Edge Turbulence Imaging in NSTX and Alcator C-Mod

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NSTX

UCLA
9/18/02

Alcator C-Mod

Outline

- Motivations and Goals
- Gas Puff Imaging (GPI) diagnostic
- C-Mod results (B=5 T, I= MA, R/a=0.67 m / 0.23 m)
    - Videos from PSI-3 ultrafast camera*
- NSTX results (B=0.5 T I=1 MA, R/a=0.85 m / 0.68 m)
    - Videos from PSI-4 ultrafast camera*
- Tentative Conclusions
- Plans

* obtained from Princeton Scientific Instruments, Inc., USA

Motivations

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

- Edge turbulence is relatively easy to study compared with core turbulence
  - edge turbulence is normally very large ($\tilde{n}/n \geq 10\%$)
  - theory is relatively simple (collisional fluid model)

Goals

- 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

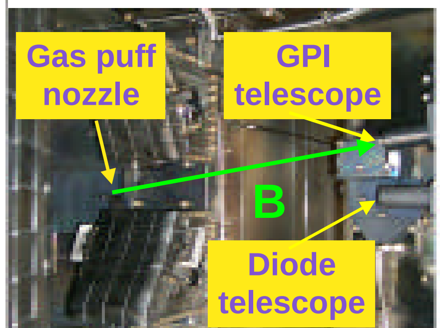
- Learn how to control edge turbulence and transport to test our understanding and to help control a "burning plasma"

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.



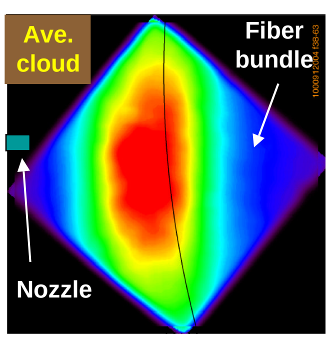
- Space and time variation of neutral light emission is measured with fast-fast gated cameras and photodetectors on discrete chords to determine edge turbulence structure (assumes $k_{||} << k$)

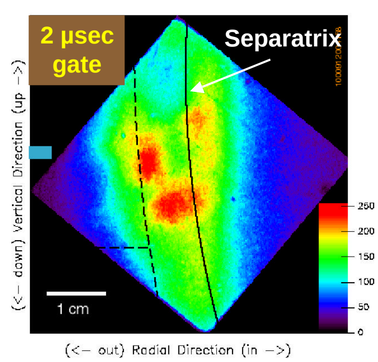
- Gas puff changes plasma density by ≈ 1-10% in C-Mod and NSTX, but this does not change the edge plasma or edge turbulence significantly

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

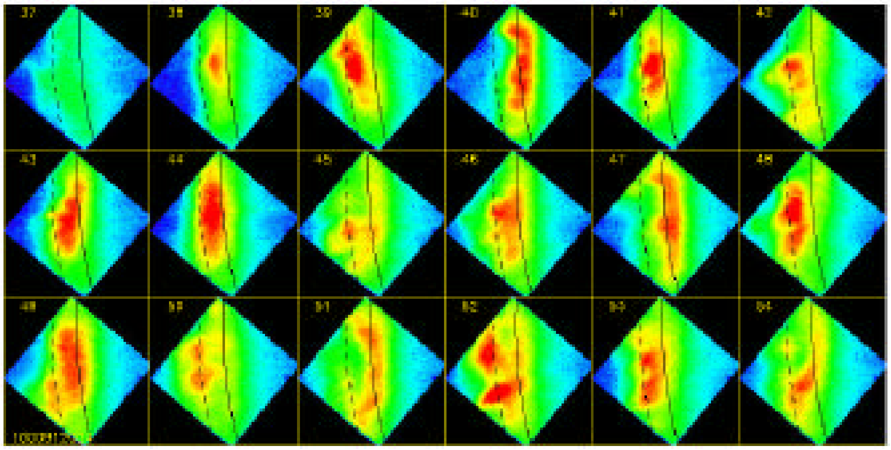
- Turbulence can be seen with camera gating of ≈ 2 μsec/frame as structure within time-averaged envelope of D_α cloud





Typical Images During a Discharge

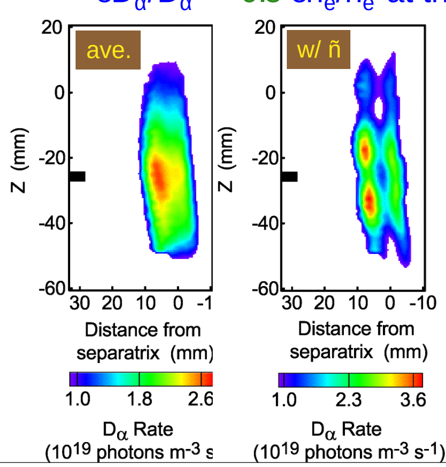
- Camera takes images with 2 µsec gating @ 60 frames/sec
- Time between frames >> turbulence autocorrelation time

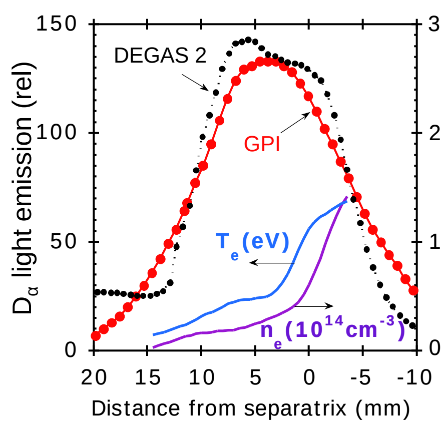


Interpretation of GPI Using DEGAS 2

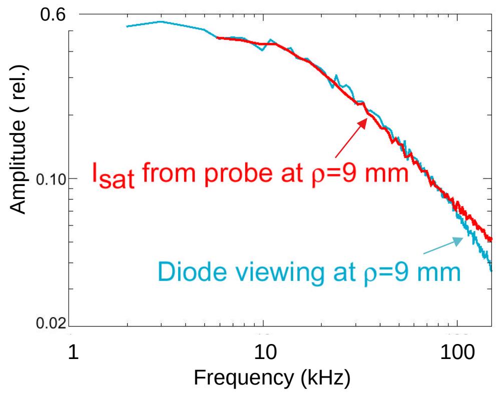
- 2-D neutral/atomic physics model of D_2 gas puff (Stotler)
- D_α $n_o f(n_e,T_e)$ $n_e^{0.5}$ $T_e^{0.5}$ just outside separatrix

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

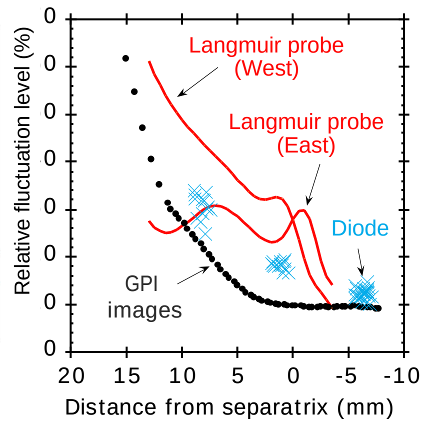




Comparison of GPI and Langmuir Probe



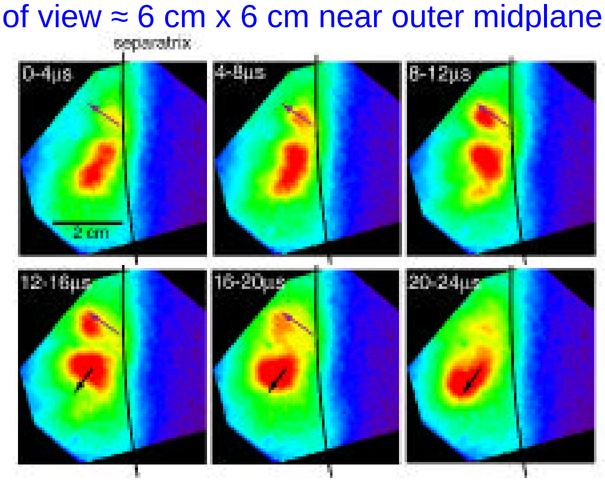
Frequency spectra of GPI and Langmuir probe similar (as at ASDEX and Caltech)



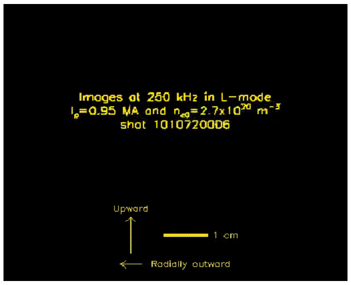
Relative fluctuation level of GPI and Langmuir probe are similar (contains both $\delta n_e/n_e$ and $\delta T_e/T_e$)

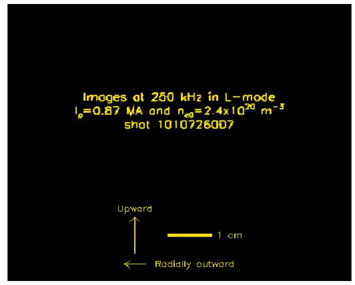
Motion of Edge Turbulence

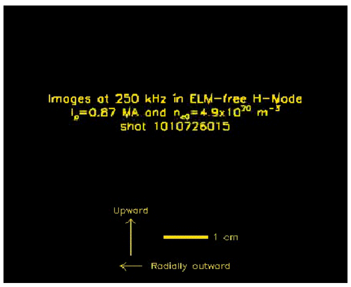
- Made with Princeton Scientific Instruments PSI-3 camera, with 12 frames of 64 x 64 pixels at 4 µsec/frame
- Field of view ≈ 6 cm x 6 cm near outer midplane

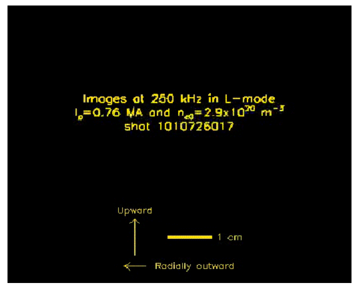


GPI Video at 250,000 frames/sec









Simulations of C-Mod Edge Turbulence

- Both BOUT and DBM codes use 3-D EM fluid (Braginskii) eq's for edge simulation, which are good when:
  - gyroradius small: k $\rho_s \approx 0.026$
  - collisionality large: $\alpha_d \approx 0.35$ ($\lambda_{ie}/L_{||} \approx 0.1$)
  - beta small: $\alpha_{mhd} \approx 0.03$ ($\beta \approx 3 \times 10^{-5}$)

- 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

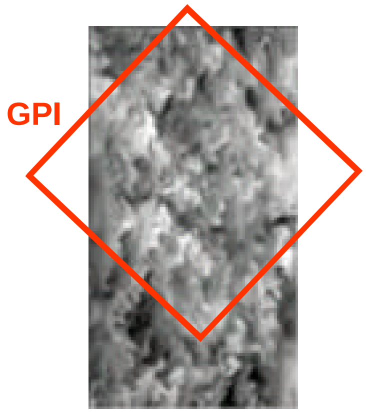
Images of C-Mod Simulation Results

Local “DBM”

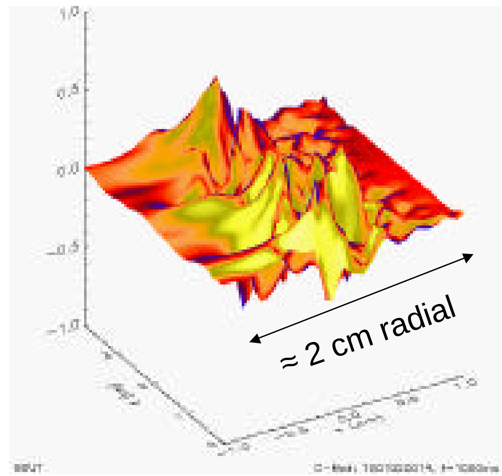
(Hallatschek, Rogers)

BOUT

(Xu, Nevins)



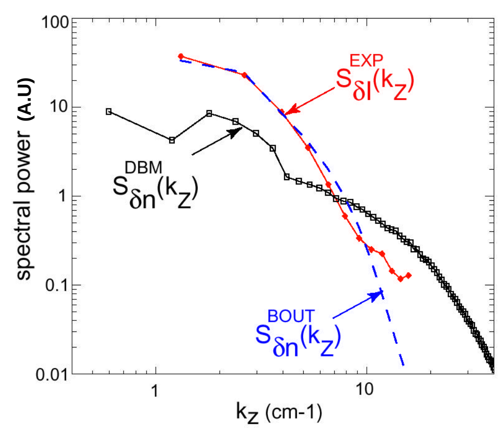
≈ 5 cm radial



Comparison of Experiment and Simulations

Comparison with Local Simulation:

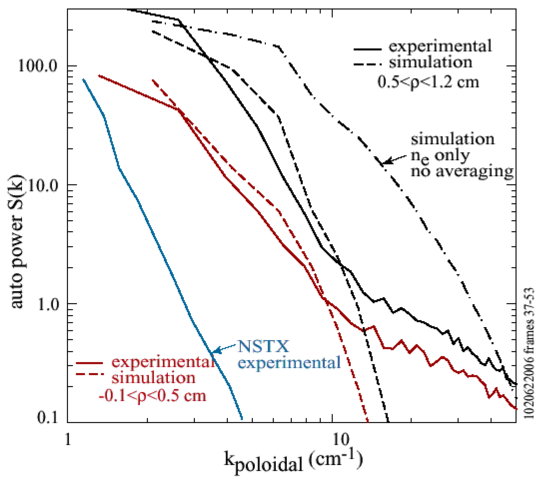
- $L_{pol} \approx 0.6$ cm in simulation
  $L_{pol} \approx 0.8 \pm 0.2$ cm in GPI
- $\tilde{n}/n \approx 18\%$ in simulation
  $\delta T_e/T_e \approx 13\%$ in simulation
  $\delta I/I \approx 25\text{-}35\%$ in LP/Diode
- $\tau_{auto} \approx 5\text{-}6$ μsec in simulation
  $\tau_{auto} \approx 10\text{-}20$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

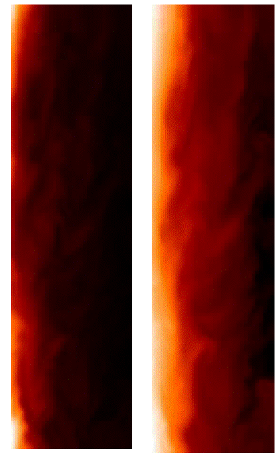


=> Initial comparisons are encouraging

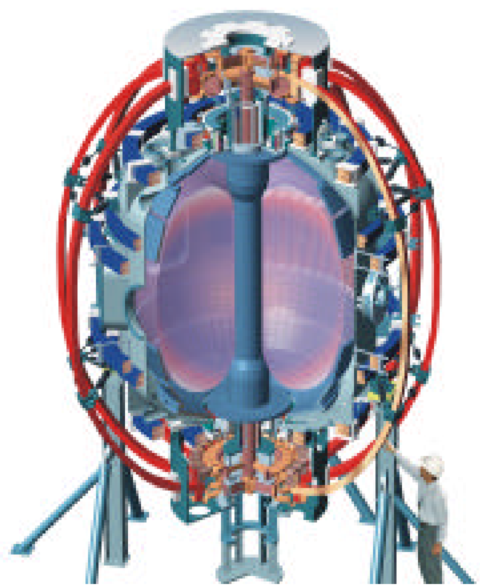
Update on Comparison with Hallatschek Model

- Non-local model with limiter and improved geometry
- Smoothed in time and space like GPI (0.3 mm/2μs)





National Spherical Torus Experiment



R = 85 cm

a = 68 cm

A = 1.25

I ≤ 1.5 MA

B ≤ 6 kG

5 MW NBI

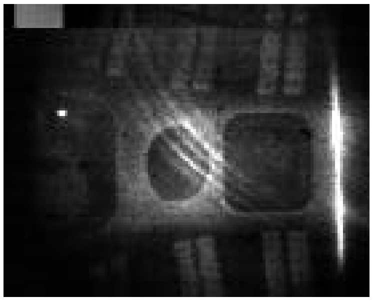
6 MW ICRH

$\beta_T \leq 32\%$

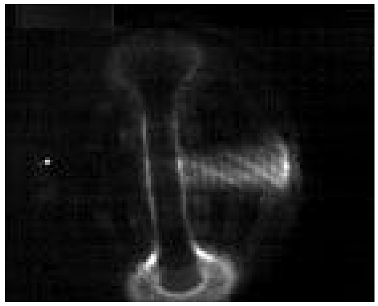
Side View of Edge Turbulence in NSTX

- **Toroidal vs. poloidal view from across machine**
- **Integrates over radius ≈ 5-10 cm of D_α emission**

D puff from big port



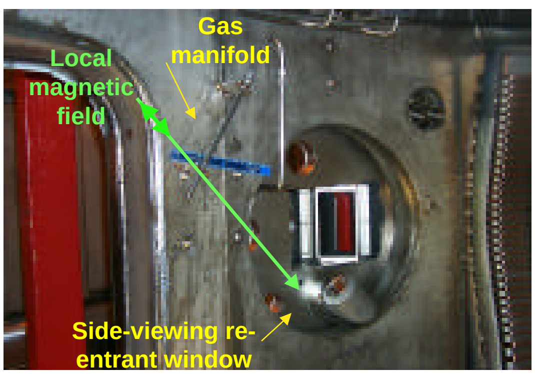
Recycling from antenna

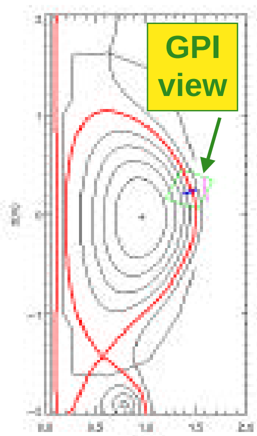


LANL camera, no filter, 10 μsec exposure time

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)

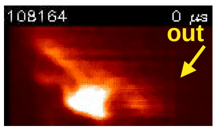




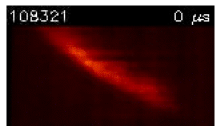
Sample GPI Videos for NSTX

- GPI with He gas puff with HeI (587.6 nm) filter
- Taken with PSI-4 with 28 frames at 100,000 frames/sec

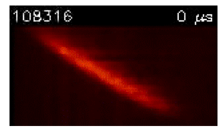
Ohmic



L-mode

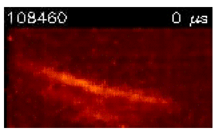


H-mode

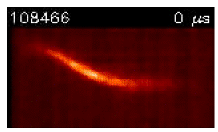


30 cm

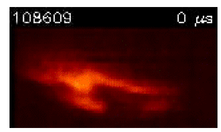
H-mode + blob



H-mode + wave



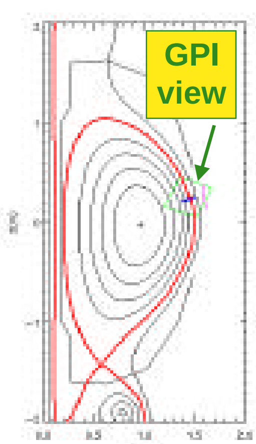
Zonal flow ?

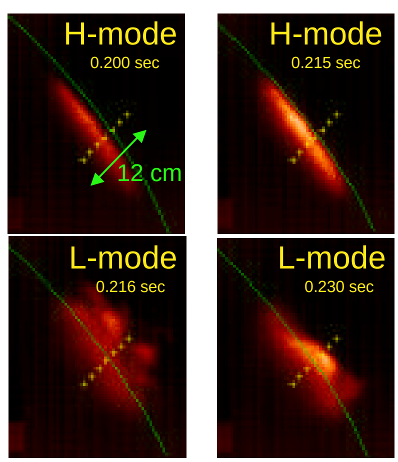


- for more examples see http://w3.pppl.gov/~szweben/psi/

Radial Array of Fast GPI Chords

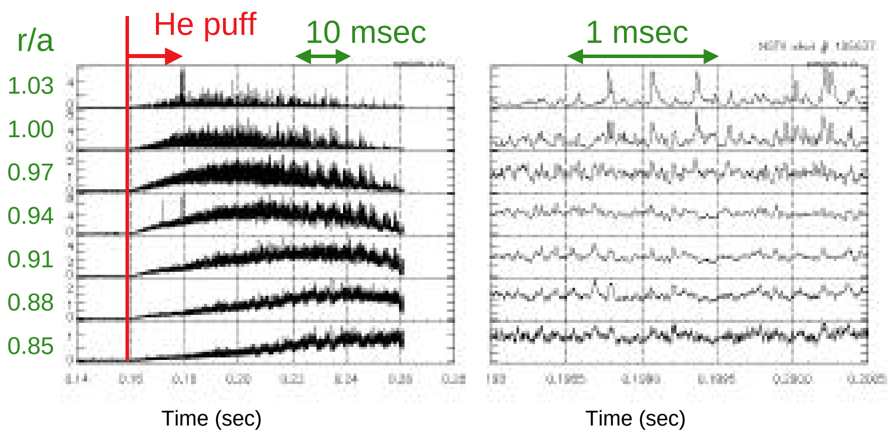
- Fast chords view 2 cm diameter "spots" in 7 channel radial array with PM tube (bandwidth ≈ 100 kHz)





Typical Signals from Fast GPI Chords

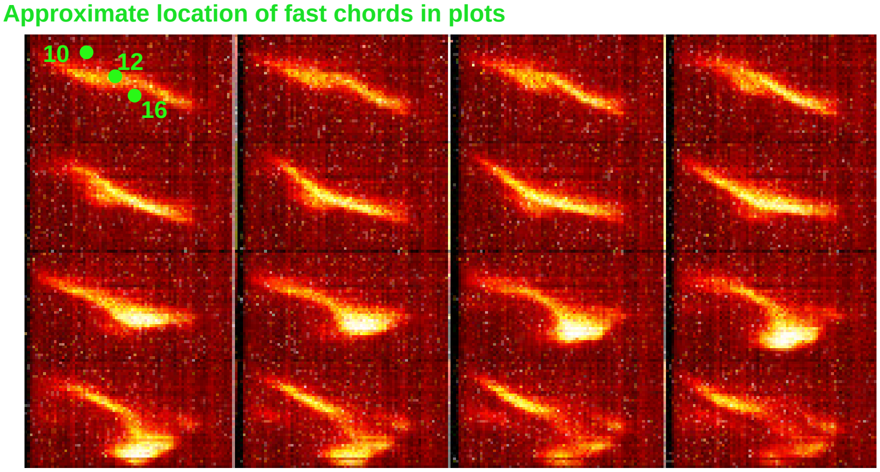
- Signals from 7 chords digitized for 0.128 msec @ 500 kHz
- Near outer wall see “intermittant” ≈ 100% fluctuations
- Nearer plasma center, see “Gaussian” ≈ 20% fluctuations



ELMs vs. Blobs in Fast GPI Chords

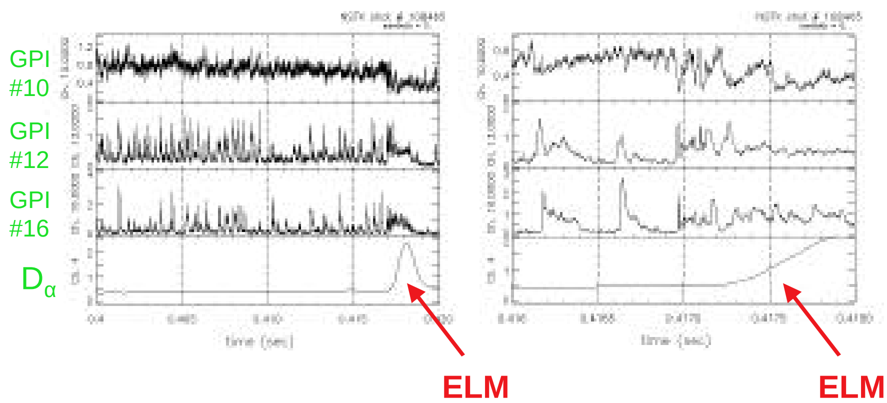
- Fast chords view 2 cm diameter “spots” in PSI camera field of view using phototubes with bandwidth ≈ 100 kHz

Approximate location of fast chords in plots



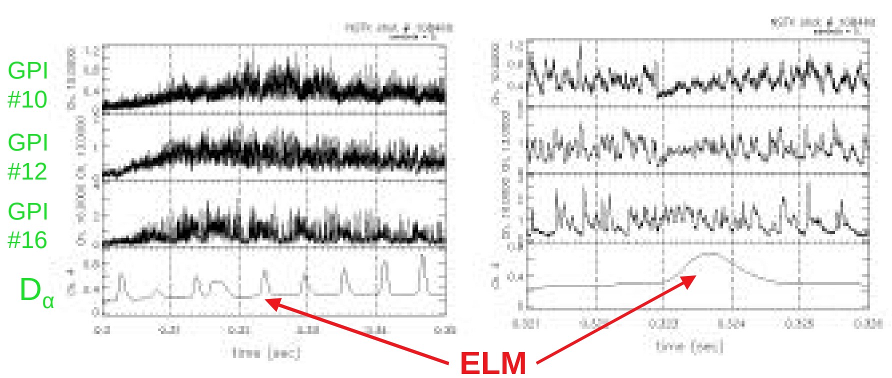
Bursts During ELM-Free H-mode

- Bursting activity seen GPI chords during “ELM-free” phase, typically with duration ≈ 0.2 msec (probably “blobs”)



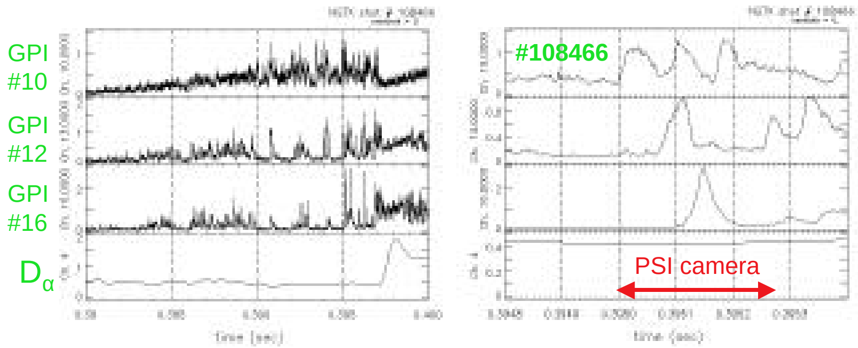
Fewer Bursts During Large ELMs

- Many short bursts between large ELMS, but no increase in burst size before or during large ELM
- Apparently these bursts and ELMs are different things



Quasicoherent Bursts During H-mode

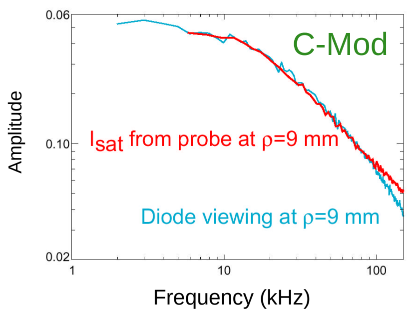
- Clear coherent oscillation sometimes seen on camera with ≈ 20 cm poloidal wavelength and f≈ 10 kHz
- Coincides with brief burst of coherent mode in chords, not a stationary continuous mode (#108466)

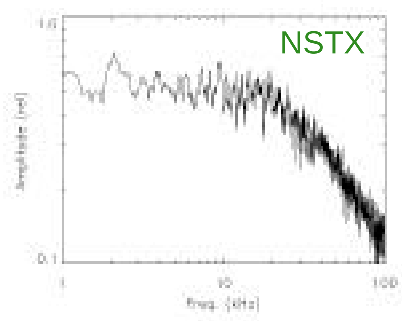


Initial Comparison of NSTX with Theory

- 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

Comparison of C-Mod and NSTX





- Frequency spectra look similar, as seen previously for other tokamaks and stellarators (e.g. Pedrosa et al PRL ‘99)
- Size ≈ 1 cm in C-Mod, ≈ 5 cm in NSTX, roughly consistent with $k\ \rho_s \approx 0.1$, but also scales with RBM wavelength $L_o \approx 0.2$ cm for C-Mod and $L_o \approx 2$ cm for NSTX

Tentative Conclusions

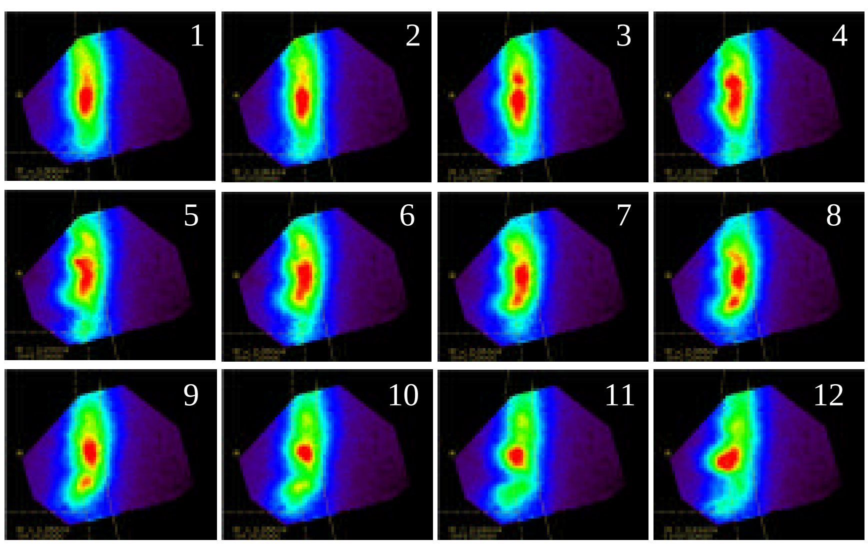
- Edge turbulence structure looks like a combination of “blobs” and “waves”, similar to that seen with other diagnostics
- Initial comparisons with simulation / theory are encouraging
- Definitive comparisons with theory will have to address what are the appropriate “inputs” needed for the simulations:
  - 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
- Try to control edge turbulence using RF, gas puffing, etc

GPI Video at 250,000 frames/sec

shot #1010720006 - Ohmic plasma with I_p=0.95 MA, B_o=53 kG, and a line averaged density of $n \approx 3x10^{14}$ cm^{-3}

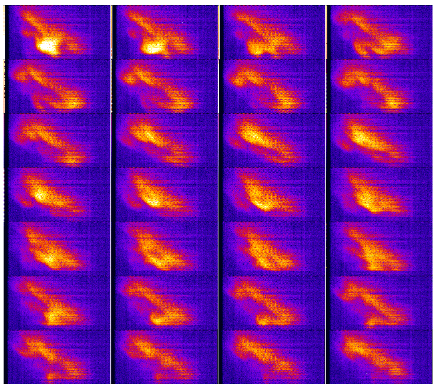


GPI Videos for NSTX

- GPI using He gas puff with HeI (587.6 nm) filter
- PSI-4 camera with 28 frames at 100,000 frames/sec

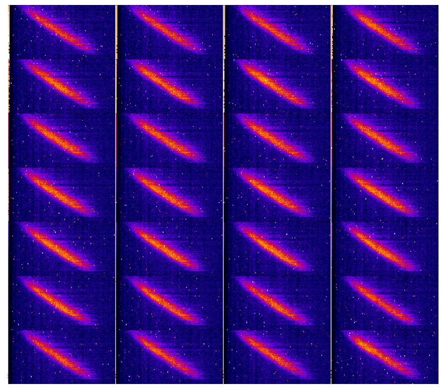
Ohmic plasma

NSTX Shot # 108164, 100 kHz, 800 kA, 3 kG, He



H-mode plasma

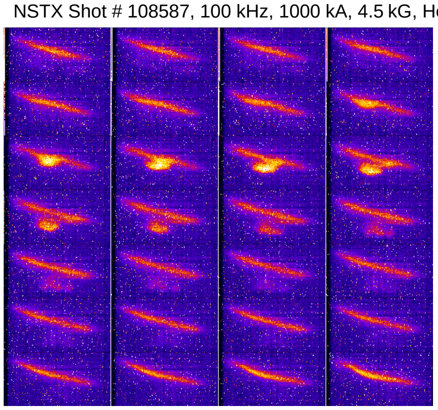
NSTX Shot # 108316, 100 kHz, 890 kA, 3.5 kG, He



Examples of GPI Videos for NSTX…cont…

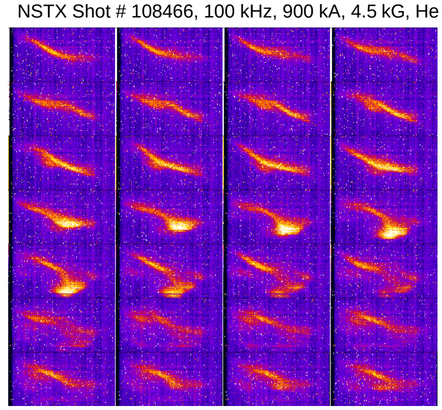
H-mode with blob

NSTX Shot # 108587, 100 kHz, 1000 kA, 4.5 kG, He



Wavy H-mode with blob

NSTX Shot # 108466, 100 kHz, 900 kA, 4.5 kG, He



- for more examples see http://w3.pppl.gov/~szweben/psi/