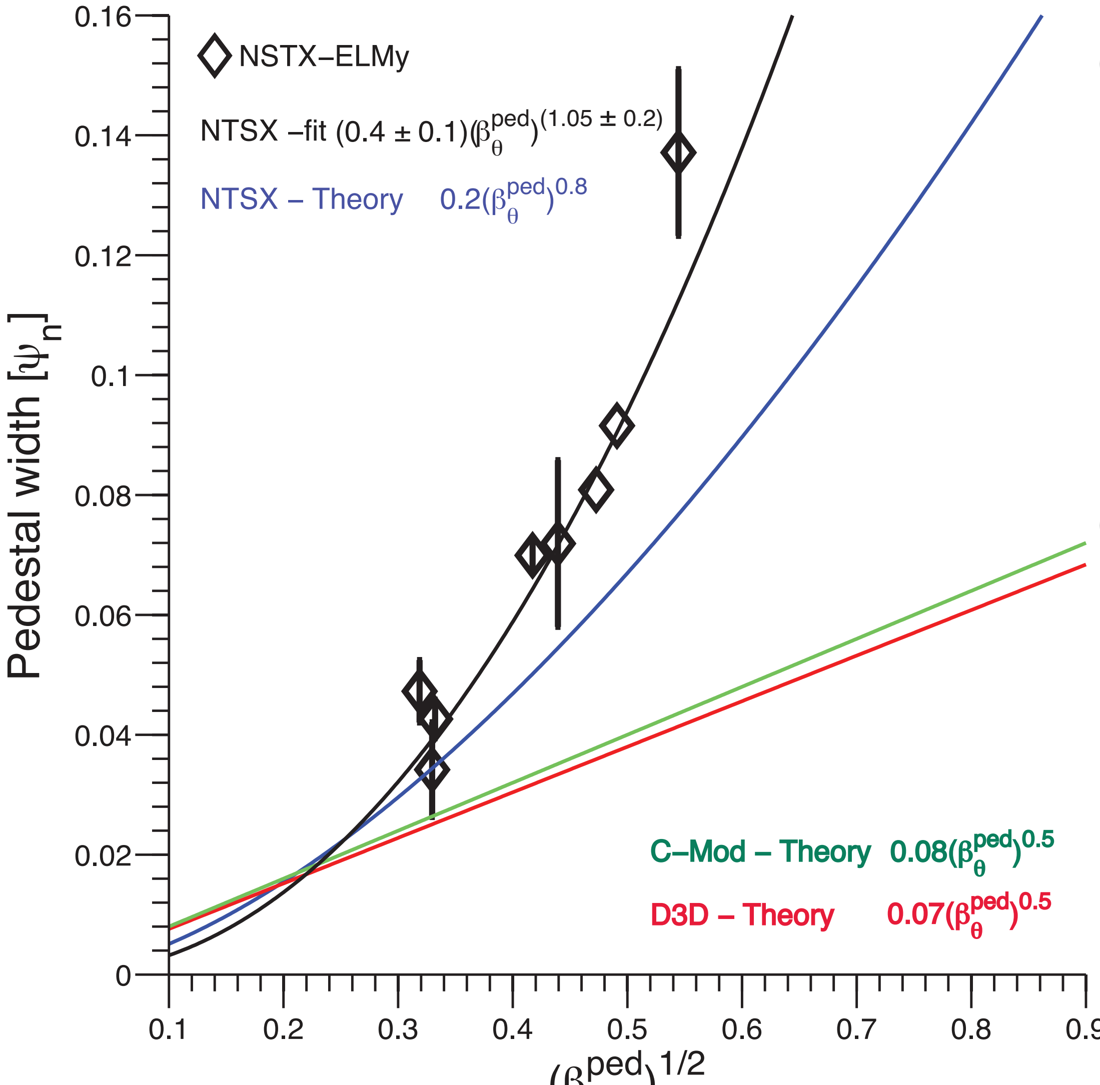


- Equilibria around experimental point are generated by varying the edge pressure gradient at fixed edge current and vice-versa.
- Stability of each equilibrium is computed using the ELITE MHD code
  – n = 3, 6,12, 15

- Using the recent implementation of XGC0-bootstrap current model, the experimental point is in the kink/peeling unstable region during the last part of the ELM cycle.
  – The XGC0 current model is described in C-SChang TH/P4-12
  – These results agree with previous NSTX stability analyses.

Boyle PPCF (2011)

NSTX measured pedestal pressure width scales like $(\beta_\theta)^\alpha$ with exponent ranging from 0.8 to 1 consistent with (*preliminary*) predicted KBM-constrained pedestal



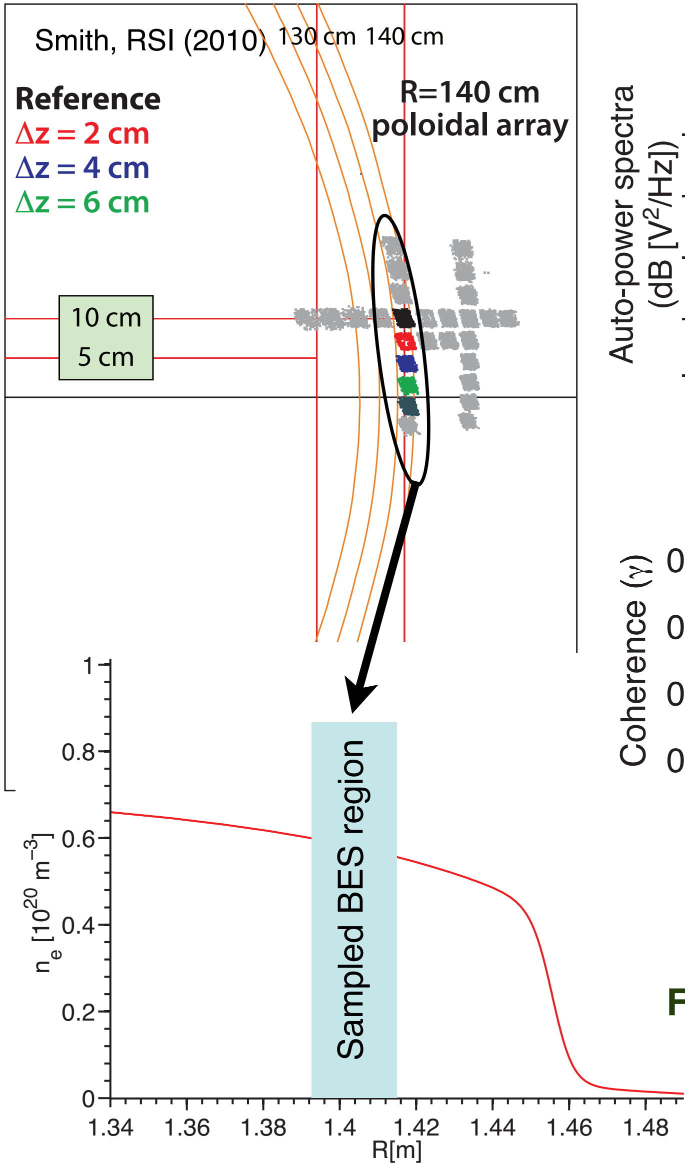
P. Snyder IAEA 2012

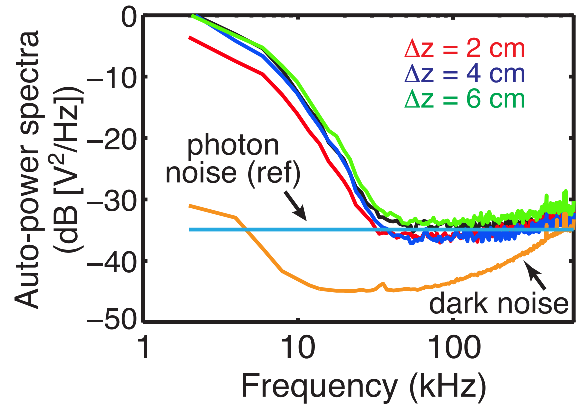
- In NSTX, the observed width is larger than conventional tokamaks
  - NSTX pedestal width is 1.7 and 2.4 larger than MAST and DIII-D & C-Mod respectively
- Pedestal width scaling is consistent with predicted width for KBM constrained pedestal
  - "ballooning critical pedestal"- BCP technique from EPED Model [Snyder Nucl. Fusion (2011)]
  - Conventional tokamaks show an exponent of 0.5.

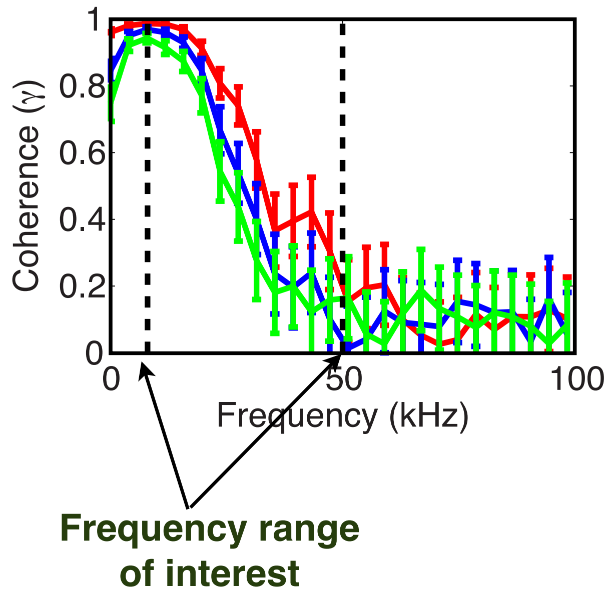
Role of the edge density fluctuations on setting the pedestal structure during the inter-ELM phase

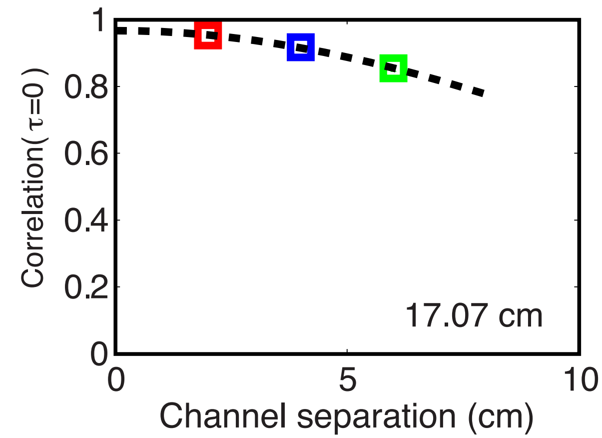
- Pedestal gradient has been predicted to be constrained by the onset of kinetic ballooning mode (KBM)* *Snyder PoP 9 (2002)
  - Recent DIIID work has shown observations of modes localized in the pedestal region with features similar to KBM Yan PRL 107 (2011)
  - KBM characterized by:
    - $k_{\perp}\rho_i < 1$ similar to ITG
    - modes have radial scales of the order few cm in the pedestal region of NSTX
    - fast rising growth rate increasing with electron β
    - propagation in the ion diamagnetic direction.
- NSTX: We look for evidence of pedestal-localized microinstabilities, and their correlation with the ELM cycle
- Perform gyrokinetic simulation to identify the mode at play
  - Here both GENE and XCG1 are utilized.

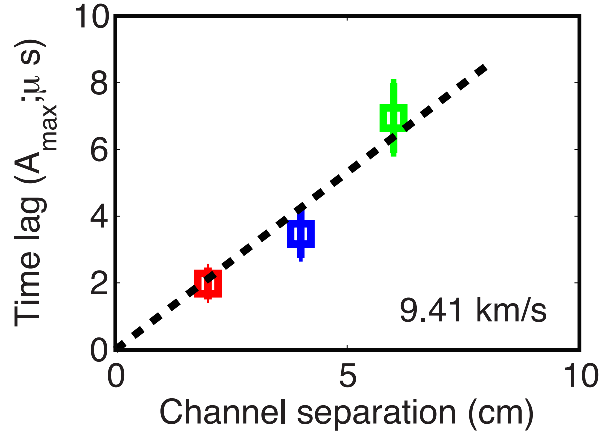
BES yields characterization of density fluctuations the density pedestal top





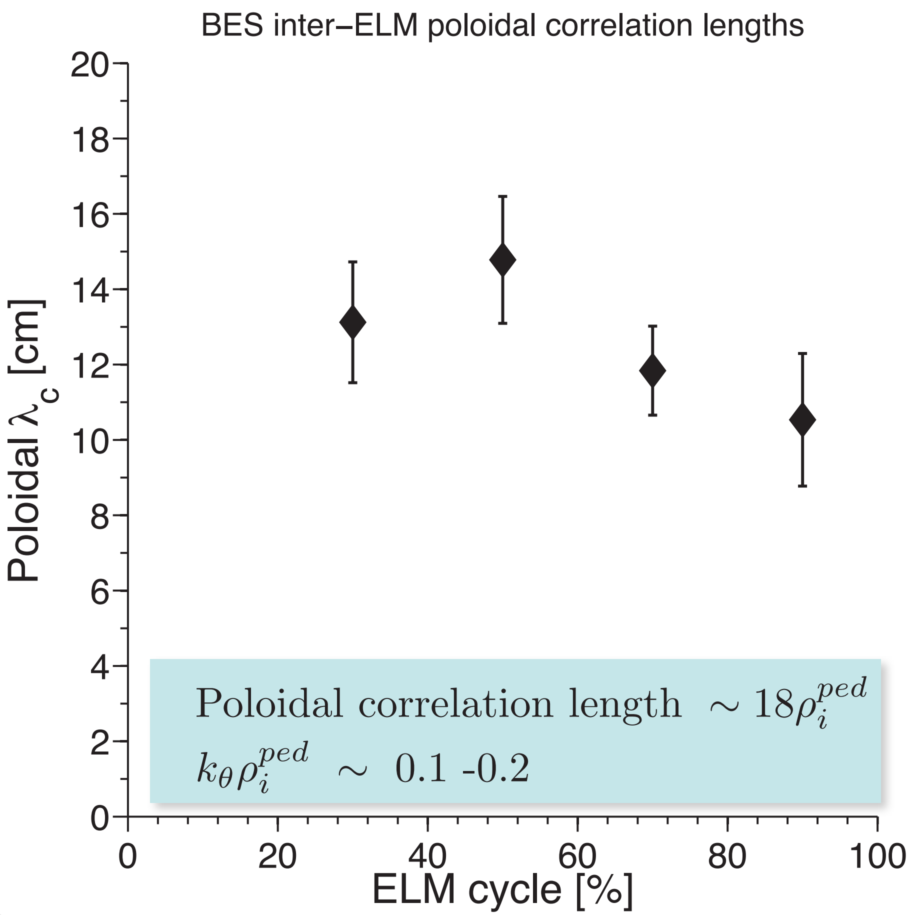


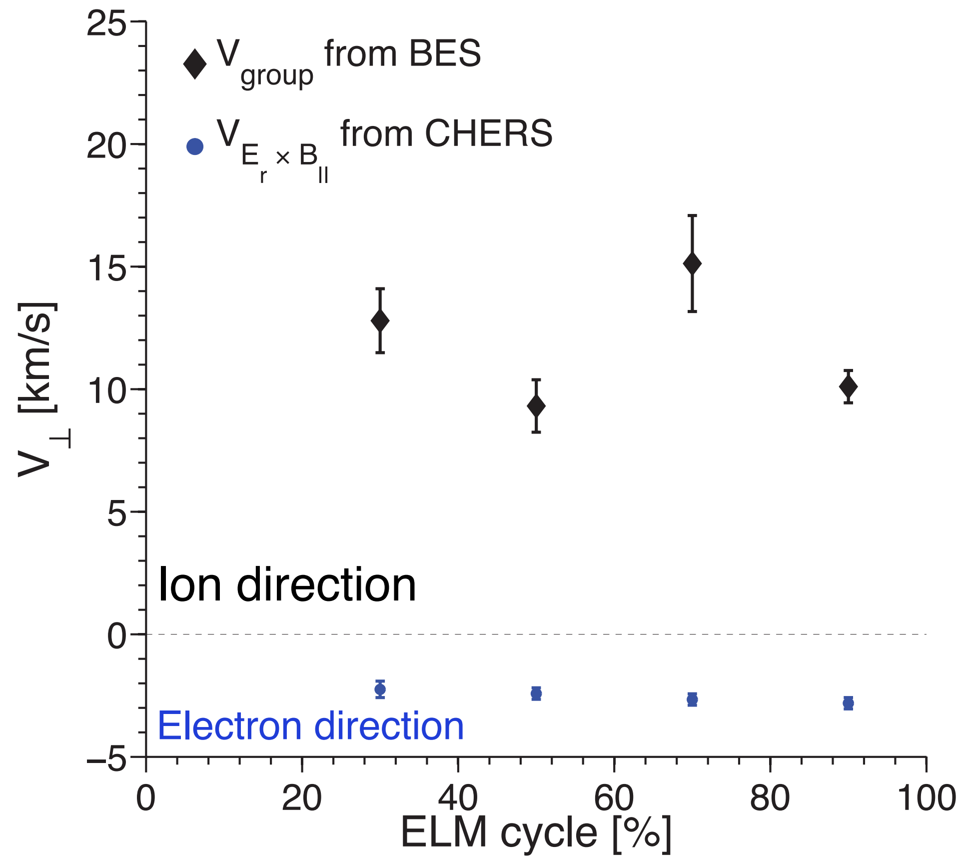




D. Smith EX/P7-18

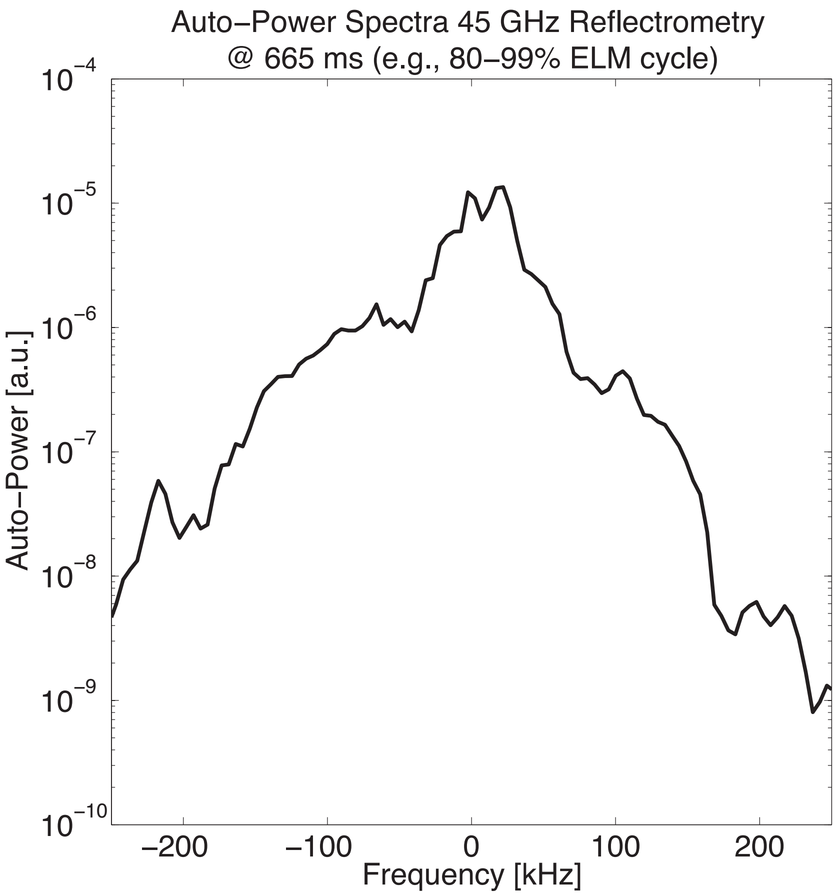
BES provides measurements of the poloidal correlation length and poloidal velocity

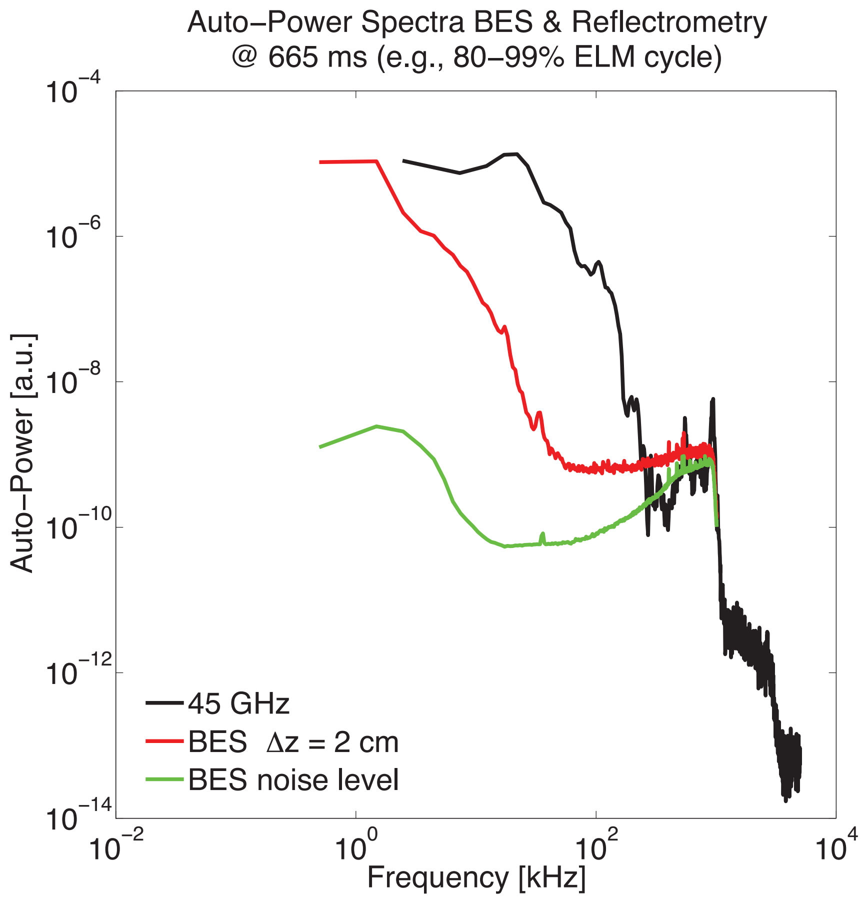




- Modest change in poloidal correlation length during the inter-ELM phase
  - Poloidal correlation length corresponds to toroidal mode number (rk_θ/q) n = 2 - 3
- Measurements show ion scale fluctuation in the pedestal top

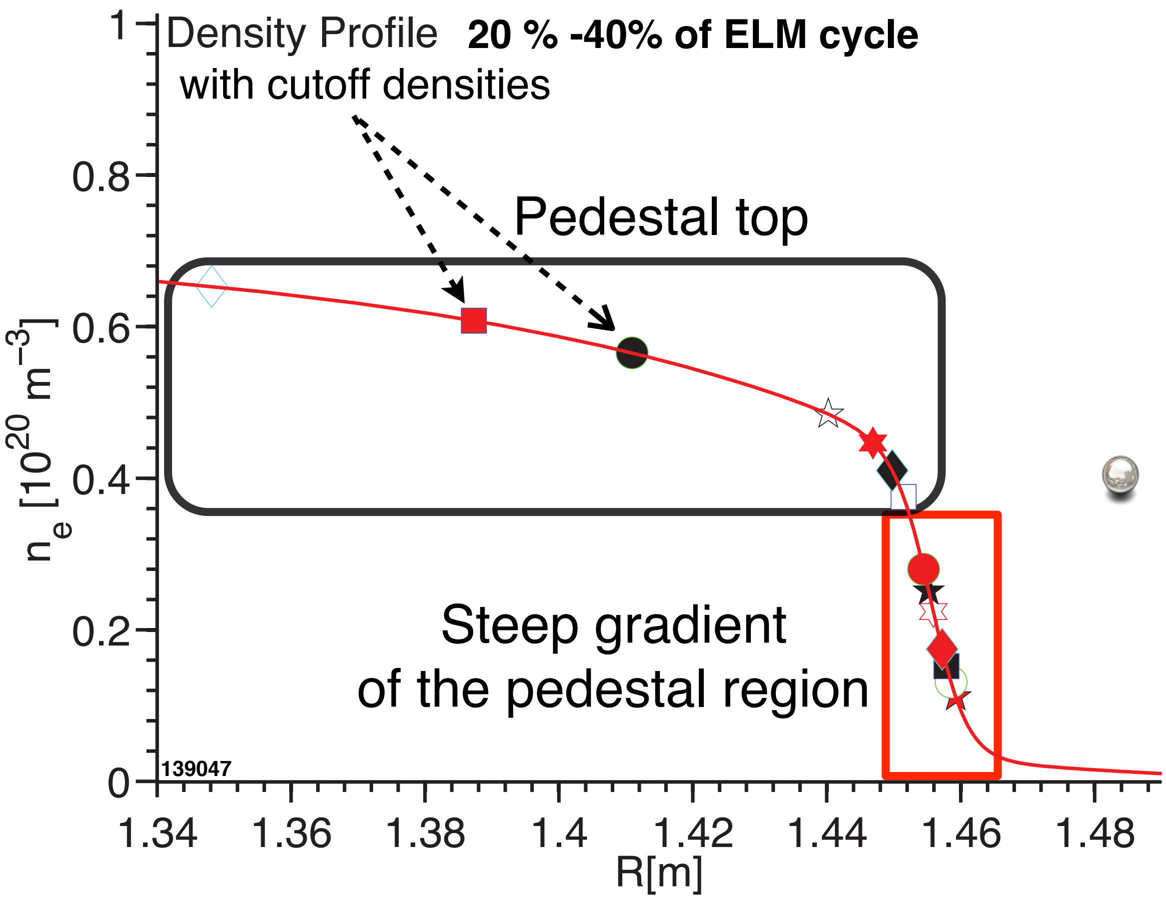
Both BES and reflectometry systems show similar broadband power spectra





- Fluctuations at the pedestal top during ELM cycle are broadband as indicated by both reflectometry and BES system

Radial density correlation lengths at the pedestal top and steep gradient region

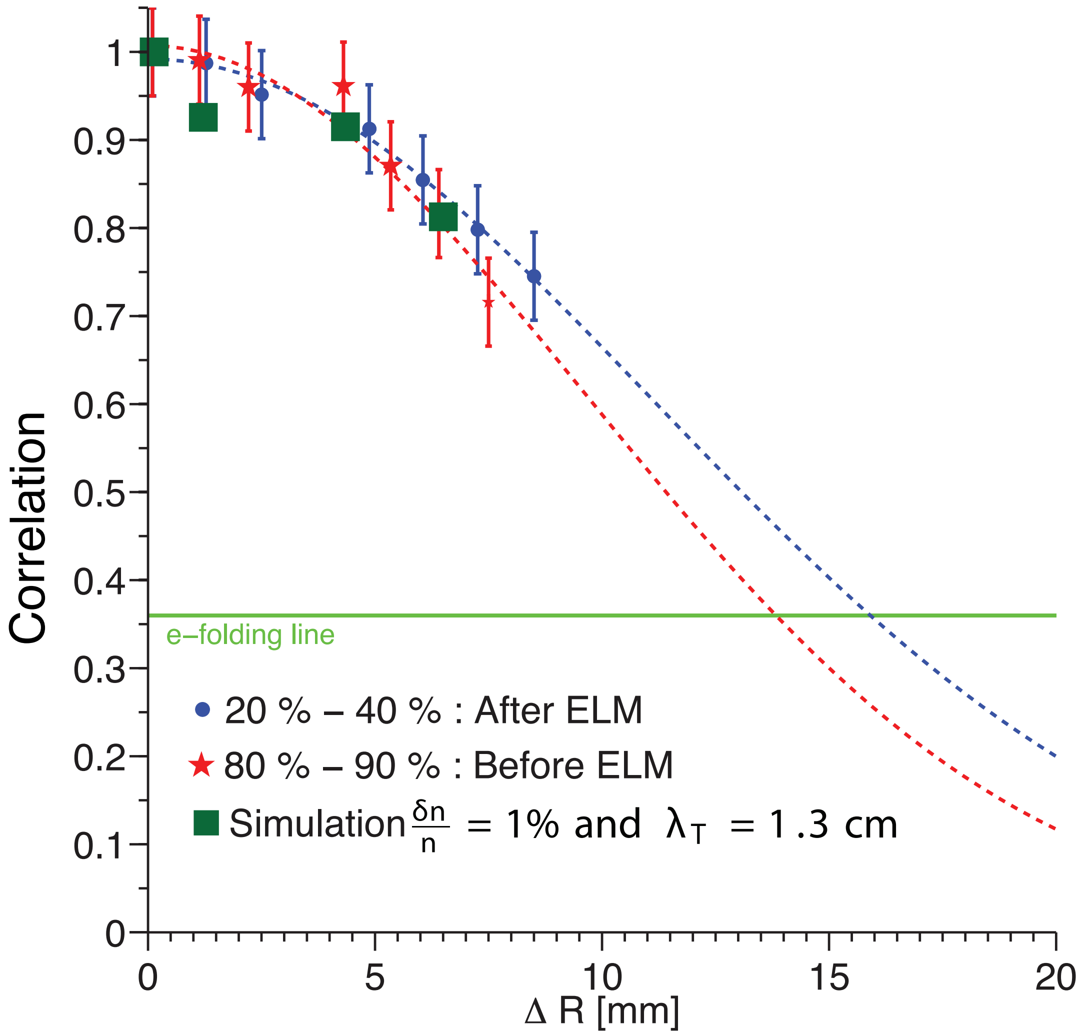


- The density fluctuations are measured using a 16-channel O-mode reflectometer

Crocker, PPCF (2011)

- Using two-point correlation the radial correlation function is determined.
  - tracks the equilibrium plasma motion

2D full wave simulation of correlation function inside pedestal region reproduces measurements

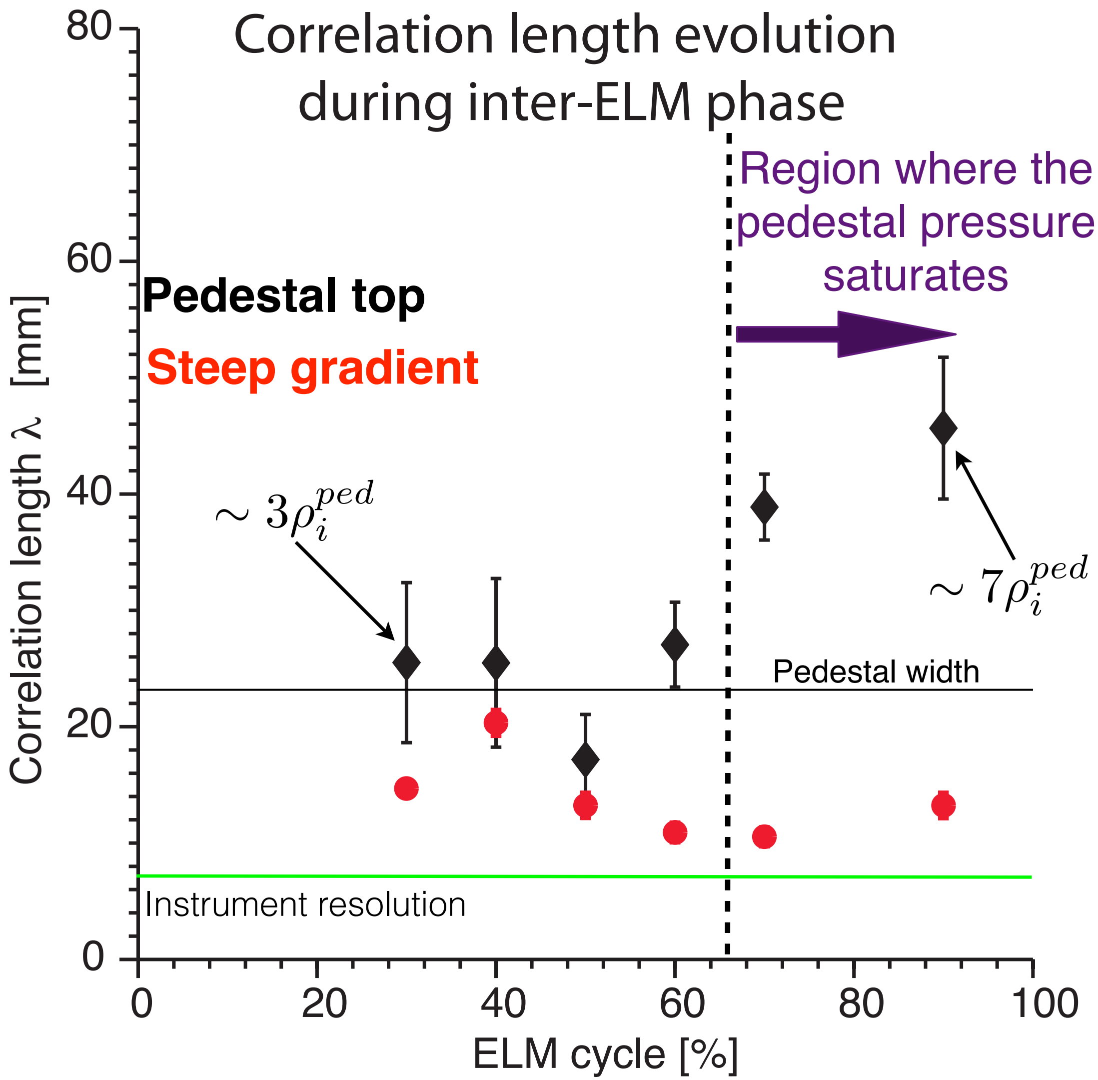


Observed correlation length corresponds to an average eddy size of ~ 1.3 cm with fluctuation level in the vicinity of 1% in the gradient region.

Reflectometry:Radial correlation length evolution depends on location inside pedestal region(steep gradient and pedestal top)

UCLA

- Radial correlation length increases at the pedestal top
  - A factor of 2 increase during the last 50% of ELM cycle
  - Increase size of eddies
    - ➡ suggesting enhanced radial transport during the ELM cycle
- Steep gradient correlation length is unchanged
- Caveat: quantify the geometric effects on the measured correlation.



Simulating the Edge Turbulence during ELM cycle using XGC1

- Comprehensive gyrokinetic code
- Diverted magnetic field geometry with material wall boundary condition
  - Includes magnetic axis: wall to wall simulation
- Wall recycling of neutral particle with atomic physics
- Particle-momentum-energy conserving collision operator
- Multiscale simulation of neoclassical, **turbulence**, neutral particle,and atomic physics
  - Present XGC1 capability:
    - ITG + neoclassical + neutral in diverted geometry
    - E&M turbulence in non-diverted geometry
    - Soon to come:ITG-TEM + neoclassical + neutrals in separatrix geometry

See C-S Chang & S-H Ku at this meeting

Role of the edge density fluctuations on setting the pedestal structure during the inter-ELM phase

- Pedestal gradient has been predicted to be constrained by the onset of kinetic ballooning mode (KBM)* — *Snyder PoP 9 (2002)
  - Recent DIIID work has shown observations of modes localized in the pedestal region with features similar to KBM — Yan PRL 107 (2011)
  - KBM characterized by:
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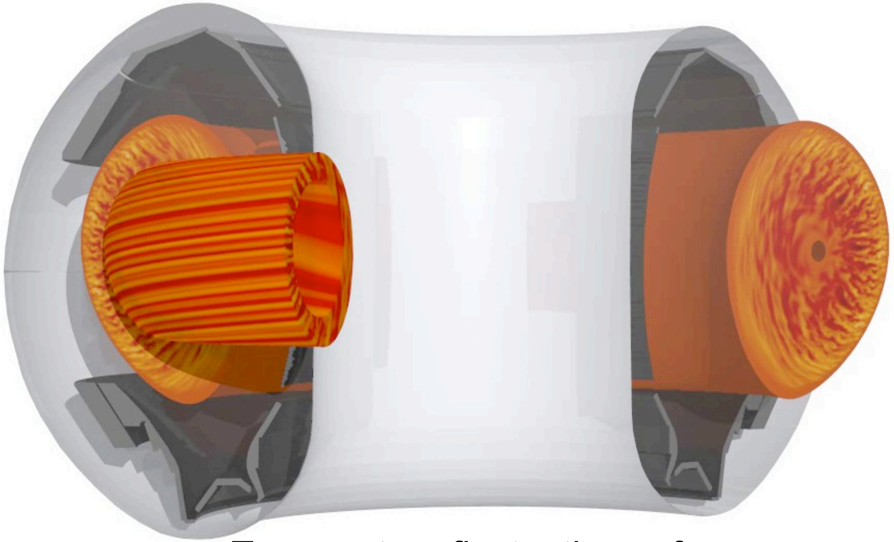
    - modes have radial scales of the order few cm in the pedestal region of NSTX
    - fast rising growth rate increasing with electron β
    - propagation in the ion diamagnetic direction.
- NSTX: We look for evidence of pedestal-localized microinstabilities, and their correlation with the ELM cycle

- Perform gyrokinetic simulations to identify the instabilities at play
  - Linear gyrokinetic simulation using GENE
  - Nonlinear XCG1 with adiabatic electrons for now.

The gyrokinetic code GENE

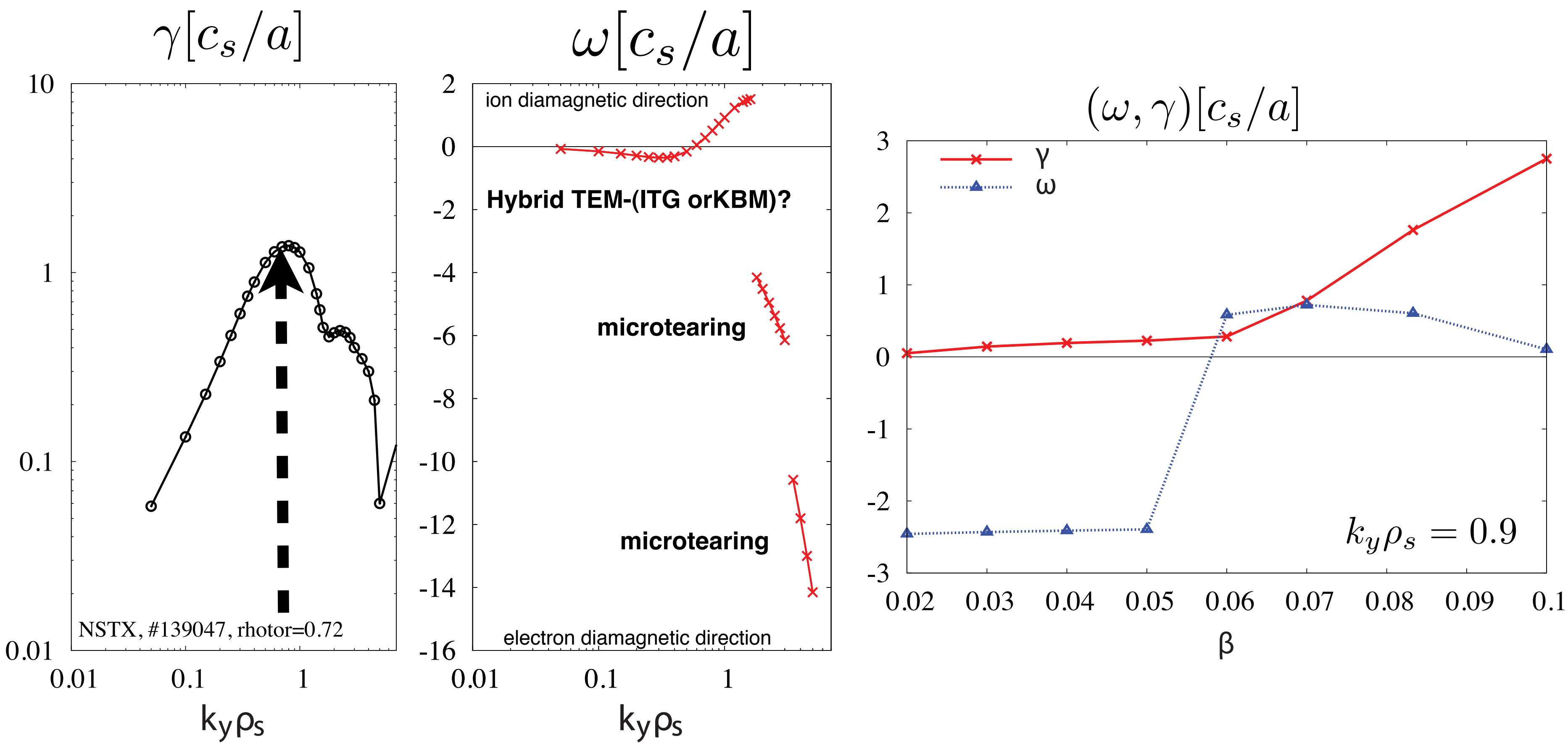
- GENE is a physically comprehensive Vlasov code which
  - allows for kinetic electrons electromagnetic fluctuations, collisions, and external ExB shear flows
  - is coupled to various MHD and transport codes
  - can be used as initial value or eigenvalue solver
  - supports local (flux-tube) and global (full-torus), gradient- and flux-driven simulations
  - well benchmarked and hyperscalable



Temperature fluctuations of a global GENE simulation for ASDEX-Upgrade

see: gene.rzg.mpg.de and F. Jenko's talk

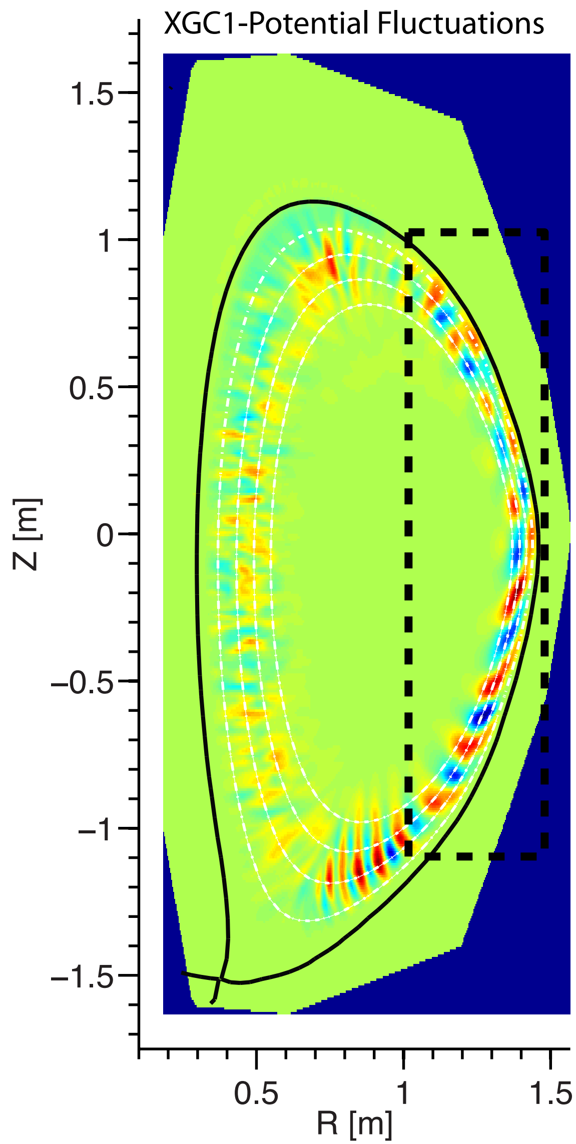
Linear gyrokinetic simulations using GENE (including full magnetic perturbation) at the pedestal top indicate presence of ITG/KBM-TEM hybrid modes along with microtearing modes



- The characteristic scales of these instabilities appear to be consistent with experimental scales determined with BES system
- TEM modes are "hybridized" with KBM as identified by the β scan

Nonlinear simulations using XGC1 are performed for cases during the last part of the ELM cycle

- δf mode in XGC1
  - 200 x 60 spatial grid
  - simulation box up to $\psi_n \sim 0.95$ to include the unstable region
  - Using experimental profiles
- Collisions and flows are not included in this simulation
  - Adiabatic electrons
- Probing the fully nonlinear phase of the simulations
- Characteristic poloidal structures propagating in the ion diamagnetic direction.
  - ITG resides at the pedestal top, but nonlinearly and nonlocally penetrated into the pedestal region.
  - Sampling a region encompassing both BES and the reflectometer measurements



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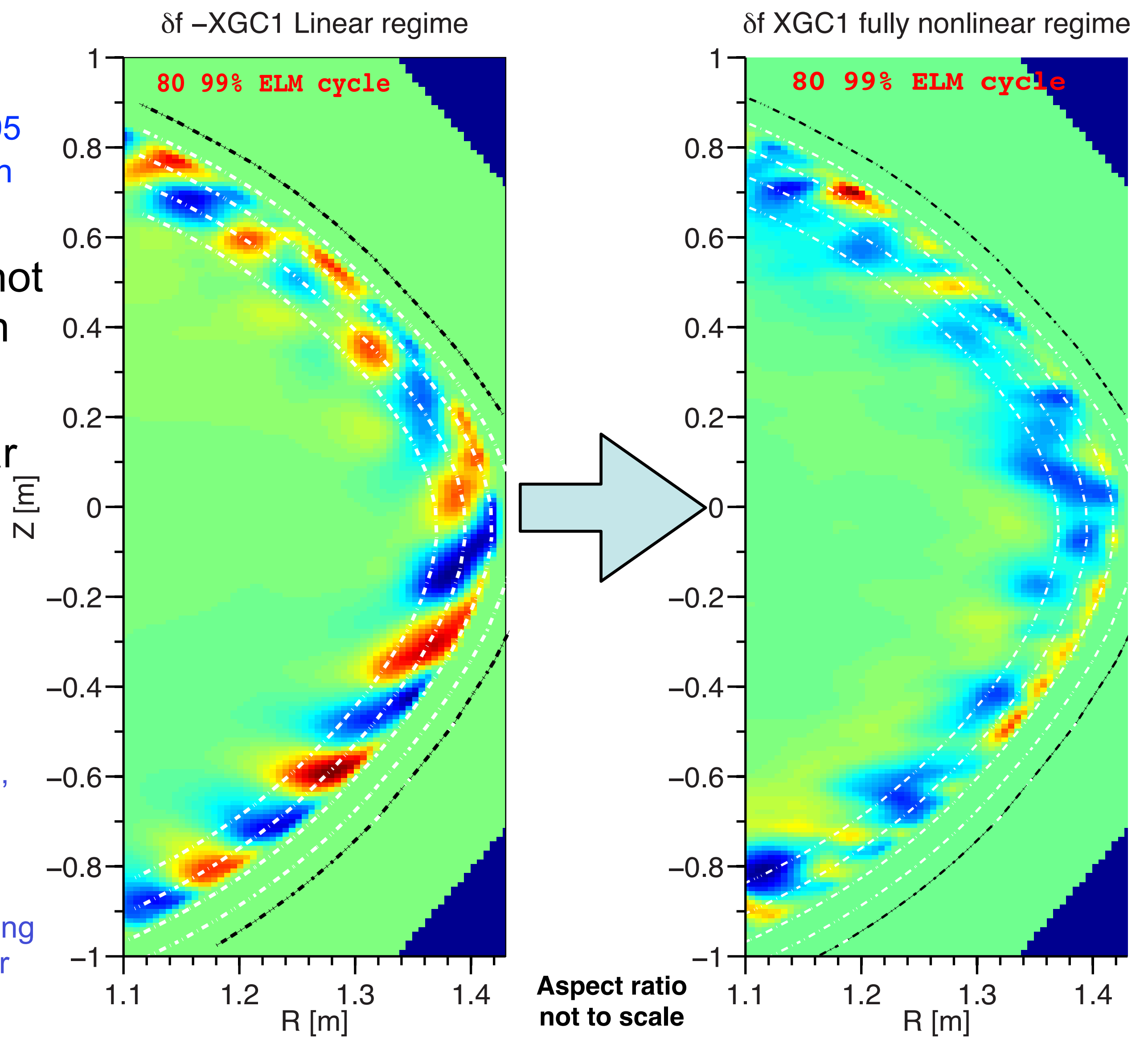
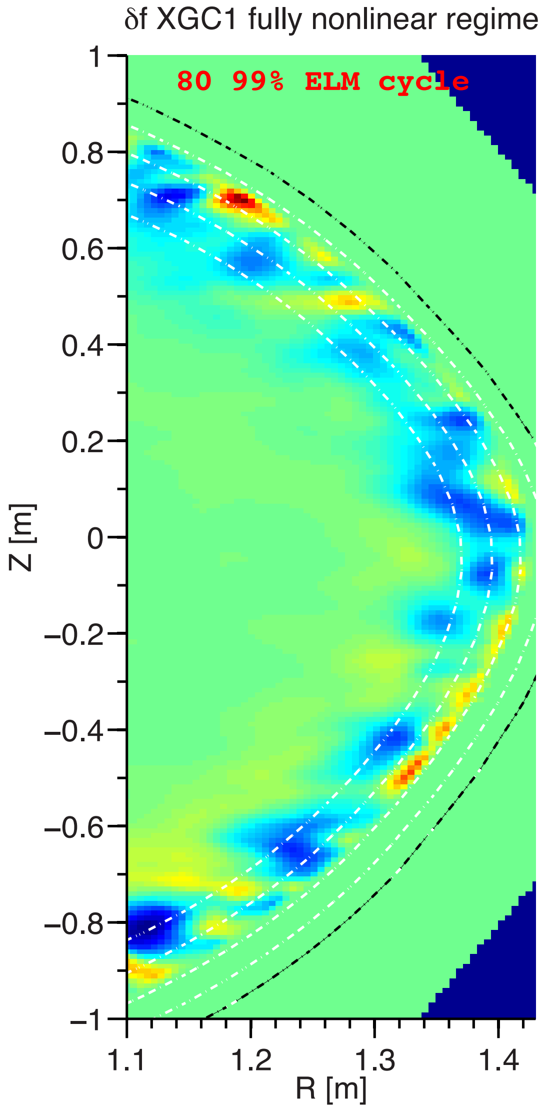
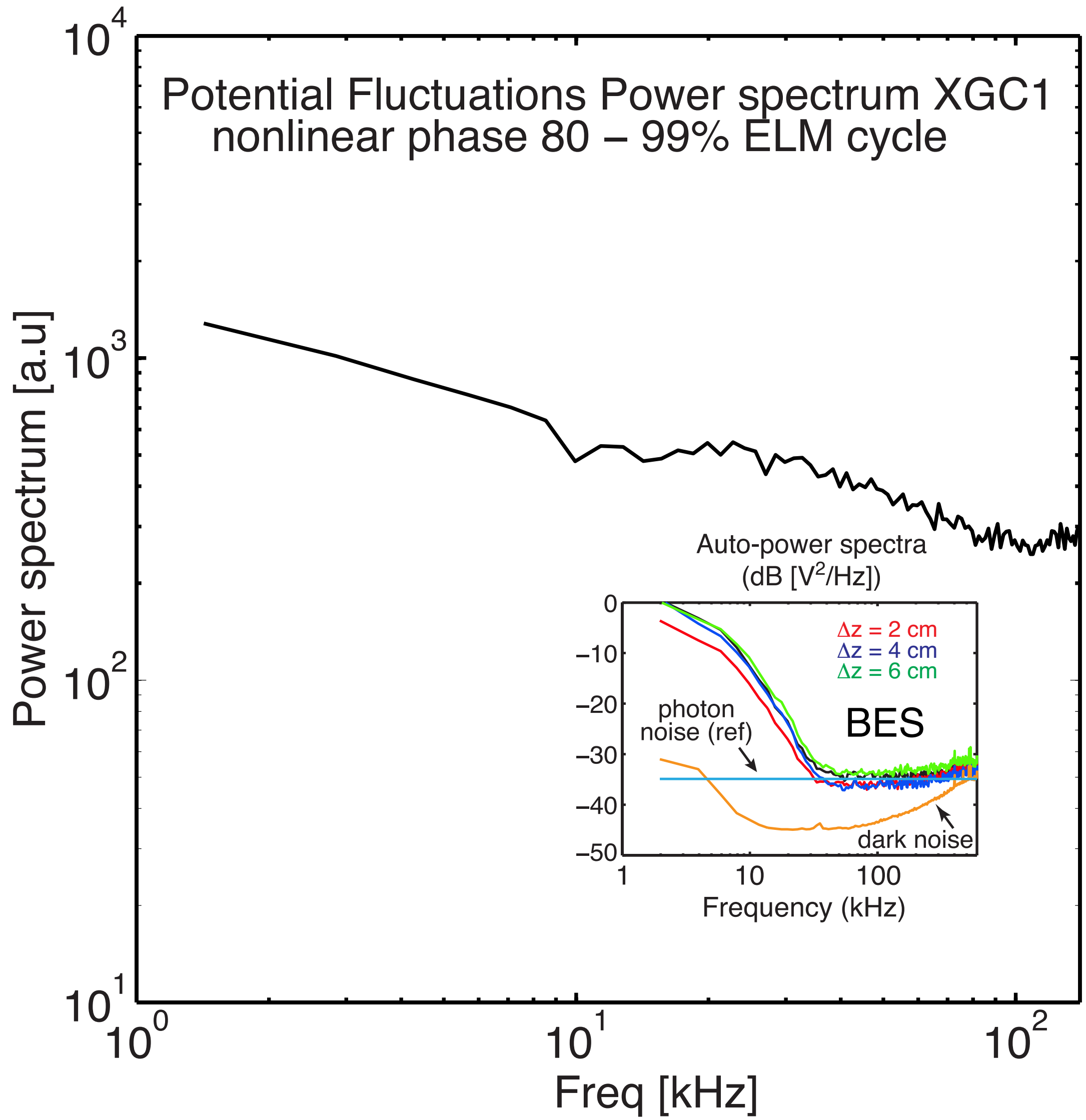


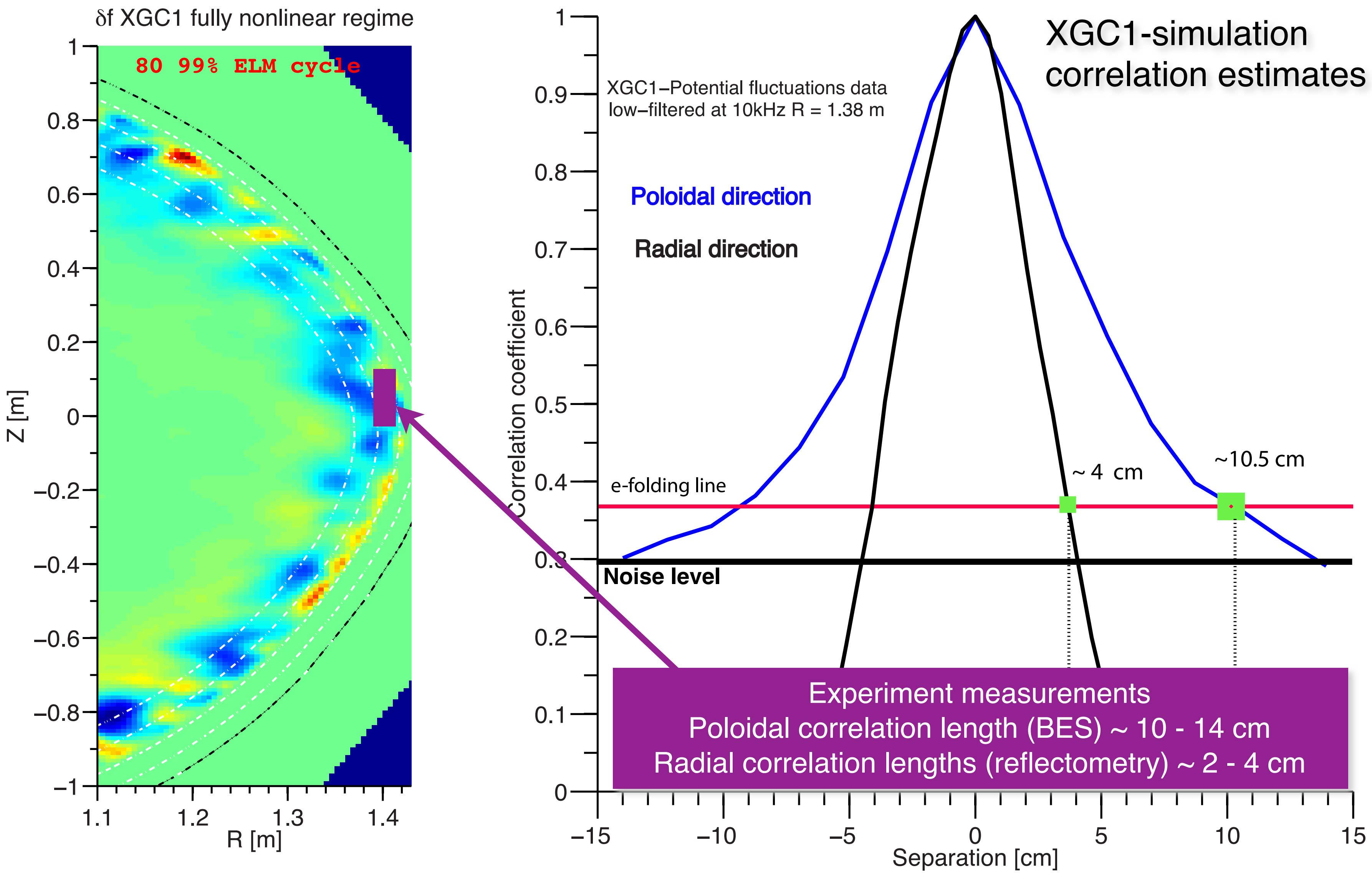
Aspect ratio not to scale

Simulations from XGC1 indicate localized fluctuations with broadband power spectra





Nonlinear simulations from XGC1 show localized fluctuations with experimental level radial and poloidal correlation lengths



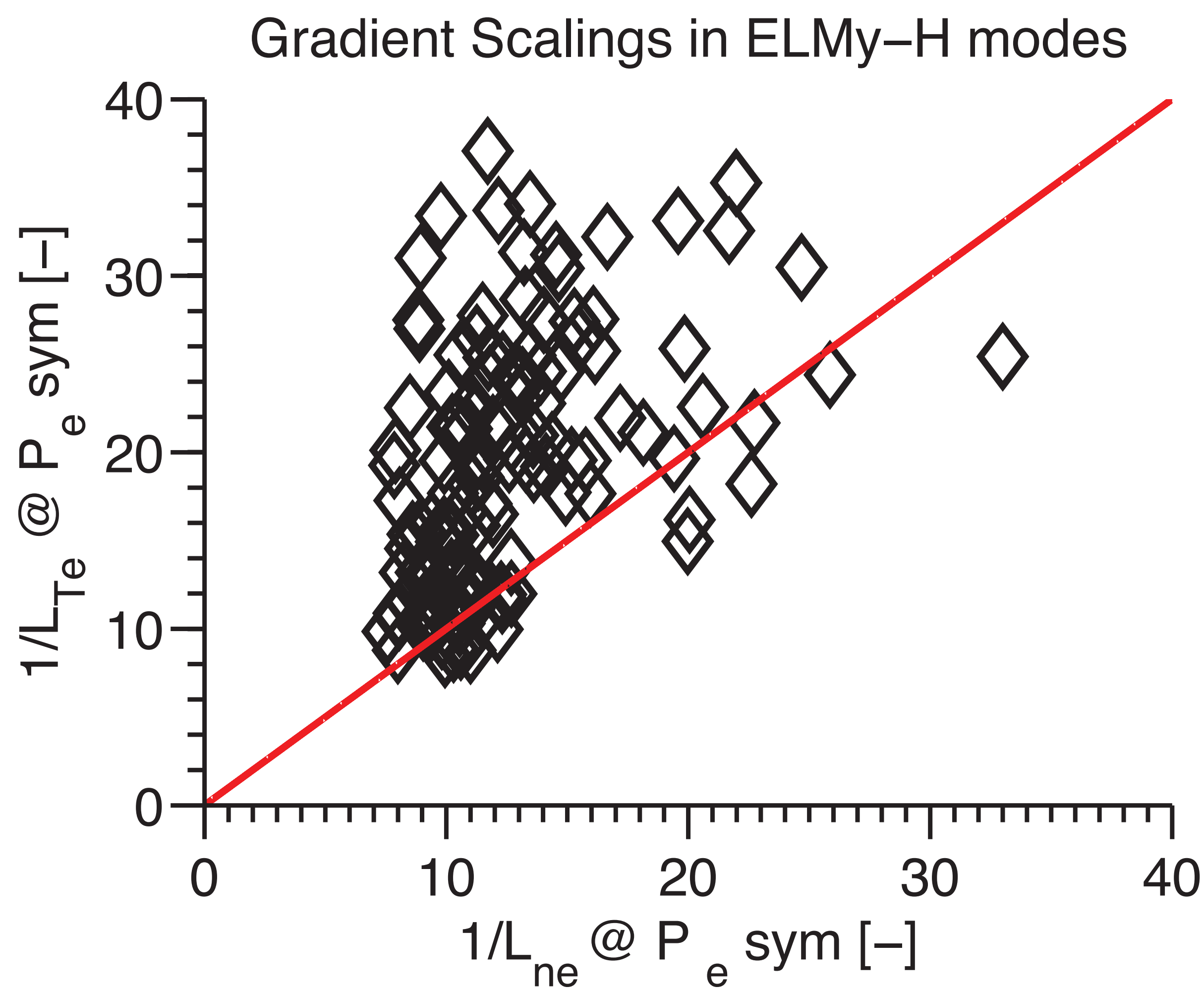
Summary/Future work

- Continuous increase of the electron temperature and much less variation in electron density and pressure build up and at time saturation prior to the ELM onset
  - Pressure gradient, however, is clamped during most of the ELM cycle
  - NSTX exhibits wider pedestal widths than conventional tokamaks
  - Pedestal width scaling like $(\beta_\theta)^{0.8}$ in agreement with predicted KBM-constrained pedestal
- Pedestal stability are performed using MHD codes
  - NSTX pedestal during the last 50% of the ELM cycle is found to be kink-peeling unstable
    - Calculations were performed using ELITE code
  - Using “ball” a module of GS2, pedestal top is found to be unstable to ideal high-n-ballooning modes
- Characterization of the fluctuations during the inter-ELM phase
  - BES and reflectometry confirm ion scale turbulence $0.2 \leq k_\perp \rho_i \leq 0.7$
  - Poloidal correlation is larger than radial correlation length
- XGC1 preliminary simulation results: correlation lengths agree with experimental observations
    - Most unstable mode is ITG in simulation: study will be extended to full-f nonlinear XGC1 simulation
- Linear GENE simulation also show the presence dominant hybrid ITG/KBM-TEM modes at the pedestal top with subdominant microtearing.

- Extend the simulation to full-f mode using XGC1 and account for measured flows and add collisions.

Sign-up sheet

Most of the drive appears to be provided by the electron temperature gradient



- ETG/TEM could be playing a role in the pedestal scaling