Gas Puff Imaging in NSTX

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DPP01/APS Poster: QP1.027
Nov. 1, 2001
LAUR-01-5787

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Abstract

Neutral gas puffs are injected into NSTX's edge to visualize edge turbulence and scrape-off layer "blobs" while decoupling these phenomena from natural recycling. The neutral line emission from these He or D_2 gas puffs is viewed in the radial vs. poloidal plane with a fast-gated (10 μs exposure), fast-framing (1 kHz frame rate), intensified, digital visible camera and also a set of discrete chords with a high bandwidth (200 kHz). The edge turbulence has the usual "filamentary" structure with a long wavelength along the magnetic field, short poloidal scale lengths of $\lambda_\perp$~7-11 cm ($k_\perp \rho_s$~0.3$) and radial scale-lengths of 3-5 cm, with a broad frequency spectra extending to ~100 kHz, and auto-correlation times of ~30 μs. These results will be compared with simulations obtained using the BOUT turbulence code of LLNL and the BAL linear stability code of Lodestar. Localized density concentrations (i.e., "blobs") are also observed within 10 cm of the separatrix during Ohmic and L-mode plasmas, but during H-modes a remarkable "quiescent" edge is observed. Results near the density limit will also be reported.

This work was supported by the U.S. DOE under Contract Nos. W-7405-ENG-36, DE-AC02-CHO3073, and DE-FG03-00ER54593.

Edge Turbulence Studies
Objective

- Understand physics of edge turbulence to gain access to: anomalous transport, H-mode physics, transport outside last close flux surface, diffusion of toroidal current from edge to core, etc.

Approach

- Measure visible emission from the plasma edge.
- Use localized, controlled gas puffs to de-couple emission from natural recycling phenomena.
- Use intensified imaging camera to view gas puff, i.e., **Gas Puff Imaging**.
- Correlate structures seen on edge emission with electron density filaments/eddies.
- Complement scale length studies from imaging with fast (~200 kHz) discrete chord measurements of gas puff emission.
- **Interactive comparison with numerical modeling.**

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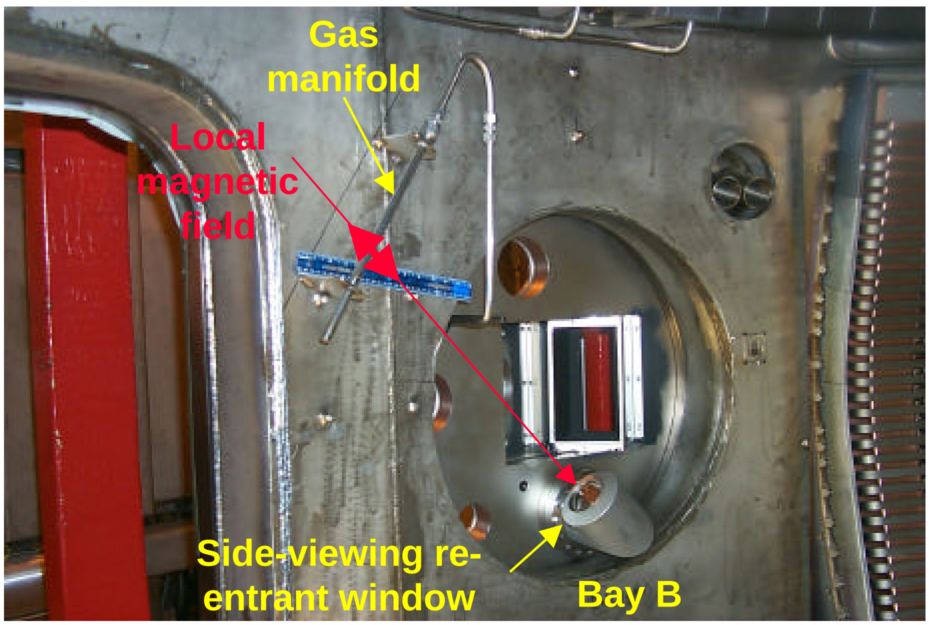
GPI Implementation on NSTX

- Use Kodak EM1012 fast-framing intensified camera for 2-D imaging
  - 10 μs exposure time
  - 1000 frames/s at 239x192 8-bit pixels
  - He gas puff and HeI line filters at 587.6 nm
- View gas puff along B field line: (radial vs. poloidal)



- Supplement with fast time series
  - 7 fiber-optic chords, ~2 cm diameter each, obtained "radially" on puff
  - light detected by photomultiplier tubes
  - frequency response to ~200 kHz

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Edge turbulence measurements, comparison with simulations

Goal:

Characterize the cross-field scale-length and frequency spectrum of this turbulent filaments, and compare the experimental results with those of the **BOUT** and **BAL** codes.

- **BOUT** is a *Bou*ndary Plasma *T*urbulence Code
  X. Xu, W. Nevins, LLNL
- **BAL** is a linear eigenvalue stability code
  J. Myra, D. D'Ippolito, Lodestar Research

• Codes have predicted/observed that the scale-size, frequency and growth rate of the turbulence depend on the toroidal field and plasma current, with some characteristics invariant for constant edge q.

• Growth rate in inner wall limited discharges is smaller than in double null discharges.

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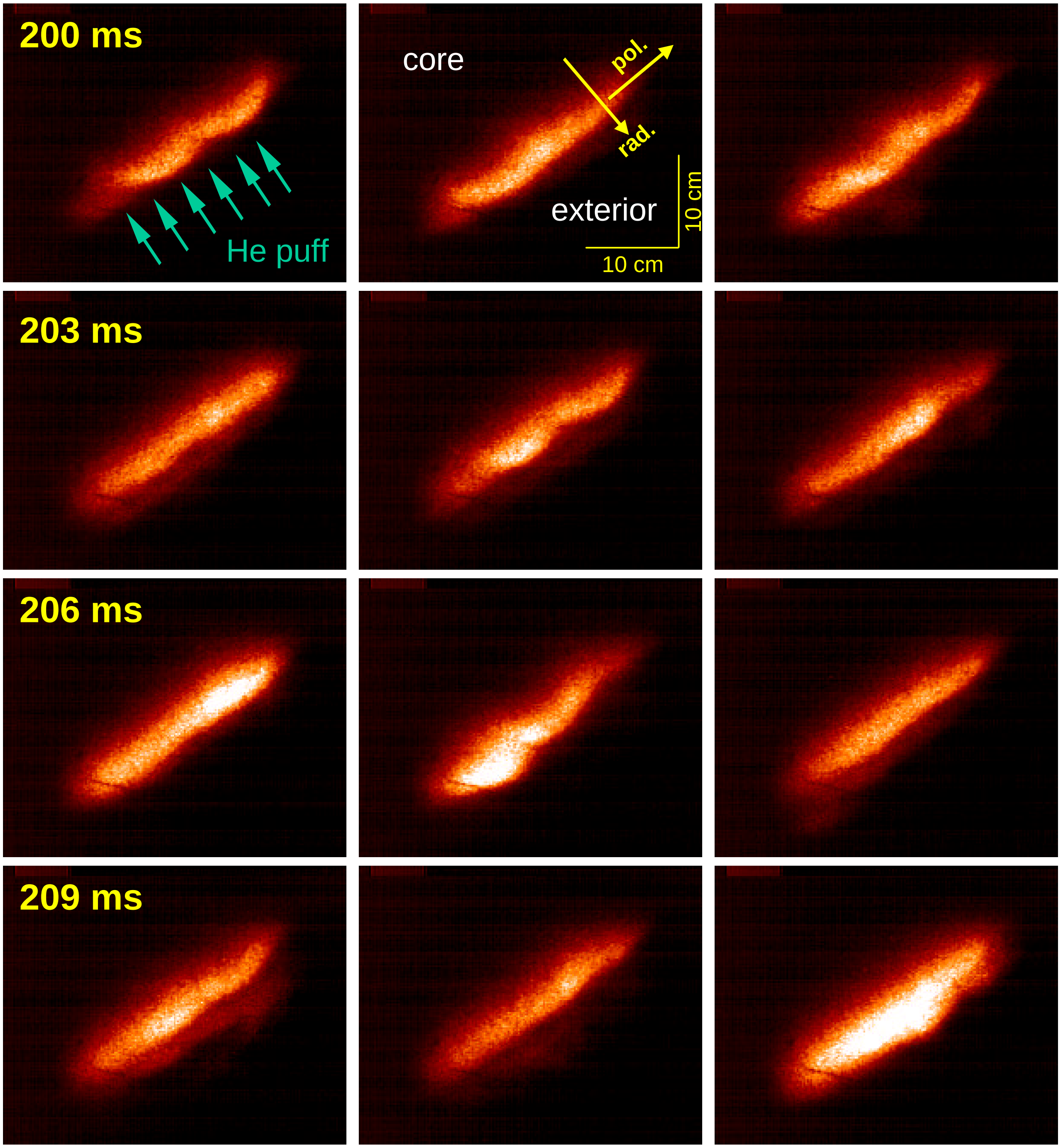
1.0 MA, 0.3 T

He puff on D_2 discharge, HeI filter, 10 μs exposure

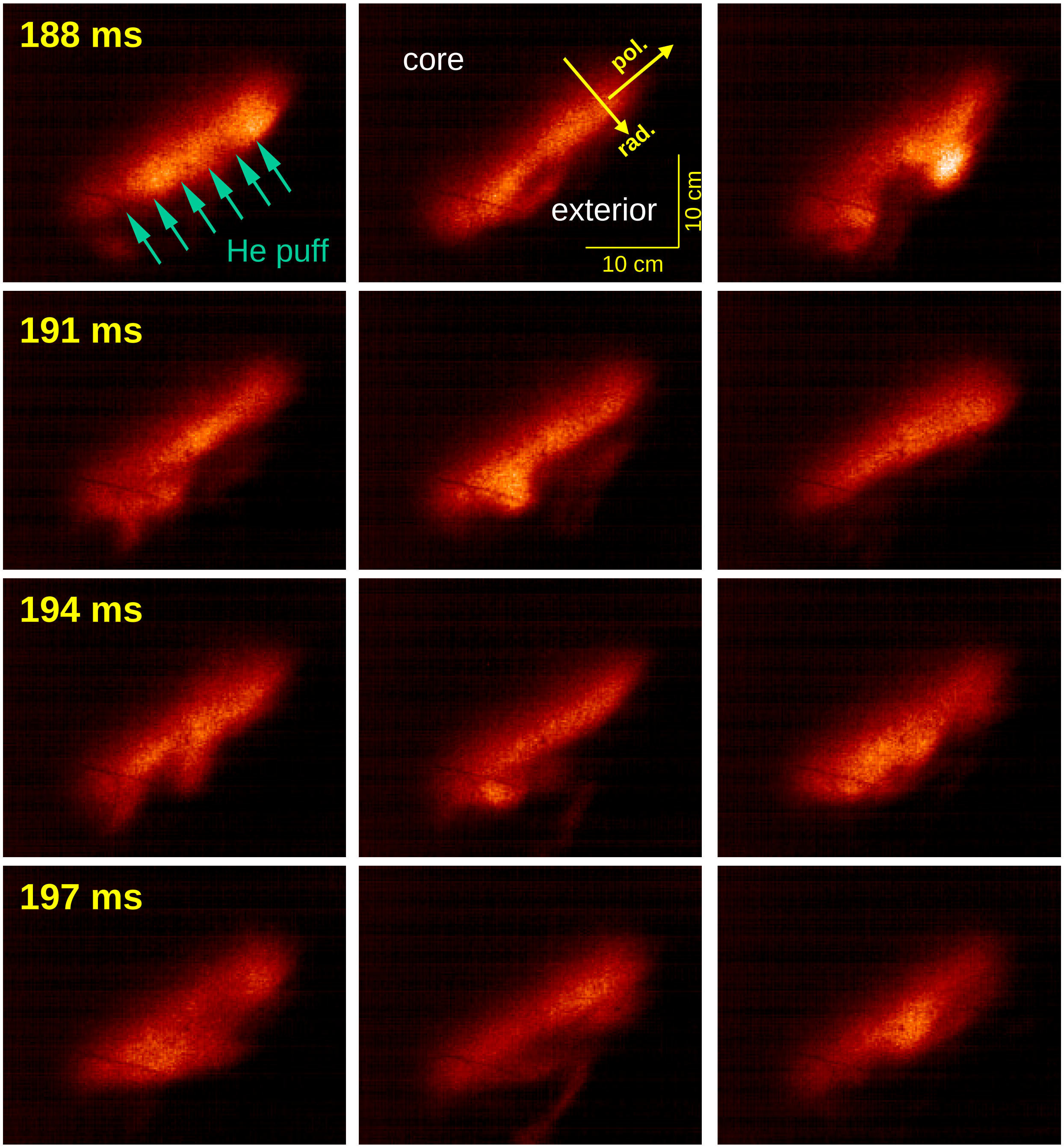


Shot 105766

MPEG clip

1.0 MA, 0.45 T

He puff on D_2 discharge, HeI filter, 10 μs exposure



Shot 105711

MPEG clip

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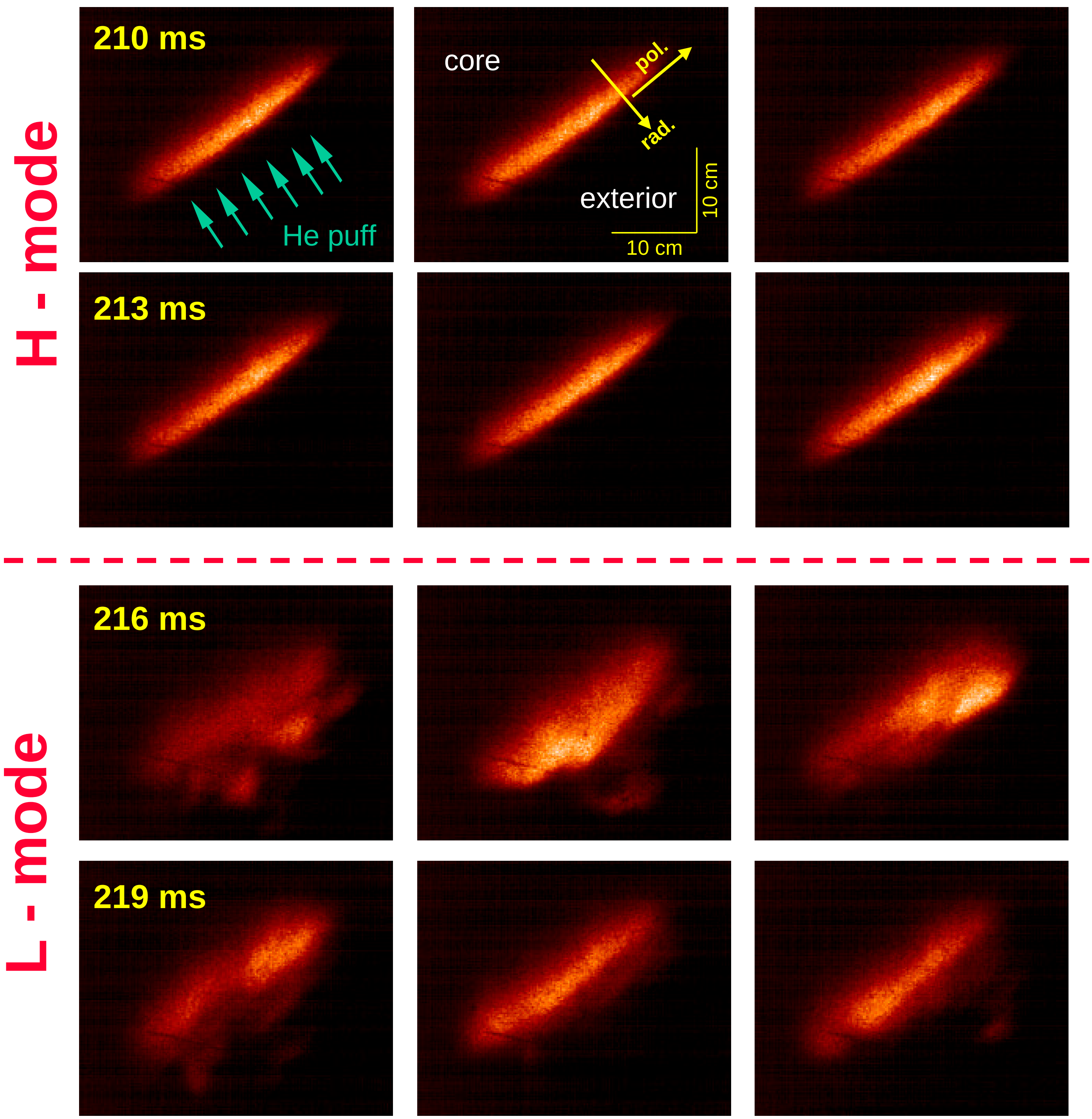
H - L transition
1.0 MA, 0.45 T

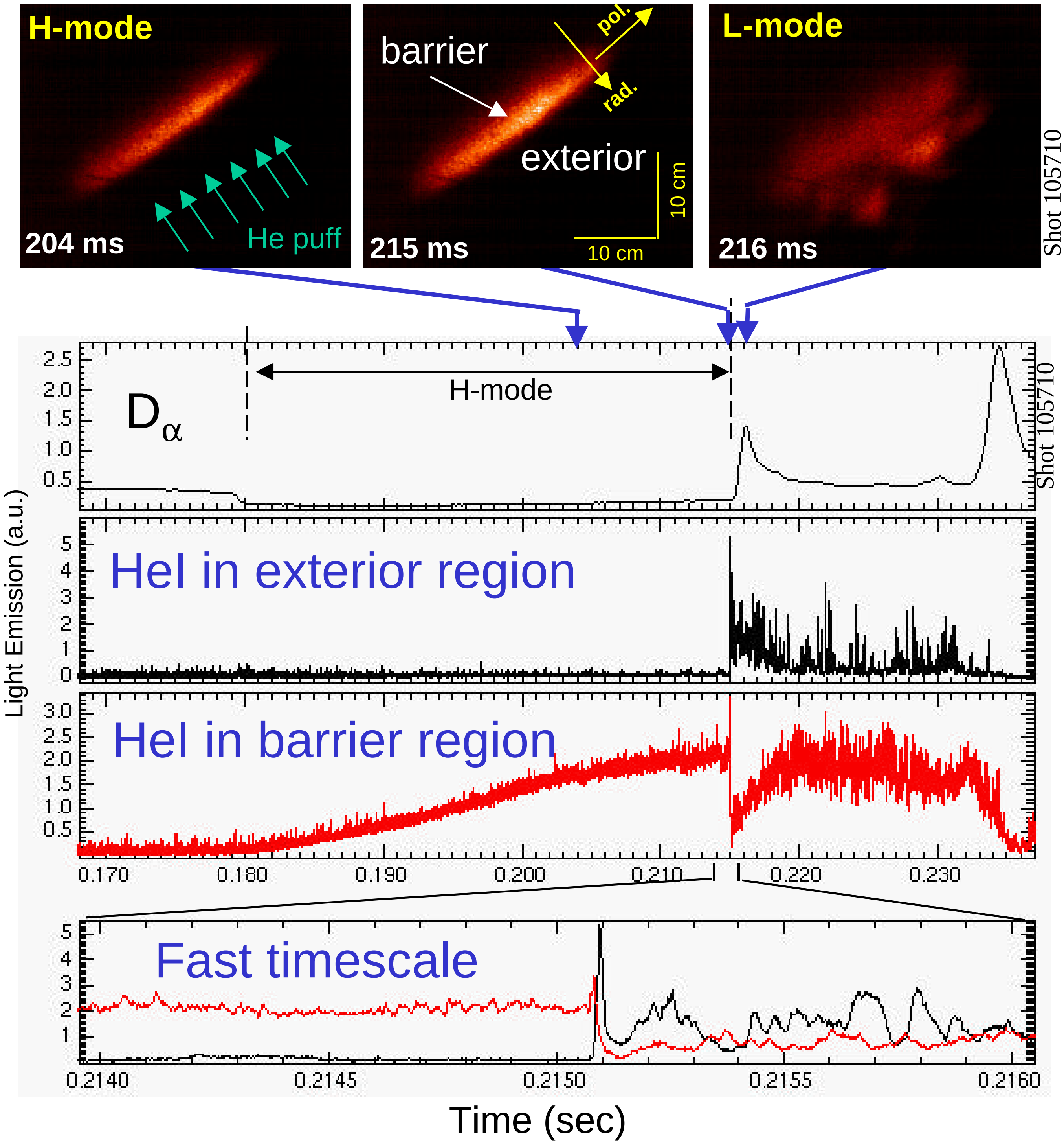
MPEG clip

He puff on D_2 discharge, HeI filter, 10 μs exposure



Shot 105710

Differences in edge turbulence observed between H and L modes



Timescale for H-L transition is similar to auto-correlation time: 20-30 μs.

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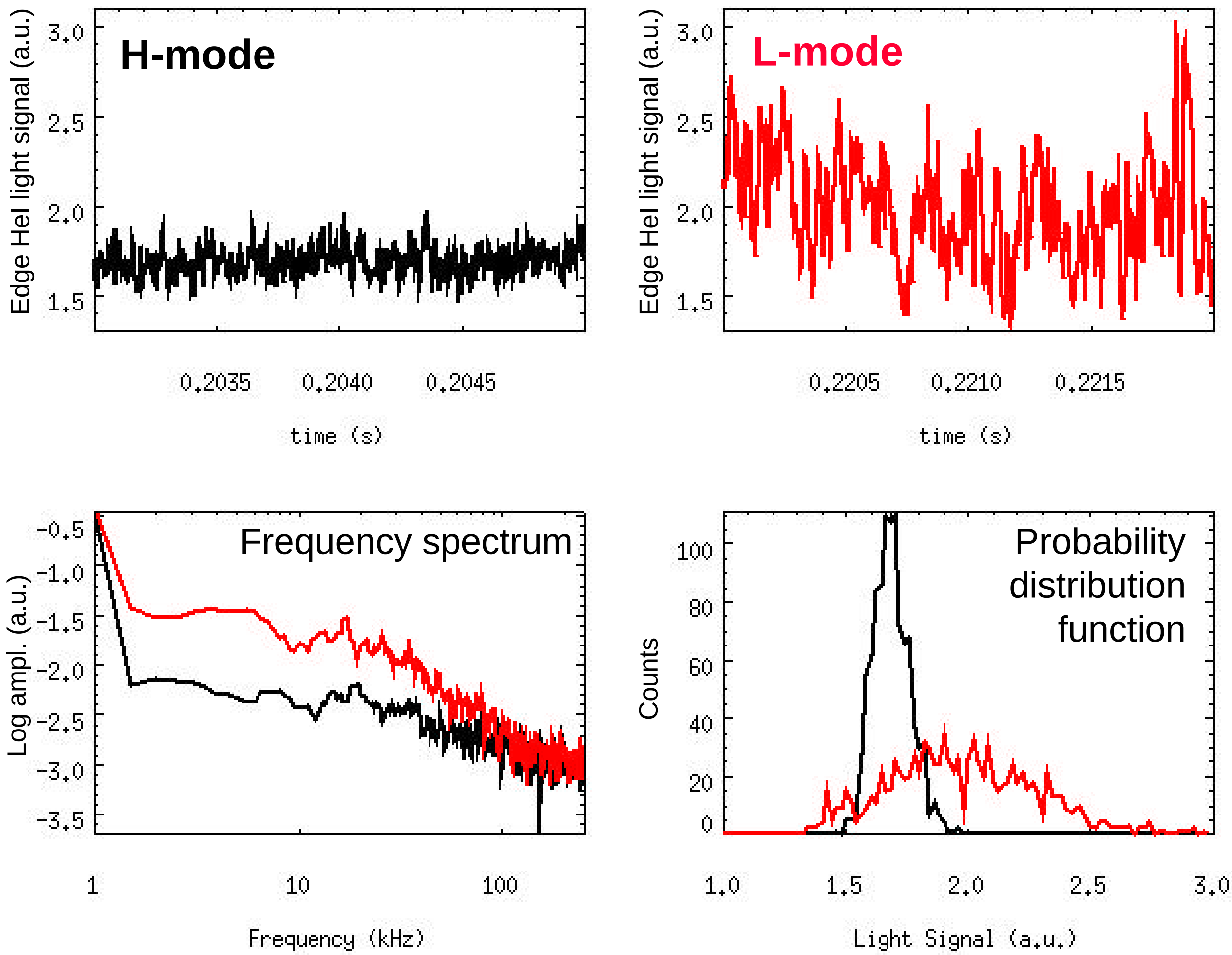
Time series analysis

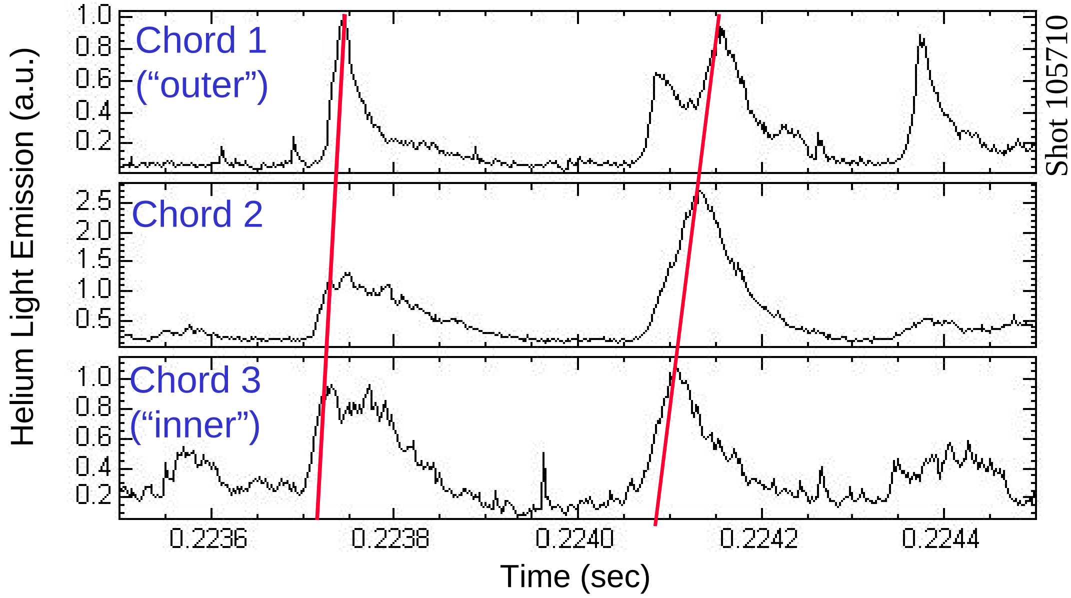
Shot 105710

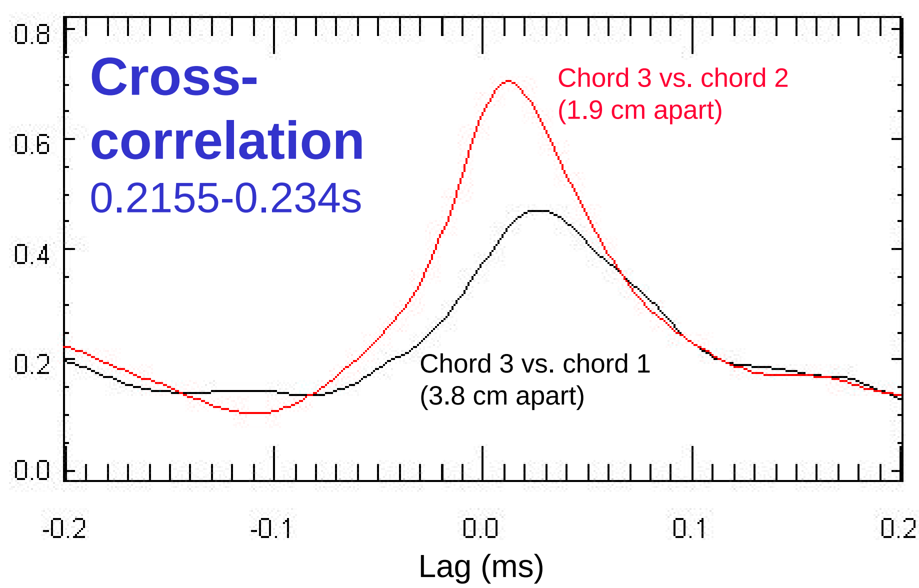


Intermittent "blobs" observed in L-mode (Ohmic) scrape-off layer

Blob characteristics similar to those observed in PISCES and Tore Supra

[G.Y. Antar et al., Phys. Rev. Lett. 87.065001]



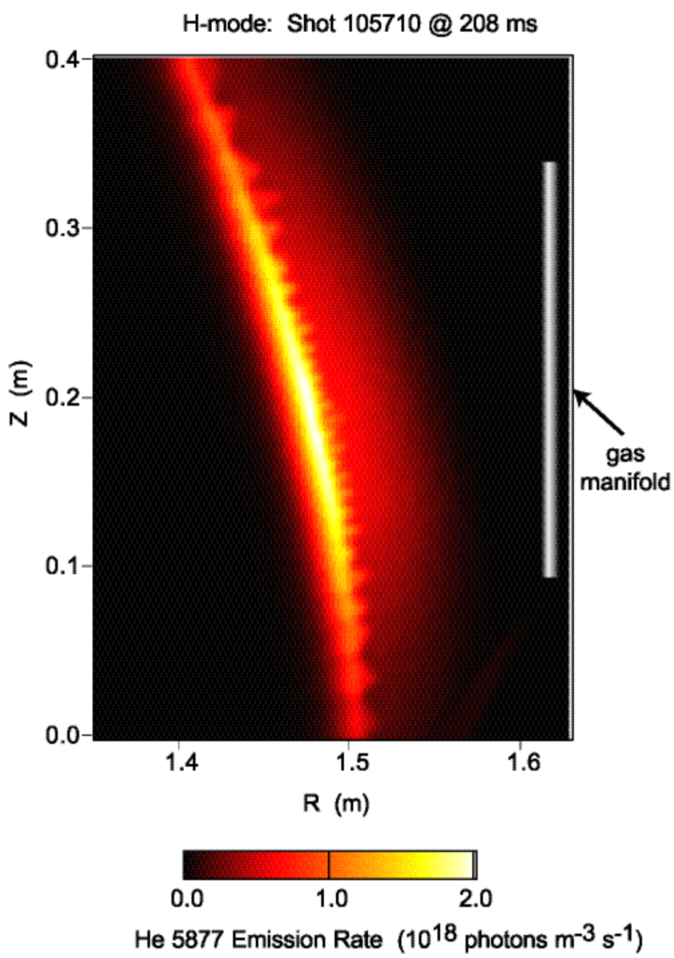


Mean radial velocity ~1700 m/s

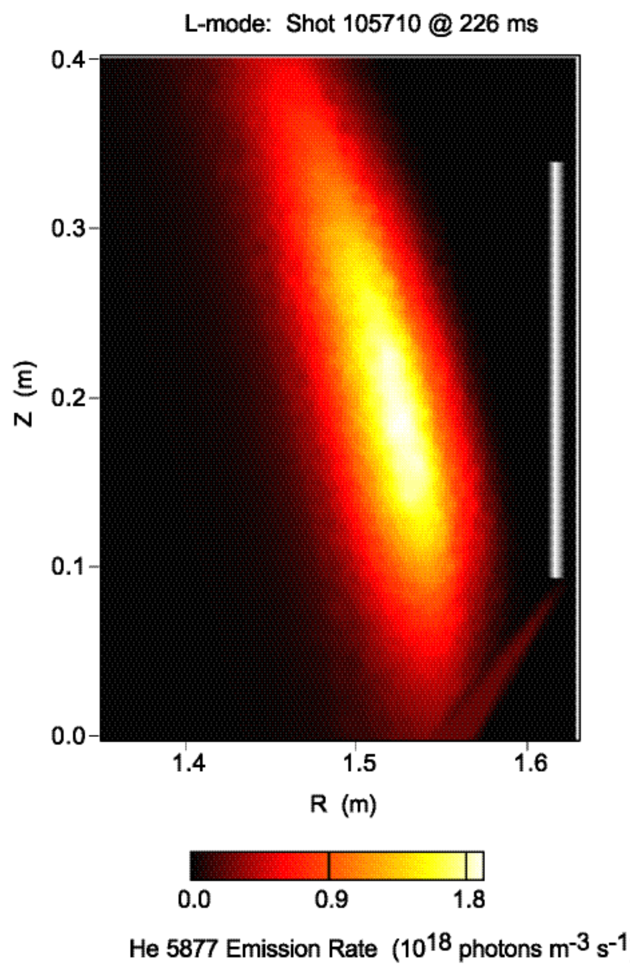
DEGAS-2 Simulation of GPI in NSTX

A thinner emission region observed during H-mode

H-mode



L-mode



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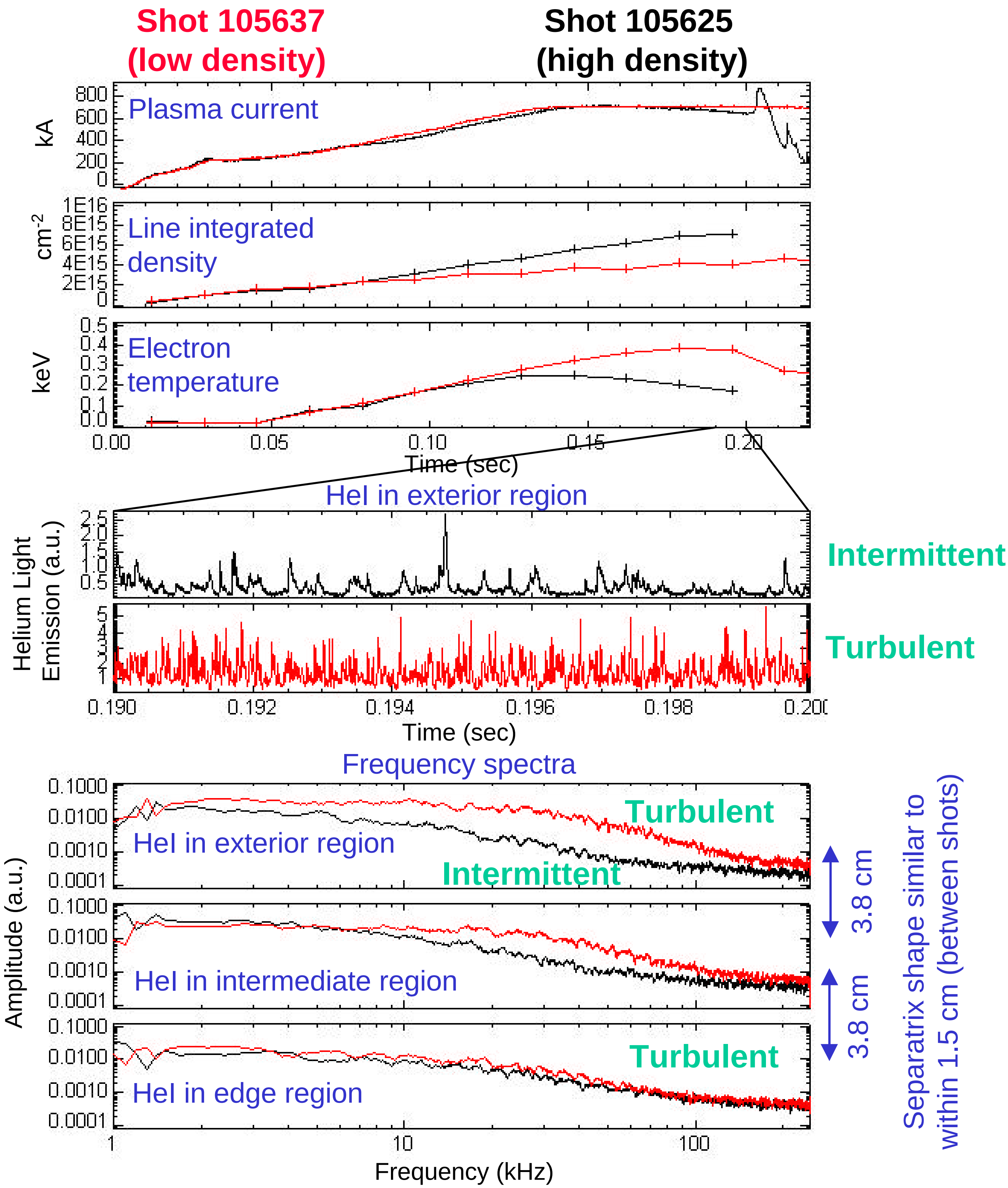
Turbulent vs. intermittent SOL



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BOUT simulation for NSTX

BOUT is a ***Bou***ndary Plasma ***T***urbulence Code

X. Xu, W. Nevins, LLNL

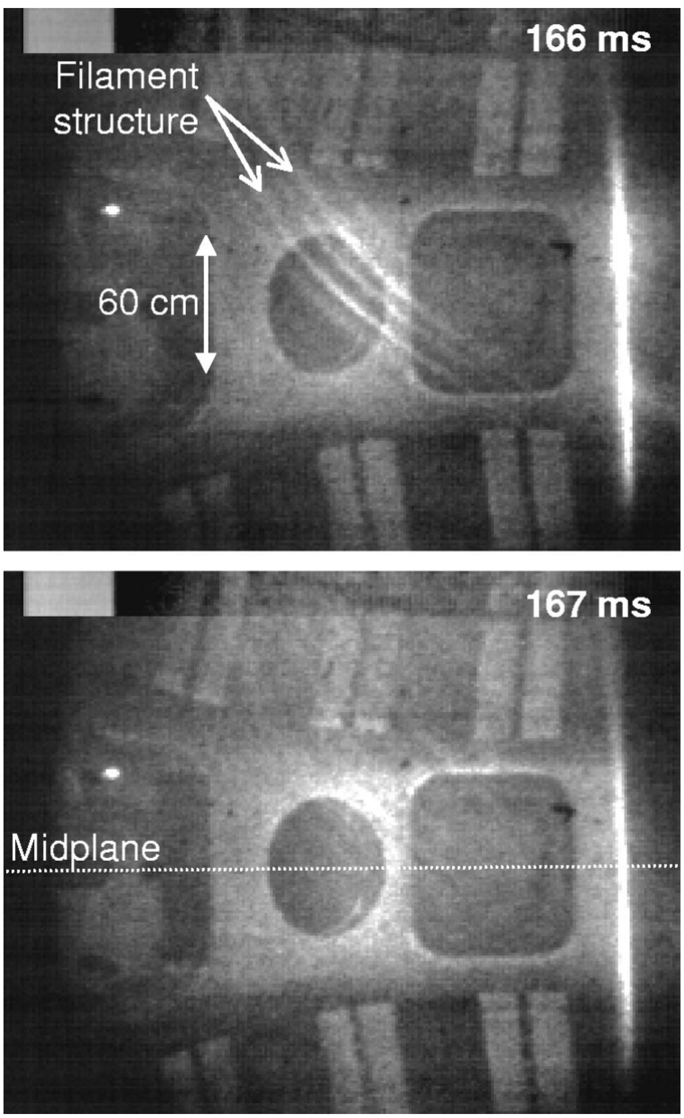
- 2-fluid 3D Braginskii equation turbulence code with:
  - realistic geometry
  - open and closed flux surfaces
  - background and turbulence evolution in time

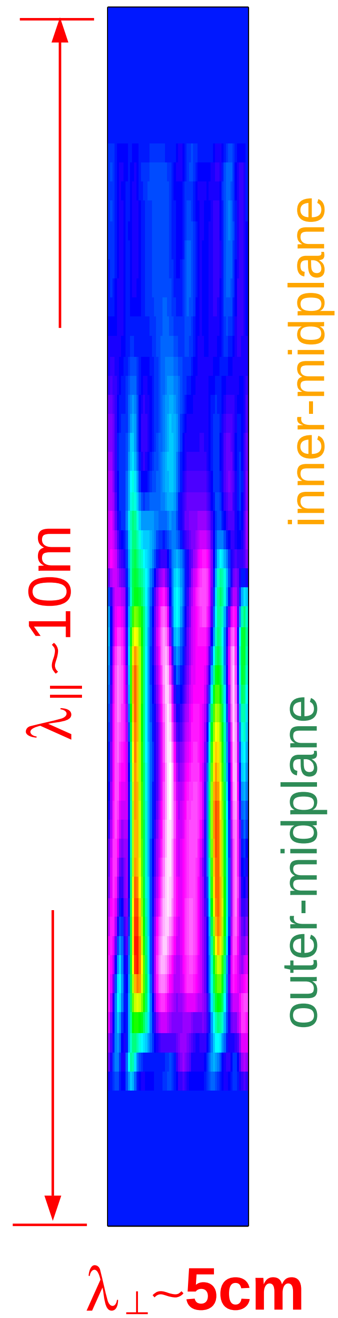
- BOUT possesses many sources of turbulence, most important one appears to be **resistive ballooning**.

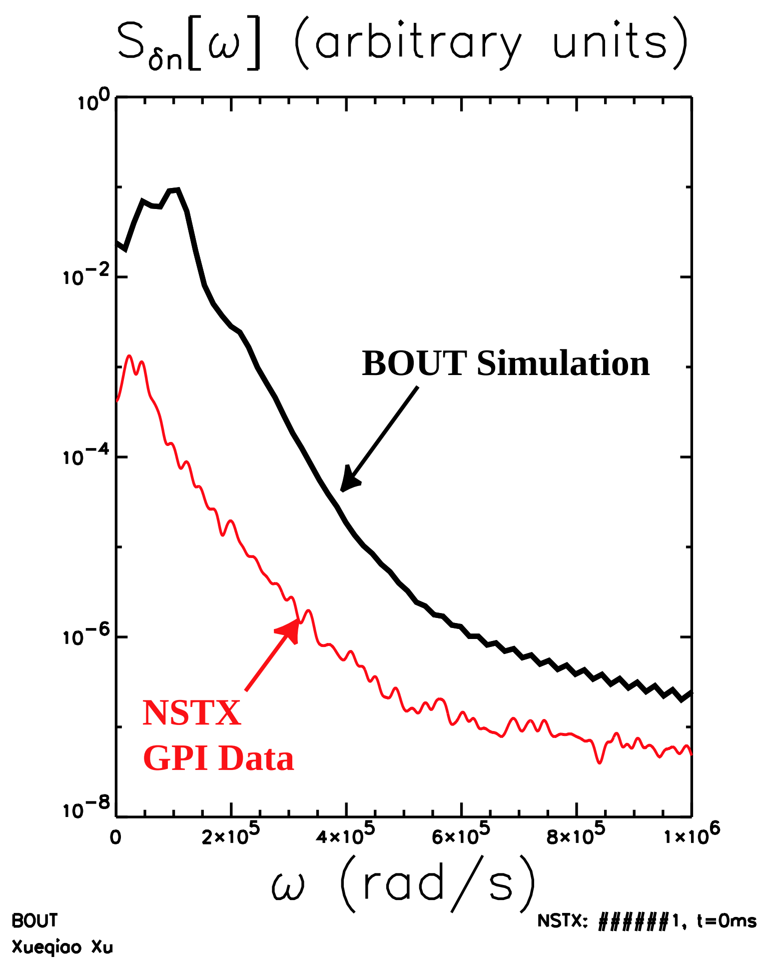
- Input to the code is provided from experimental data:
  - plasma current and magnetic equilibrium data
  - edge electron and ion temperatures (estimates)
  - edge electron density (estimate)

- Turbulence results from the numeric simulation are compared with experimental turbulence results.

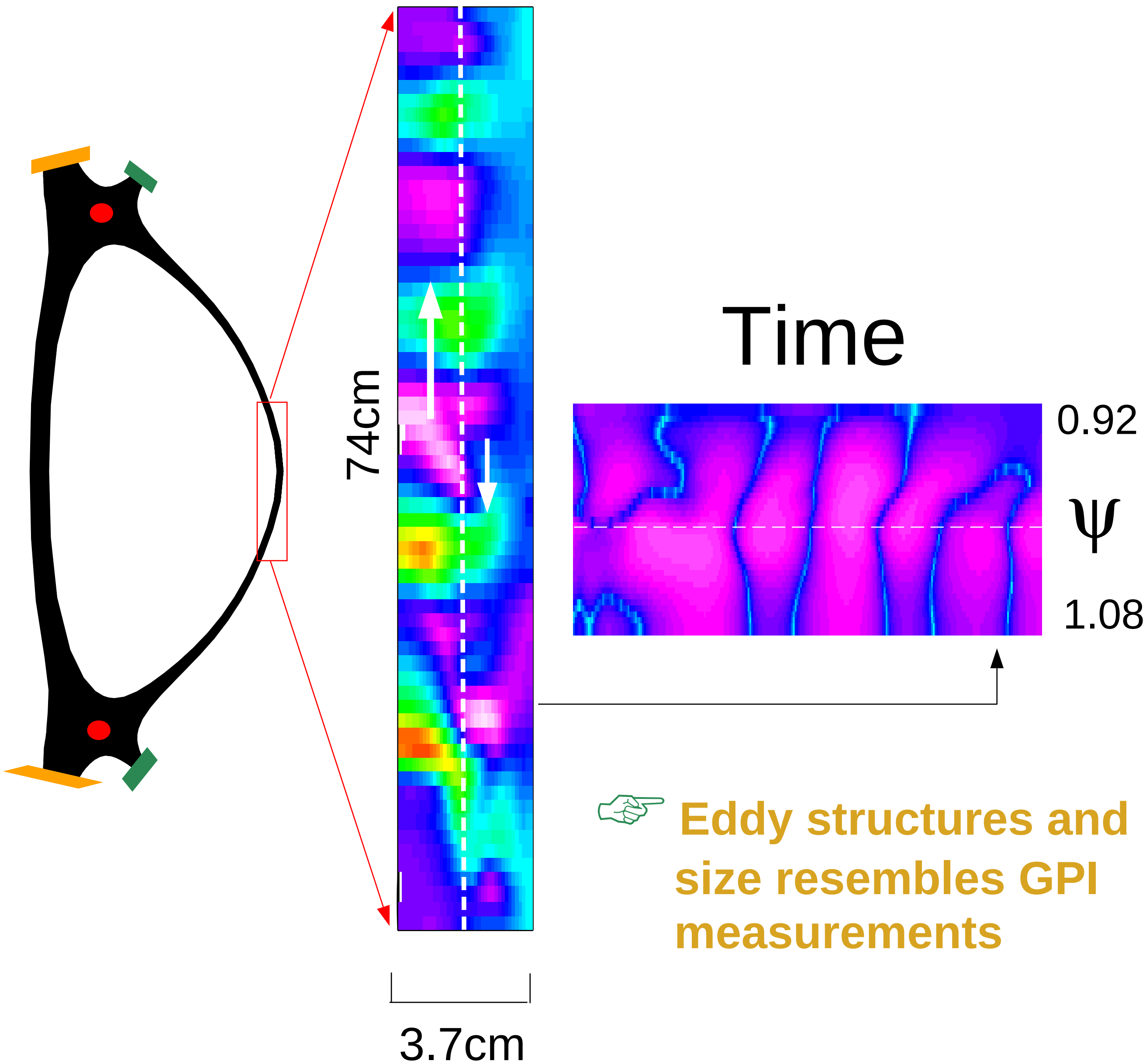
Filament-like structures observed in BOUT and GPI






$S_{\delta n}[\omega]$ (arbitrary units)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
2×10^5
4×10^5
6×10^5
8×10^5
1×10^6
ω (rad/s)
BOUT Simulation
NSTX
GPI Data
BOUT
Xueqiao Xu
NSTX: ######1, t=0ms

Fluctuating density shows sheared poloidal flow and radial streamer structures across the separatrix



☞ **Eddy structures and size resembles GPI measurements**

BAL results

J. Myra, D. D'Ippolito, Lodestar

- **BAL** is a linear eigenvalue (stability) code.
- Code can treat both the closed and open flux surface regions.
- Physics of pressure driven modes and divertor flux plate sheaths are included.
- Code employs the same magnetic geometry mode and input files that are used by BOUT.
- BAL has been important in understanding the unstable modes in X-point geometry and the corresponding turbulence seen in BOUT.

- As q is increased (constant B) , scale size increases, frequencies are smaller and growth rate doesn't change much.
- As B and Ip are reduced (constant q), scale size gets larger, frequencies are similar and growth rate decreases.
- Growth rate in inner wall limited discharges is smaller than in double null discharges.

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Summary

Results

- From these and previous observations we know that:
  - Filaments are well aligned with magnetic field.
  - $\lambda_\perp$ ~ 7-11 cm
  - $k_\perp \rho_s$ ~ 0.3
  - Radial scale-length appears to be 3-5 cm
  - Frequency spectra extends to ~ 100 kHz
  - Auto-correlation lifetime ~ 30 μs
- Current/field variations resulted in the more pronounced differences between shots, relative to topology variations.
- **Most notable are the differences observed between H and L mode confinement regimes, with strong suppression of turbulent eddies in H-mode.**
- Intermittent "blobs" observed in L-mode scrape-off layer.
- Encouraging results have already been obtained from the interaction with numerical modeling:
  - radial scale size in BOUT ~ 1/2 GPI data
  - poloidal scale size in BOUT ~ GPI
  - parallel length scales both very large
  - frequency spectra similar

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Summary

Ongoing work

- Are the intermittent blobs born from the turbulence seen on the edge (example: shot 105766)?
- Further modeling of edge atomic physics.
- **Interactive comparison with numerical modeling.**
  Extend comparison to H-mode results.
- Use ultra-fast fast framing camera (up to 5 million frames-per-second) from Princeton Scientific Instruments to follow evolution of turbulent eddies and “blobs” in time.

Related work

Gas Puff Imaging

Edge Turbulence Imaging in Alcator C-Mod
S.J. Zweben
Friday Morning Invited Session, talk UI1.004

Imaging of Edge Turbulence in Alcator C-Mod
J.L. Terry et al.
CO1 Oral Session, talk CO1.008

"Blob" phenomena

Existence and Universality of Convective Transport in Magnetically Confined Devices
G.Y. Antar et al.
Friday Morning Oral Session, talk UO1.005

Cross-Field Blob Transport in Tokamak Plasmas
D.A. D'Ippolito
Wednesday Afternoon Poster Session, poster LP1.083

Numerical Simulation of Blob Propagation through SOL and Divertor Plasmas
S. Galkin et al.
Wednesday Afternoon Poster Session, poster LP1.082

many other at this meeting...