Edge Turbulence Imaging in Alcator C-Mod and NSTX

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Outline

- Motivations and goal
- Gas Puff Imaging (GPI) diagnostic
- C-Mod imaging results

    Comparison of k-spectrum with simulations
- NSTX imaging results

    Transition from L-H mode and density limit
- Tentative Conclusions
- Plans

Motivations

- Edge plasma conditions will be important for any magnetic fusion reactor
  - boundary condition for core stability (e.g. in H-mode)
  - flow through edge determines plasma-wall interaction

- Edge turbulence seems to be a dominant mechanism which determines edge plasma conditions
  - edge radial transport is normally >> neoclassical
  - edge turbulence is normally very large ($\tilde{n}/n \geq 10\%$)

Goal

- Understand edge turbulence in present devices by measuring its 2-D space vs. time structure and comparing the results with non-linear edge turbulence simulations

- By *"understand"* we mean ideally:
  - measurements verified with different diagnostics
  - simulations checked by using different codes
  - experiments done on several different machines
  - experiments and simulation agree within ≈ 20%
  - simulation successfully predicts results in new regimes
  - results can be understood by simple theoretical models

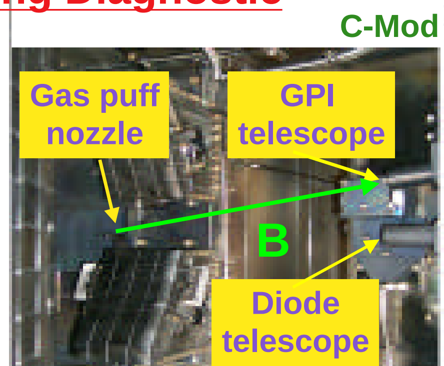
- This is a challenging scientific goal and will also help to design and/or operate a "next-step" burning plasma experiment

Gas Puff Imaging Diagnostic

- Gas puff imaging (GPI) telescope views neutral line emission from He or D_2 gas puff ≈ along B field at the plasma edge (like BES but uses neutral gas instead of NBI)

  $S(\text{photons/cm}^3) = n_o f(n_e,T_e) A$

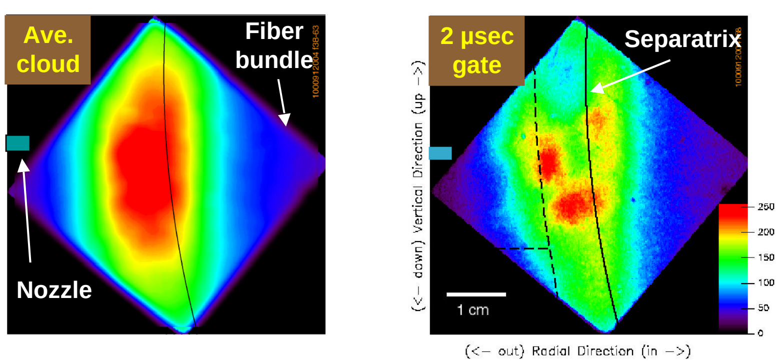
  where the radiative decay rate is $A >> 10^7\ \text{sec}^{-1}$ for these lines.



- Space and time variation of neutral light emission is measured with fast-fast gated cameras and PMs or PDs on discrete chords to determine edge turbulence structure (assumes $k_{||} << k$)
- Gas puff changes plasma density by ≈ 1% in C-Mod and ≤10% in NSTX, but this probably does not to perturb the edge turbulence significantly

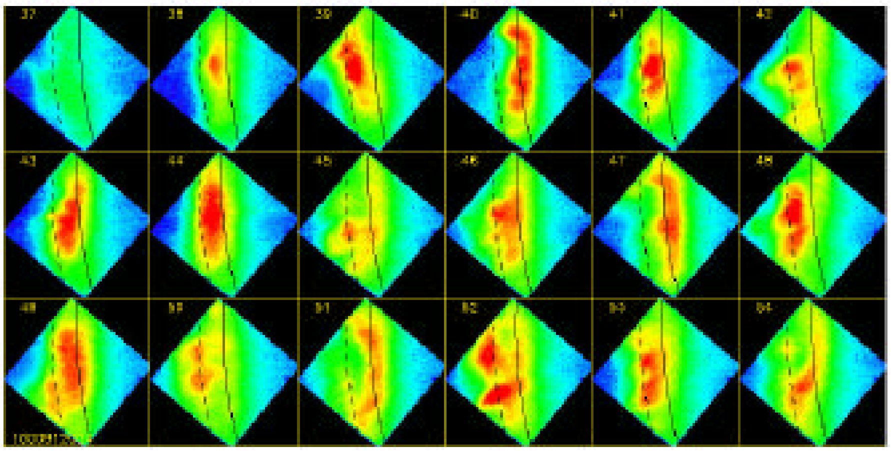
Example of 2-D GPI Image in C-Mod

- Camera images D_α (656 nm) light using optical system with ≈ 2-3 mm spatial resolution over ≈ 6 cm x 6 cm field
- Turbulence can be seen with camera gating of ≈ 2 µsec/frame as structure within time-averaged envelope of D_α cloud



Typical Images During a Discharge

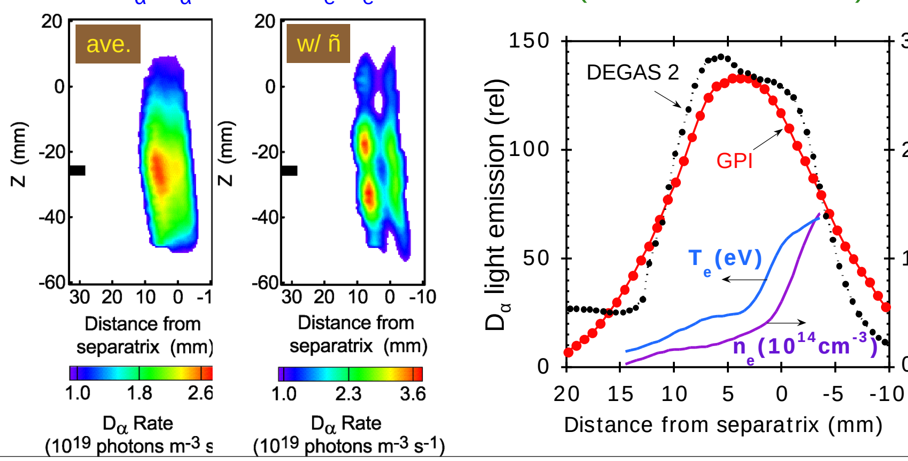
- Camera takes images with 2 μsec gating @ 60 frames/sec
- Time between frames >> turbulence autocorrelation time



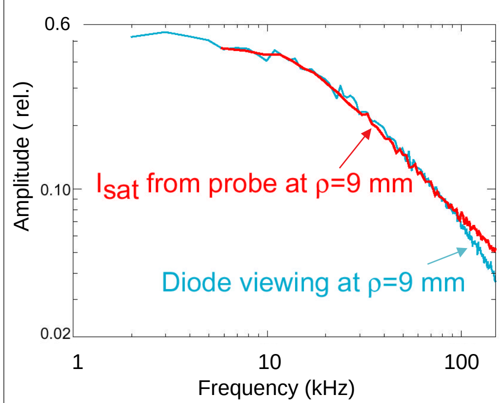
Interpretation of GPI Using DEGAS 2

- 2-D neutral/atomic physics model of D_2 gas puff (Stotler)
- D_α $n_o\, f(n_e,T_e)$ $n_e^{0.5}\, T_e^{0.5}$ just outside separatrix

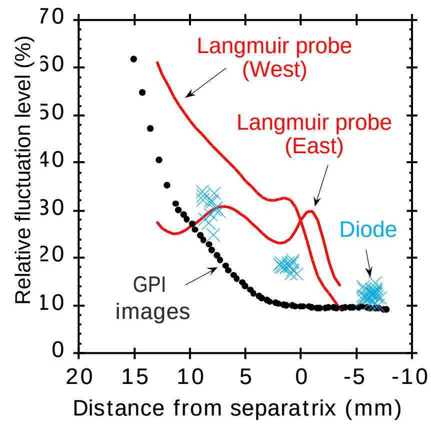
=> $\delta D_\alpha / D_\alpha$ $0.5\ \delta n_e/n_e$ at this radius (0.46 -> 0.83 vs. r/a)



Comparison with Langmuir Probe



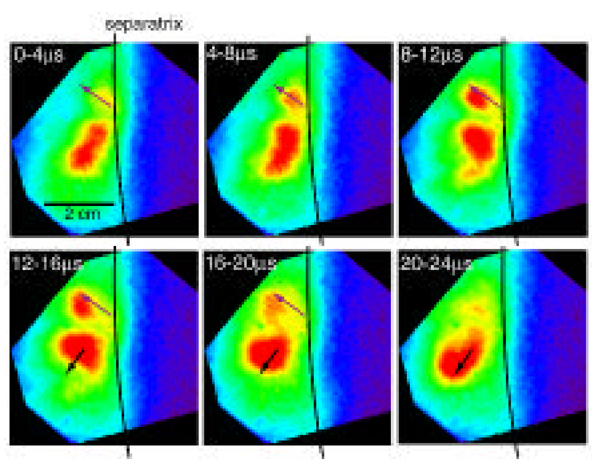
Frequency spectra of GPI and Langmuir probe similar (as at ASDEX and Caltech)



Relative fluctuation level of GPI and Langmuir probe are similar (contains both $\delta n_e/n_e$ and $\delta T_e/T_e$)

Motion of Edge Turbulence

- Made with Princeton Scientific Instruments PSI-3 camera, with 12 frames of 64 x 64 pixels at 4 µsec/frame



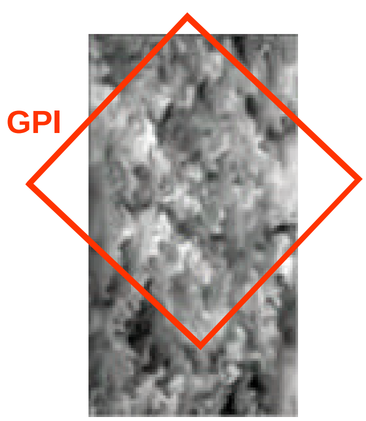
Simulations of Edge Turbulence

- Use 3-D EM fluid (Braginskii) codes for edge simulation, which are good approximations when:
  - gyroradius small: $k \ \rho_s \approx 0.026$
  - collisionality large: $\alpha_d \approx 0.35$ ($\lambda_{ie}/L_{||} \approx 0.1$)
  - beta small: $\alpha_{mhd} \approx 0.03$ ($\beta \approx 3\text{x}10^{-5}$)
- Dominant linear instability is ES resistive ballooning mode
  - typical RBM length scale: $\lambda_o \approx 2.2$ mm
  - typical RBM time scale: $t_o \approx 1.2$ μsec
- Local DBM-type code has circular closed field line geometry but may be OK at high collisionality outside separatrix
- BOUT code uses profiles and realistic magnetic geometry

Simulation Results - the videos

Local "DBM"

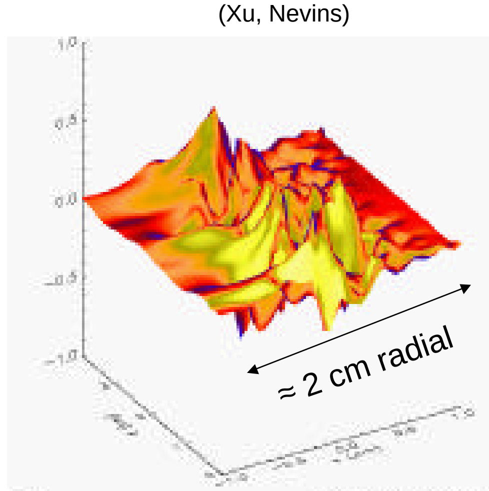
(Hallatschek, Rogers)



≈ 5 cm radial

BOUT

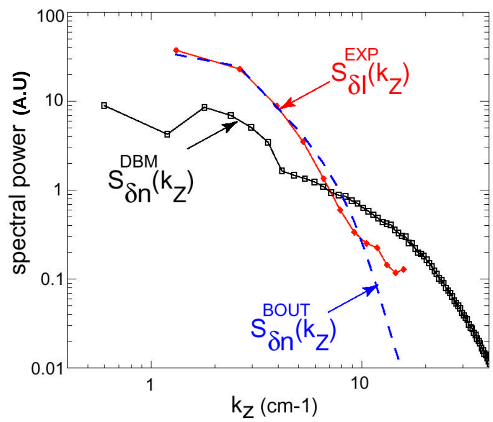
(Xu, Nevins)



Comparison of Experiment and Simulations

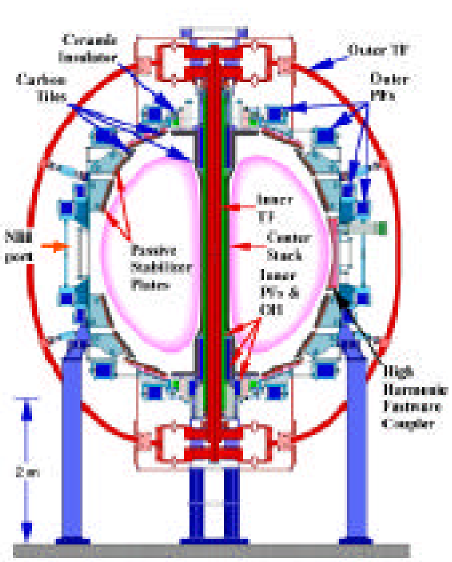
Comparison with Local Simulation:

- $L_{pol} \approx 0.6$ cm in simulation
  $L_{pol} \approx 0.8 \pm 0.2$ cm in GPI
- $\tilde{n}/n \approx 18\%$ in simulation
  $\delta T_e/T_e \approx 13\%$ in simulation
  $\delta I/I \approx 25\text{-}35\%$ in LP/Diode
- $\tau_{auto} \approx 5\text{-}6$ μsec in simulation
  $\tau_{auto} \approx 10\text{-}20$ μsec in LP/Diode
- D ~ 0.2 m^2/sec in simulation
  D ~ 0.2 m^2/sec in experiment
  (LaBombard - KP1.023)



=> Initial comparisons are encouraging

NSTX - National Spherical Torus Exp't



R = 85 cm

a = 68 cm

A = 1.25

I ≤ 1.5 MA

B ≤ 5 T

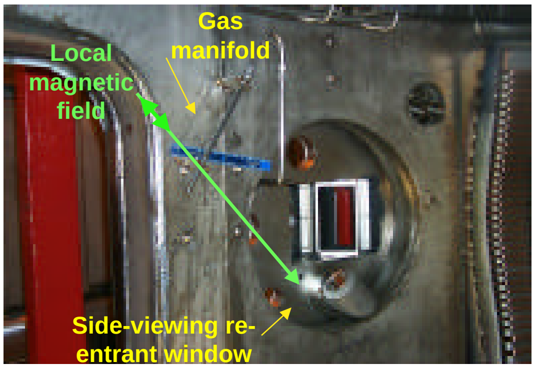
5 MW NBI

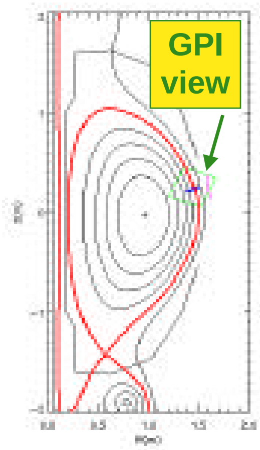
6 MW ICRH

$\beta_T \leq 32\%$

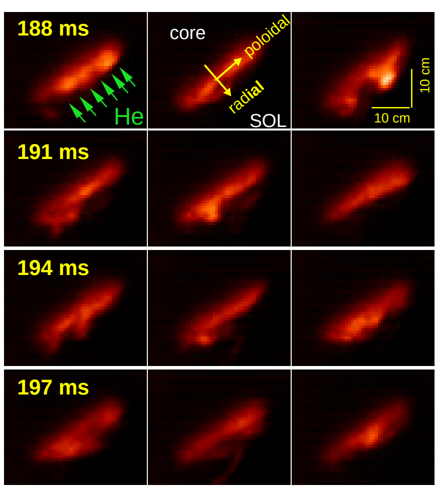
GPI Diagnostic Set-up in NSTX

- Similar to C-Mod system but using re-entrant port and linear gas manifold instead of single-point gas nozzle
- Use He puffs into D plasmas or D puffs into He plasmas (with similar results)





Typical Edge Turbulence Images in NSTX



Shot 105711

- B=4.5 kG, I=1.0 MA Ohmic
- He puff into D_2 discharge
- GPI with HeI filter (587.6 nm)
- 10 μs exposure each frame

GPI Videos for NSTX

- For LANL camera at 1000 frames/sec, images are uncorrelated from frame-to-frame

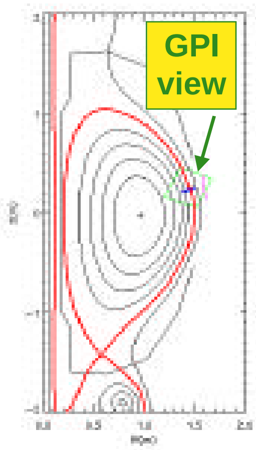
#105711	#105710	#105627
(1.0 MA, 4.5 kG)	(1.0 MA, 4.5 kG)	(0.7 MA, 3 kG)
no-H mode	H-L transition	Ohmic

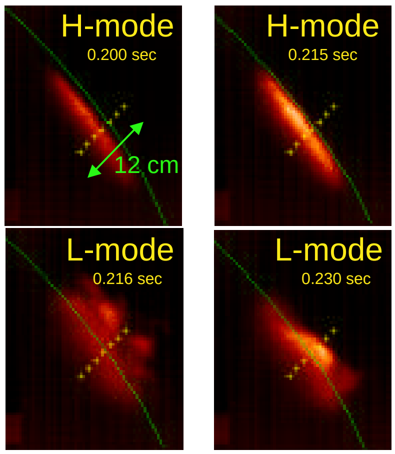
- For PSI-4 camera, captures motion at 100,000 frames/sec

108164
(0.8 MA, 3.0 T)
Ohmic

Radial Array of Fast GPI Chords

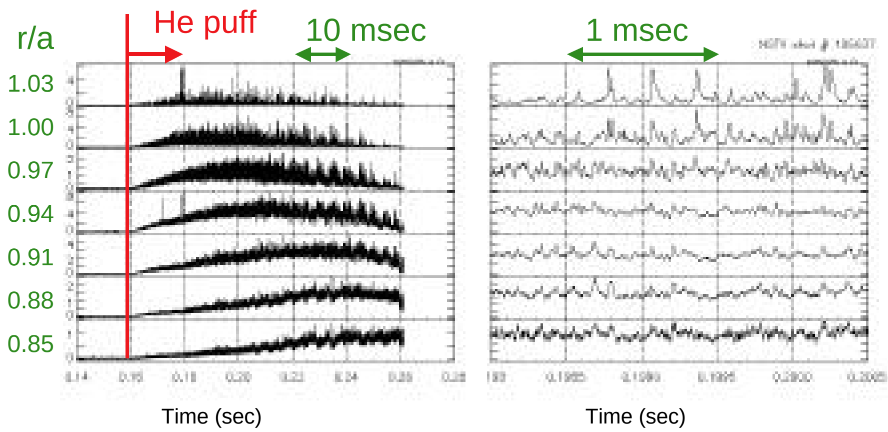
- Fast chords view 2 cm diameter “spots” in 7 channel radial array with PM tube (bandwidth ≈ 100 kHz)



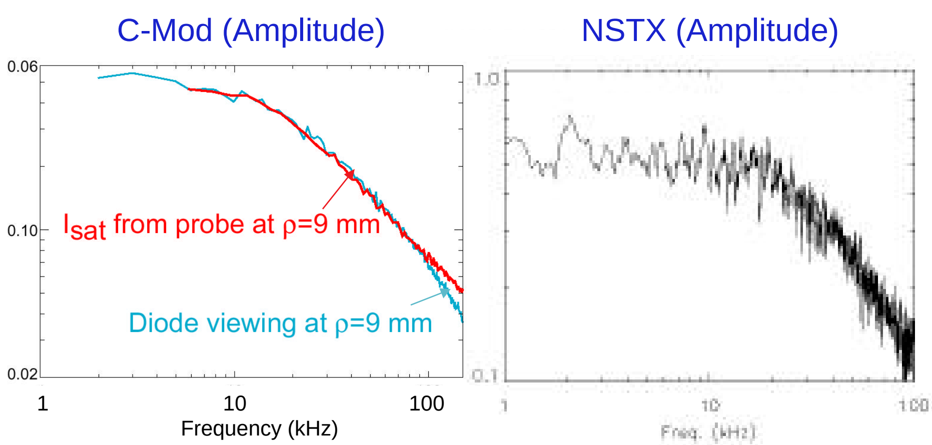


Typical Signals from Fast GPI Chords

- Signals from 7 chords digitized for 0.128 msec @ 500 kHz
- Near outer wall see "intermittant" ≈ 100% fluctuations
- Nearer center, see "Gaussian" ≈ 20% fluctuations



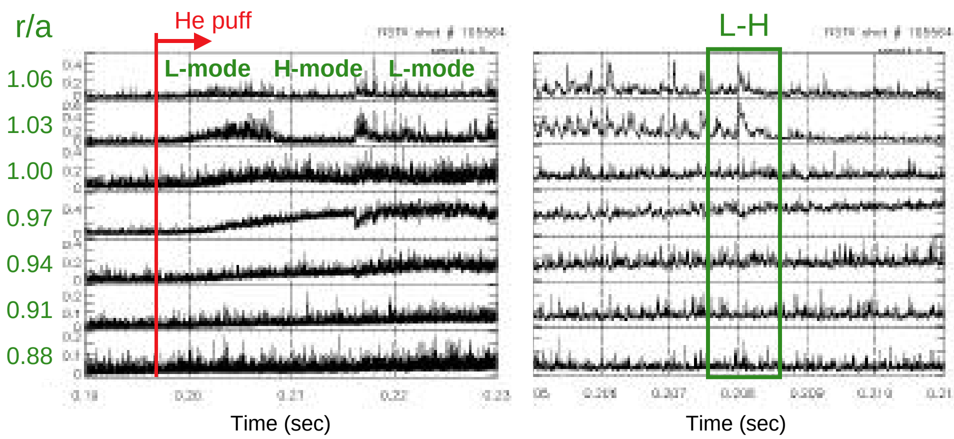
Comparison of Frequency Spectra



- Frequency spectra are similar, as seen previously for other tokamaks and stellarators (e.g. Pedrosa et al PRL '99)

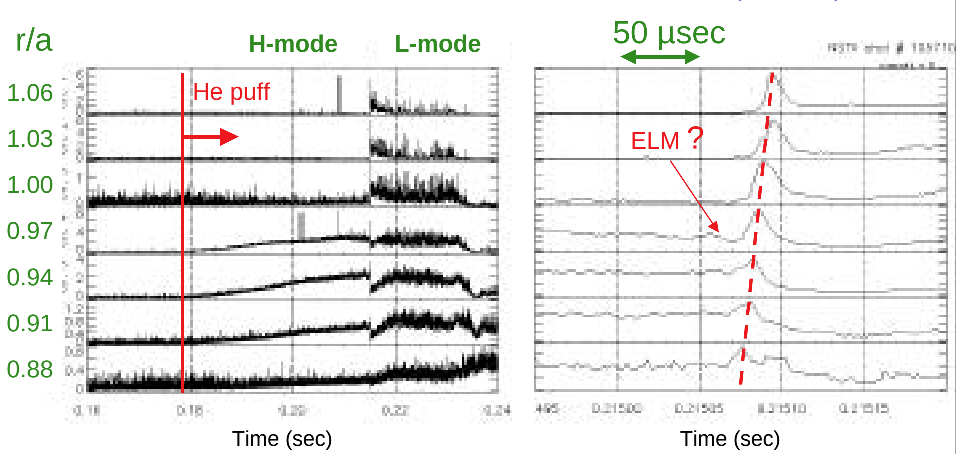
Edge Turbulence Signals at L-H Transition

- L-H transition occurs within ≈ 1 msec on most channels
- Perhaps preceeded by large “bursts” in outermost channels



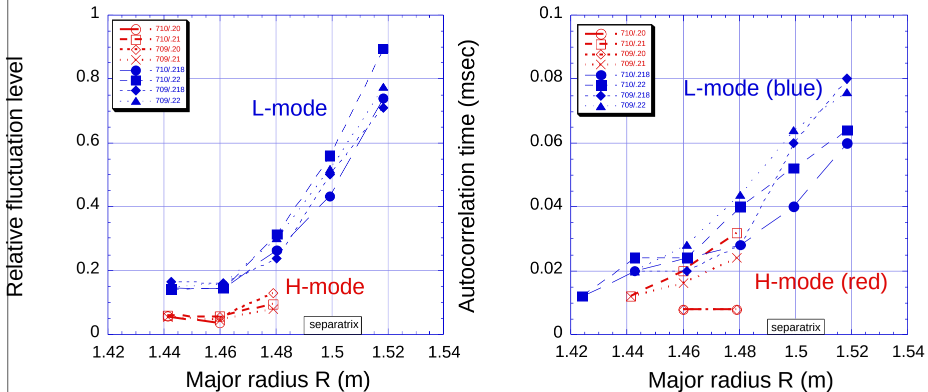
Edge Turbulence Signals at H-L Transition

- H-L transitions occurs within ≈20 μsec in most channels
- Transition seems to propagate outward at ≈ 10 cm / 20 μsec
- Transition seems to start with coherent mode (ELM ?)

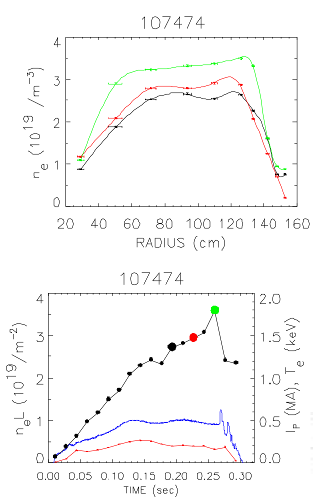


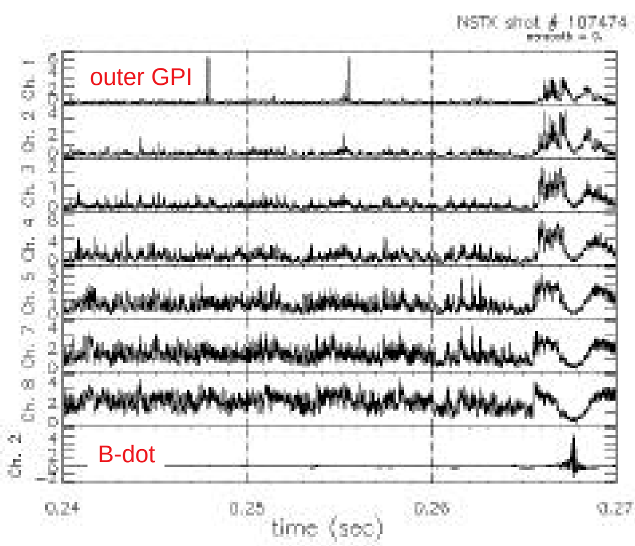
Fluctuation Profiles in H-mode vs. L-mode

- GPI fluctuation level lower in H-mode (but not-zero)
- BUT Need to consider profile changes and HeI $f(n_e, T_e)$



GPI Signals Near Density Limit





$n/n_G \approx 1.06$ @ .26 sec

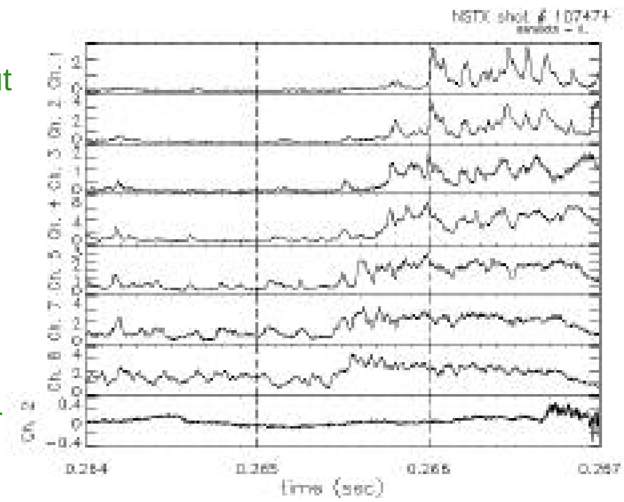
Outward Propagation Near Density Limit

- Increase in GPI signal seems to propagate from inside to outside at a speed ≈ 10 cm / 0.5 msec ≈ 200 m/sec

GPI out

GPI in

B-DOT



Initial Comparison with Theory

- BOUT simulations have been run, but only for estimated edge profiles in NSTX (not yet measured well)

- Results from BOUT are qualitatively similar to GPI results
  - autocorrelation time ≈ 15-30 μsec
  - fluctuation level δn/n ≈ 10-20% near separatrix
  - $\delta T_e/T_e$ ≈ (0.2-0.5) δn/n due to low collisionality
  - λ ≈ 5 cm, $\lambda_{||}$ ≈ 10 m near outer midplane

- Degas-2 modeling of HeI (587.6) has been started
  - S $n_e^{0.7} T_e^{0.5}$ near center of GPI cloud for NSTX
  - H-mode emission profile is narrower mainly due to the narrower time-averaged edge profiles

Tentative Conclusions

- Edge turbulence structure looks like a combination of “blobs” and “waves”, similar to that seen with other diagnostics
- Initial comparisons with simulation / theory are encouraging
- Definitive comparisons with theory will have to address what are the appropriate “inputs” needed for the simulations:
  - use time averaged profiles or fluxes through edge ?
  - need limiter configuration and/or divertor geometry ?
  - are atomic physics and neutral effects significant ?
  - can the edge really be decoupled from the core ?

Plans

- 2-color and 2-time GPI imaging in Alcator C-Mod using two Xybion intensified gated cameras (60 Hz each)
- Make more ultra-fast videos using 28 frame PSI-4 camera, and later the new 312 frame PSI-5 camera
- Ask theorists to run simulations for more cases and to “benchmark” their codes against each other
- Feed 2-D patterns of density and temperature fluctuations into DEGAS 2 model and compare with GPI data