Edge Turbulence Imaging in Alcator C-Mod and NSTX

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PPPL, MIT, FP&T, Greifswald, Garching, Lodestar, LLNL

- Motivations
- Gas puff imaging
- Results from C-Mod
- Results from NSTX

Motivations

- Edge turbulence probably determines edge and SOL parameters, which can strongly affect the global confinement and plasma-wall interactions

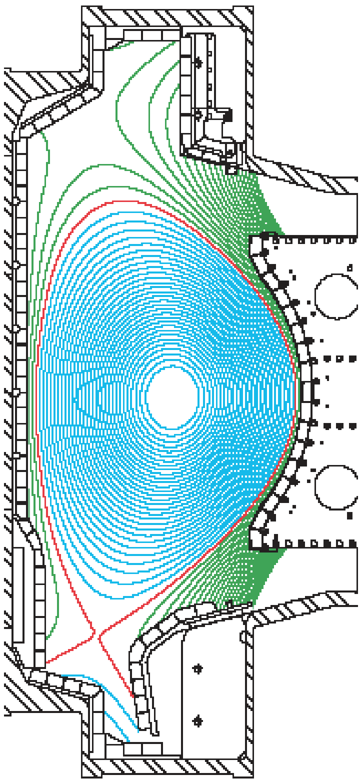
- Edge turbulence can probably be understood from first principles by comparing turbulence data with theory (both simulations and simplified physics models)

Some topics of interest:

- Coherent structures
- Intermittency
- SOL transport
- L-H transition
- Shear and zonal flows
- Edge localized modes
- Quasi-coherent modes
- Density limit

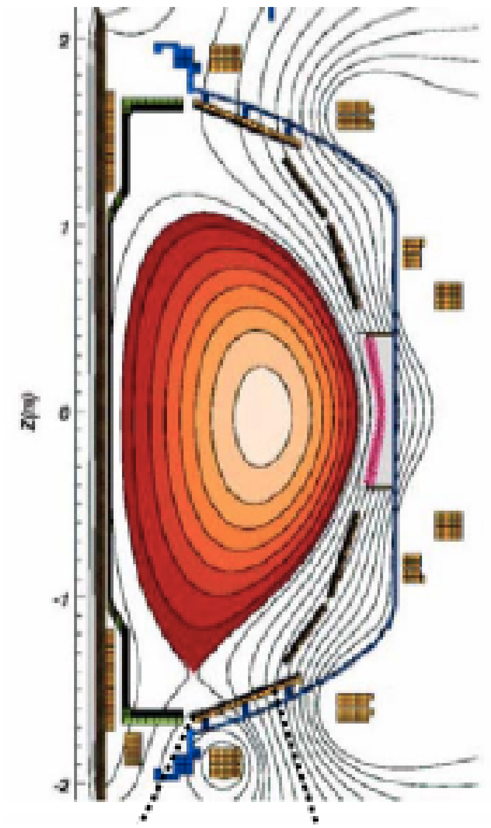
Alcator C-Mod and NSTX

C-Mod



vol ~ 1 m³

NSTX



vol ~ 10 m³

C-Mod	NSTX
R=0.67	0.85
a=0.23	0.68
$B \approx 5$ T	0.3 T
$I \approx 1$ MA	1 MA
$P \approx 6$ MW	12 MW
$\beta_T \approx 1\%$	40%

C-Mod SOL	NSTX SOL
$n \sim 2 \times 10^{13}$ cm^{-3}	5×10^{12} cm^{-3}
$T \sim 23$ eV	~ 13 eV
$L_\perp \sim 0.5$ cm	~ 3 cm
$L_{\parallel} \sim 5$ m	~ 5 m
$\rho_s \sim 0.02$ cm	~ 0.2 cm
$\beta \sim 10^{-5}$	$\sim 10^{-3}$

Gas Puff Imaging Diagnostic

- High speed cameras see “filamentation” of D_α light emission
  (e.g. Niedermeyer, Goodall ‘82, TFTR ‘89)

- Fluctuations of D_α light similar to Langmuir probe results
  (e.g. Zweben ‘83, Endler ‘95)

=> GPI diagnostic in Alcator C-Mod and NSTX (‘99 -):

- Image D_α light emission from a small gas puff

- View along B to see radial vs. poloidal structure

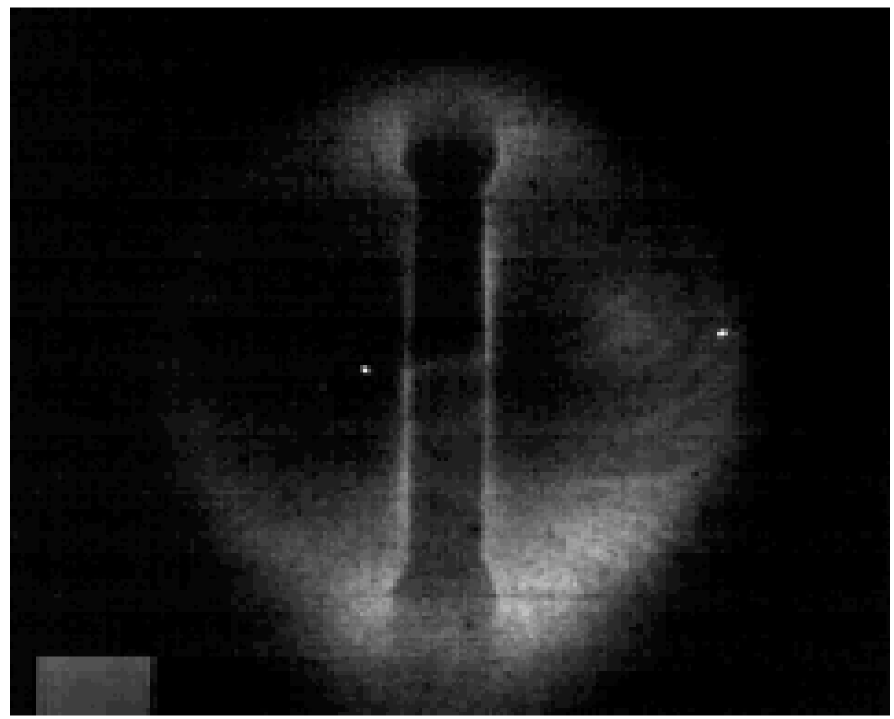
Turbulent "Filaments" in the Edge

- These movies show the short poloidal correlation and long toroidal correlation length of the turbulence

Side view of C-Mod

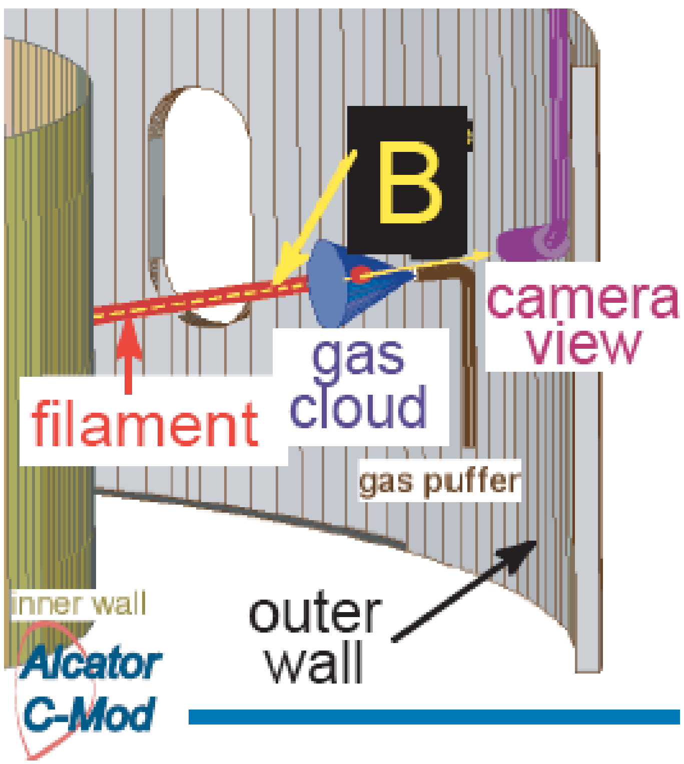
20 cm

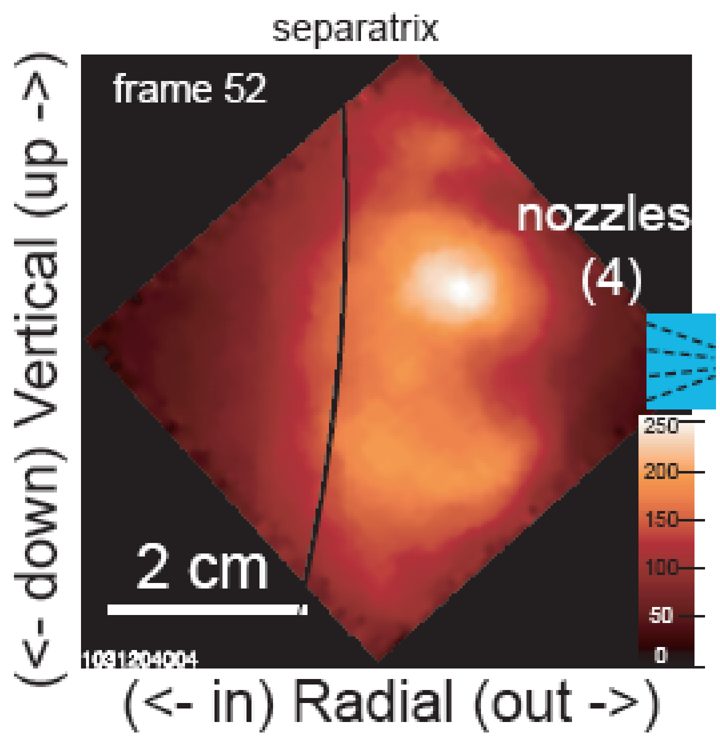
Fisheye view of NSTX



GPI Diagnostic in Alcator C-Mod

- Looks at D_α or HeI light from gas puff $I \propto n_o n_e f(n_e,T_e)$
- Views ≈ along B field line to see 2-D structure ⊥ B
- Image coupled to camera with 400x400 fiber bundle

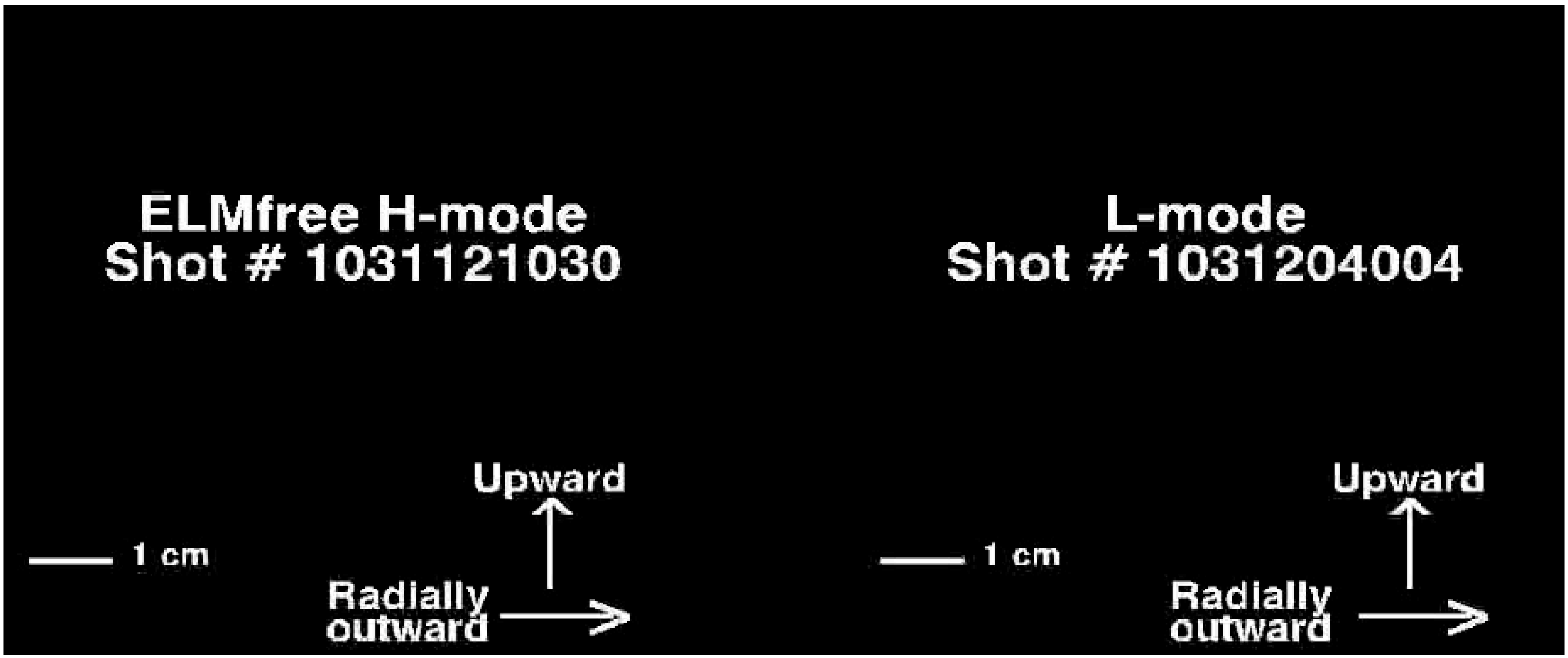




Movies of C-Mod Turbulence

- Taken at 250,000 frames/sec with PSI-5 camera
- Camera has 300 frames with 64 x 64 pixels per frame

ELM-free H-mode L-Mode



Interpretation of GPI Results

- Gas puff does not significantly perturb edge turbulence
  - GPI gas puff smaller than normal fueling puff
  - doesn't affect other fluctuation measurements
  - results ~ independent of puff size or D/He species

- Space vs. time *structure and motion* of fluctuations should be ~ independent of atomic physics $f(n_e, T_e)$, but not fluctuation *level* (e.g. if $I \propto n_e^{\alpha}$, then $\delta I/I \approx \alpha\, \delta n/n$)

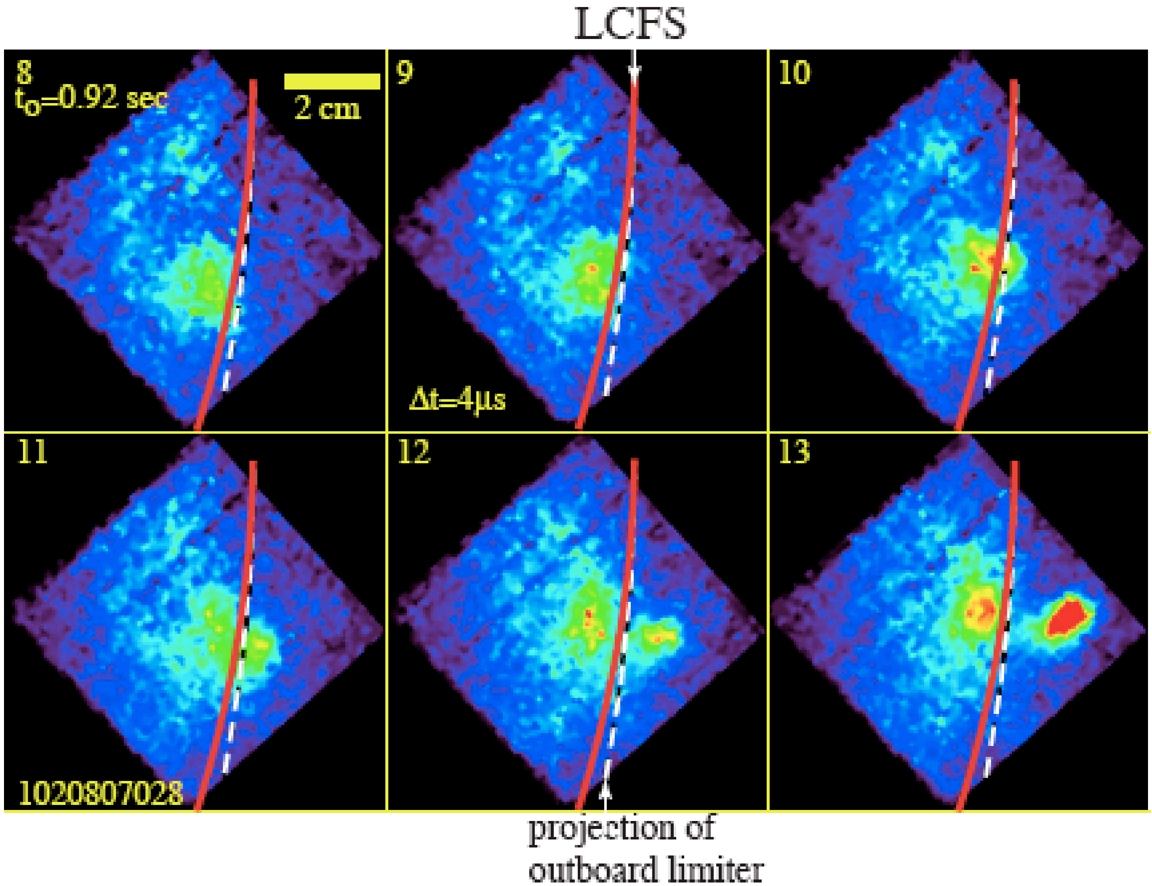
- Atomic physics can be applied to simulations for quantitative (statistical) comparison with imaging data

=> Estimate turbulence structure and motion from images

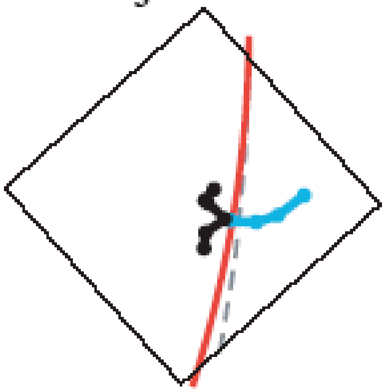
Near density limit - blobs seen inside LCFS

discharge with n_e/n_{GW}=0.7

edge cools & steep gradient region moves inside of LCFS



trajectories

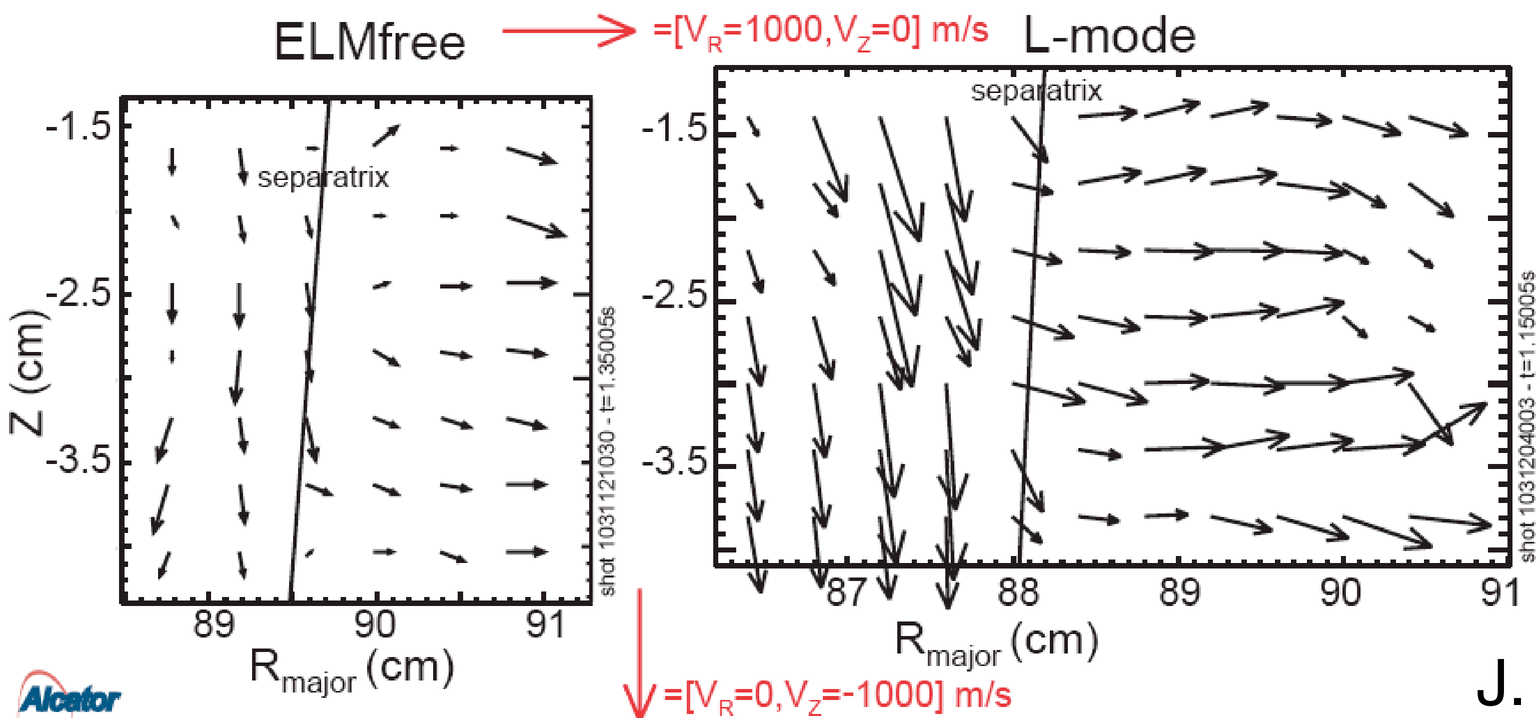


Implication: blobs form in steep gradient region,
not at boundary between open/closed field lines

J. Terry

Velocity Fields from C-Mod Imaging

- Turbulence propagation velocity can be inferred from cross-correlation of 2-D images in time
- Average velocities show radial convective motion in SOL



J. Terry

Alcator C-Mod

Some Other C-Mod Results

- Poloidal correlation lengths are ≈ 0.5 - 1 cm , somewhat rising from inside separatrix to far outside SOL (Terry)

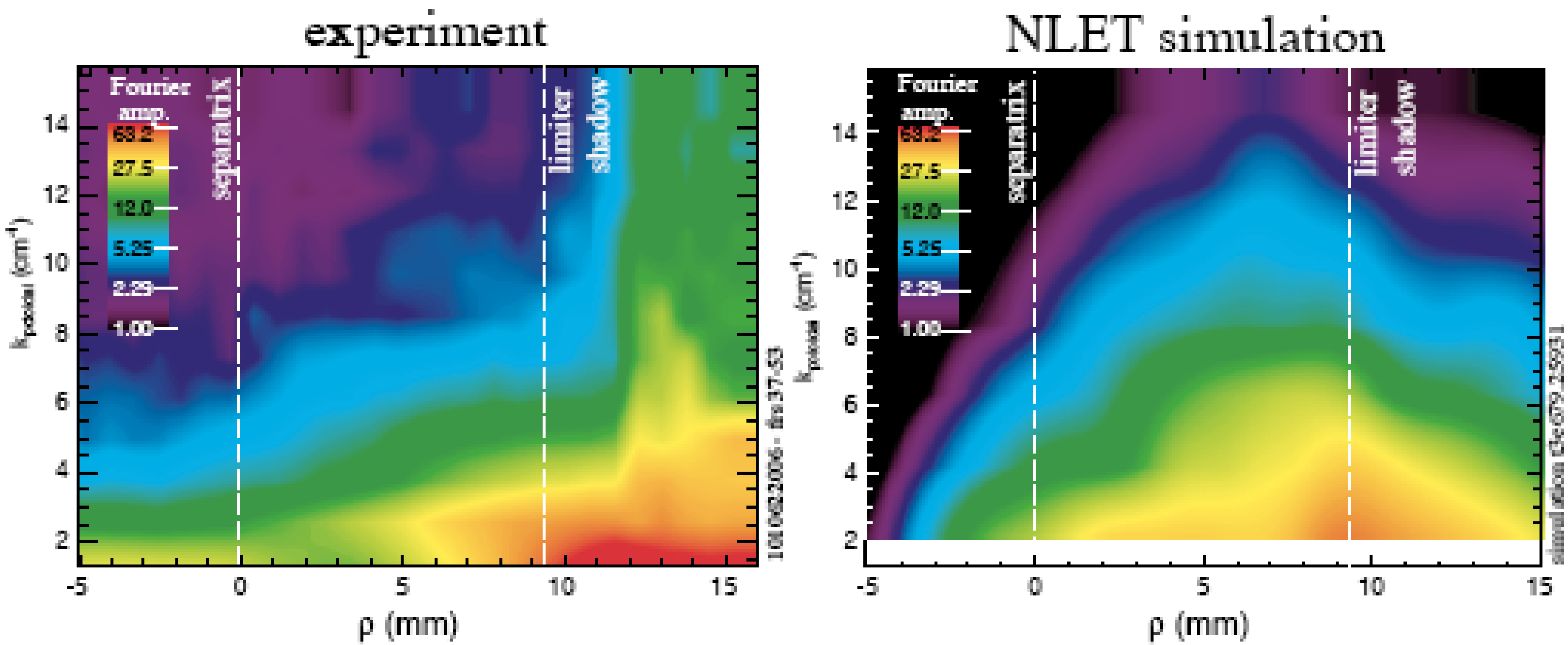
- Fluctuation level at inner midplane is ≈ 5 times less than outer midplane, showing “ballooning” character (Terry)

- GPI fluctuations are well correlated with Langmuir probe fluctuations when probe and GPI are lined up along a B-field line (Grulke)

⇒ Turbulence ~ similar to previous measurements at ege of tokamaks (and stellarators ?)

Comparison with Theory

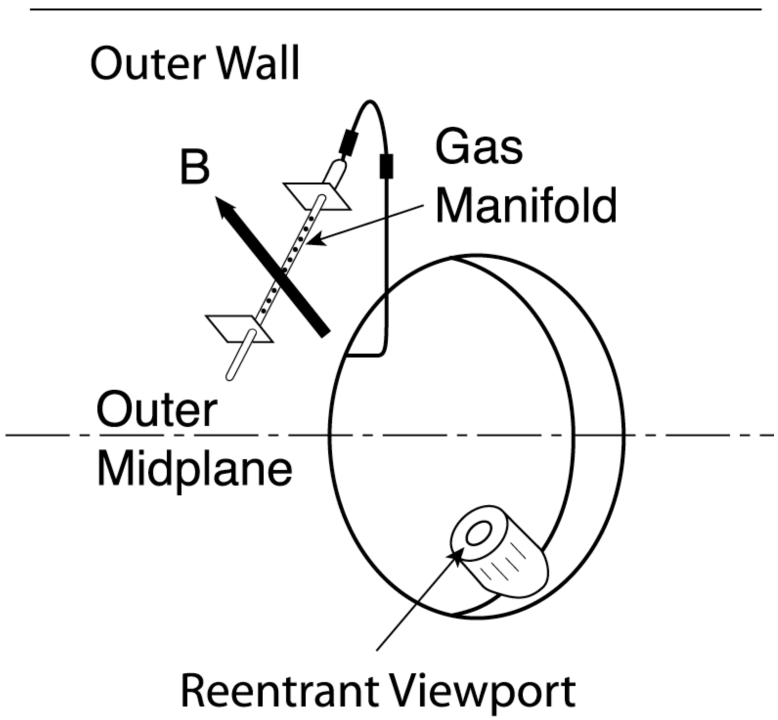
- Structures look ~ similar to model of Garcia et al (PRL '04)
- k_{pol} spectrum compared with NLET simulation (Hallatschek)

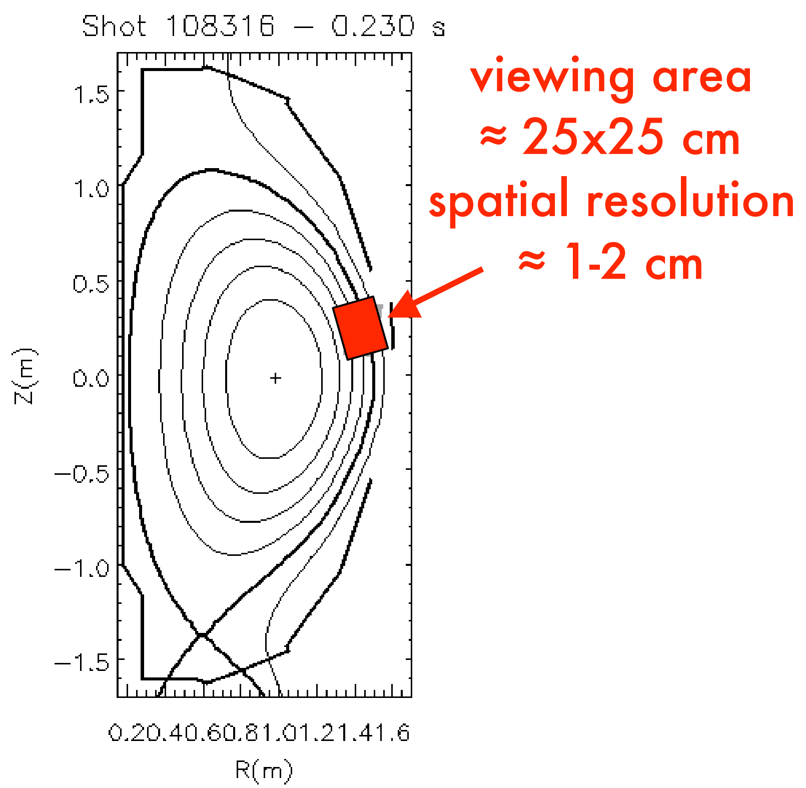


Terry et al, Phys. Plasmas '03

GPI Diagnostic in NSTX

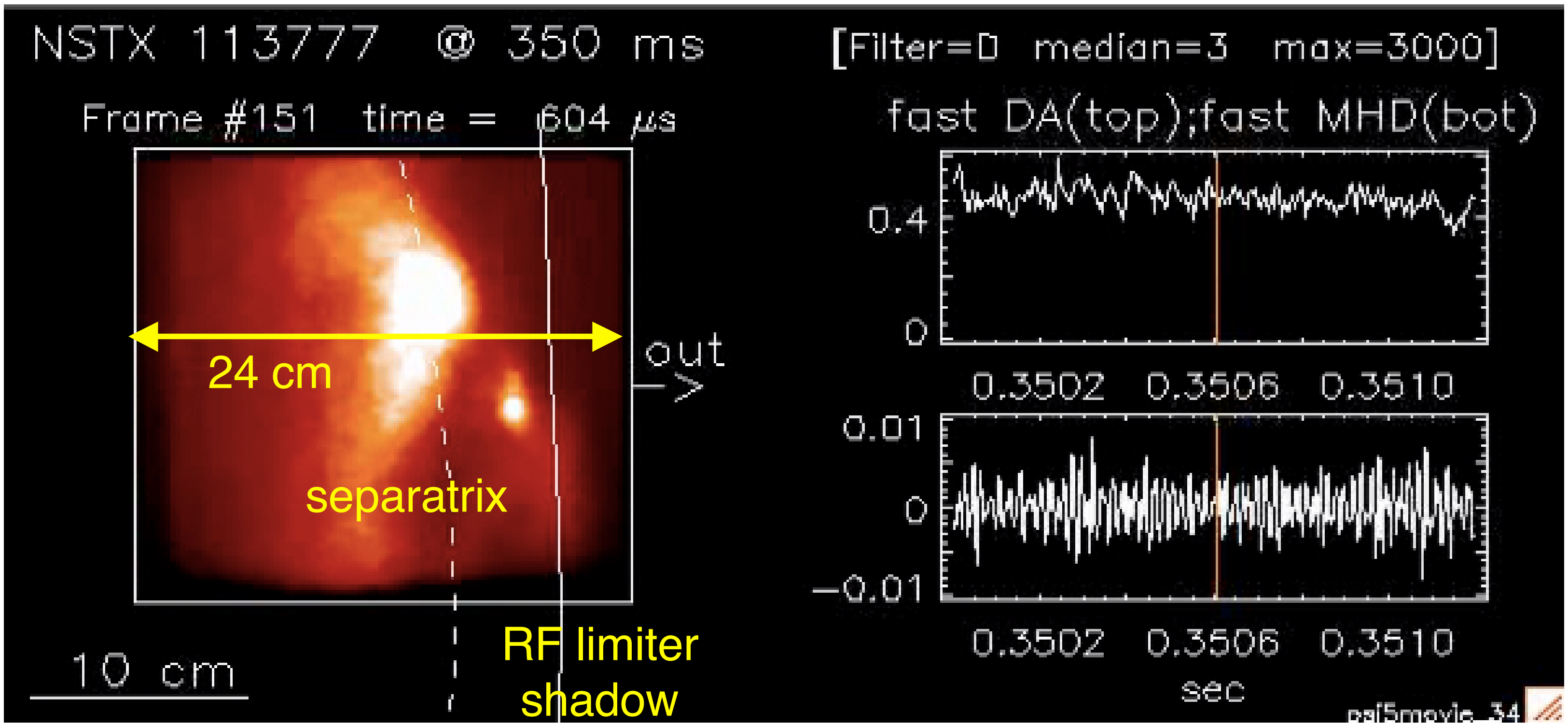
- Looks at D_α or HeI light from gas puff $I \propto n_o n_e f(n_e,T_e)$
- View ≈ along B field line to see 2-D structure ⊥ B
- Image coupled to camera with 800 x 1000 fiber bundle





GPI Data for NSTX '04 Run

- Exactly the same PSI-5 camera as used for C-Mod



see: http://www.pppl.gov/~szweben/NSTX04/NSTX_04.html

Ohmic Cases

Ohmic Plasma

NSTX #113348

B=4.0 kG, I=800 kA

$\langle n \rangle = 2.4 \times 10^{13}$ cm^{-3}

250,000 frames/sec

L-Mode Cases

NBI L-mode

NSTX #113830

B=3.0 kG, I=650 kA, 2.7 MW NBI

$\langle n \rangle = 3.3\times10^{13}\ \mathrm{cm}^{-3}$

250,000 frames/sec

H-Mode Cases

ELM-free H-mode

NSTX #113139

B=4.5 kG, I=825 kA, 0.9 MW NBI

250,000 frames/sec

Summary of NSTX Results

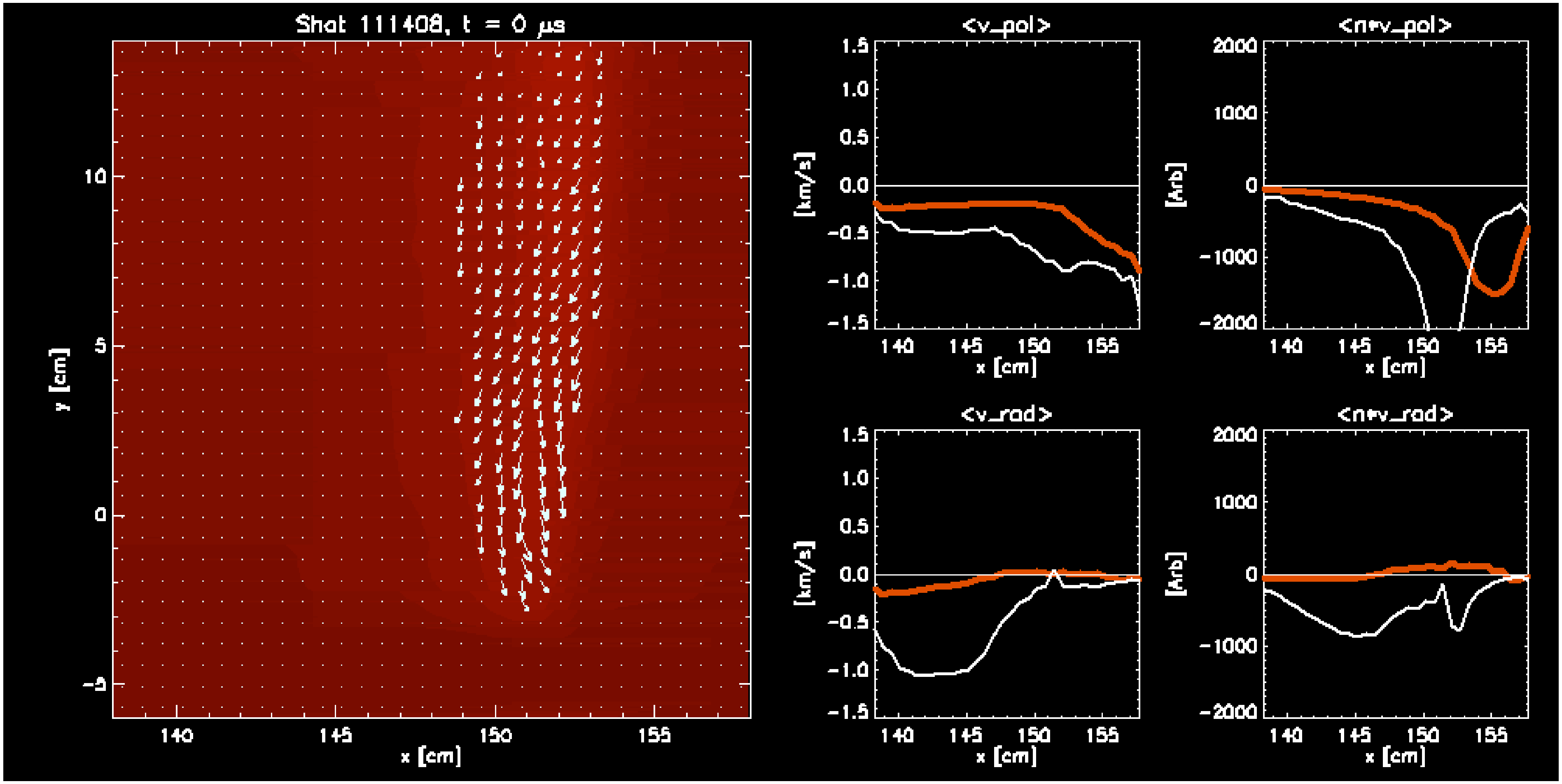
- Turbulence qualitatively similar in Ohmic and L-mode
  - size scale $\Delta_{pol} \approx 4$ cm, $\Delta_{rad} \approx 3$ cm
  - autocorrelation time $\tau \approx 30 - 70\ \mu$sec
  - light fluctuation level ≈ 20 - 80%
  - similar with LSN, USN, limited

- Edge plasma can be very quiescent during H-mode
  - quiet periods can last ≈ 10-100 msec
  - occasional “blobs” and coherent “waves”

- Frequency spectrum looks similar to Langmuir probe and edge reflectometer (at least, $f \leq 100$ kHz)

Zweben et al, Nucl. Fus. ‘04

Velocity Analysis in NSTX



Munsat

Questions for Image Analysis

- Are there patterns or structures in this turbulence ?
  - compare to blob theory & BOUT (e.g. Russell et al)
  - calculate statistical “mode-coupling” coefficients ?
  - try to match with simple dynamics (e.g. SOC, CA)

- Are there shear or zonal flows or radial streamers ?
  - calculate flow spectra from velocity maps
  - estimate vorticity, divergence, intermittency, etc.
  - compare with theory (e.g. Diamond, Hahm et al)

- Can turbulence be correlated with radial transport ?
  - roughly $D_\perp \sim \Delta^2/\tau \sim 10^5$ cm^2/sec $\sim D_{Bohm}$ ($> D_{nc}$?)
  - compare $\langle v_r \rangle_{turb}$ with $\langle v_r \rangle_{plasma} = \Gamma/n$
  - estimate $\Gamma = \langle n\, v_r \rangle$ directly from images ?

L-H Transition Cases

L-H Transition

NSTX #113079

B=4.4 kG, I=800 kA, 2.8 MW NBI

$\langle n \rangle = 1.9 \times 10^{13}\ cm^{-3}$

250,000 frames/sec

Just Before L-H Transition

1 msec Before L-H Transition

NSTX #113735

B=3.0 kG, I=790 kA, 4.4 MW NBI

$\langle n \rangle = 2.3 \times 10^{13}$ cm^{-3}

250,000 frames/sec

H-L Transition Cases

Dithering H-L Transition

NSTX #113062

B=4.4 kG, I=780 kA, 2.6 MW NBI

$\langle n \rangle = 2.1\times10^{13}$ cm^{-3}

100,000 frames/sec

ELMs

Medium ELM

NSTX #113835

B=3.0 kG, I=650 kA, 1.7 MW NBI

$\langle n \rangle = 3.2 \times 10^{13}$ cm^{-3}

250,000 frames/sec

Observations on L-H Transition

- L-H transitions look like a continuous evolution from turbulent blobs to a quiescent state in ≤ 0.1 ms, apparently without new spatial features or flows

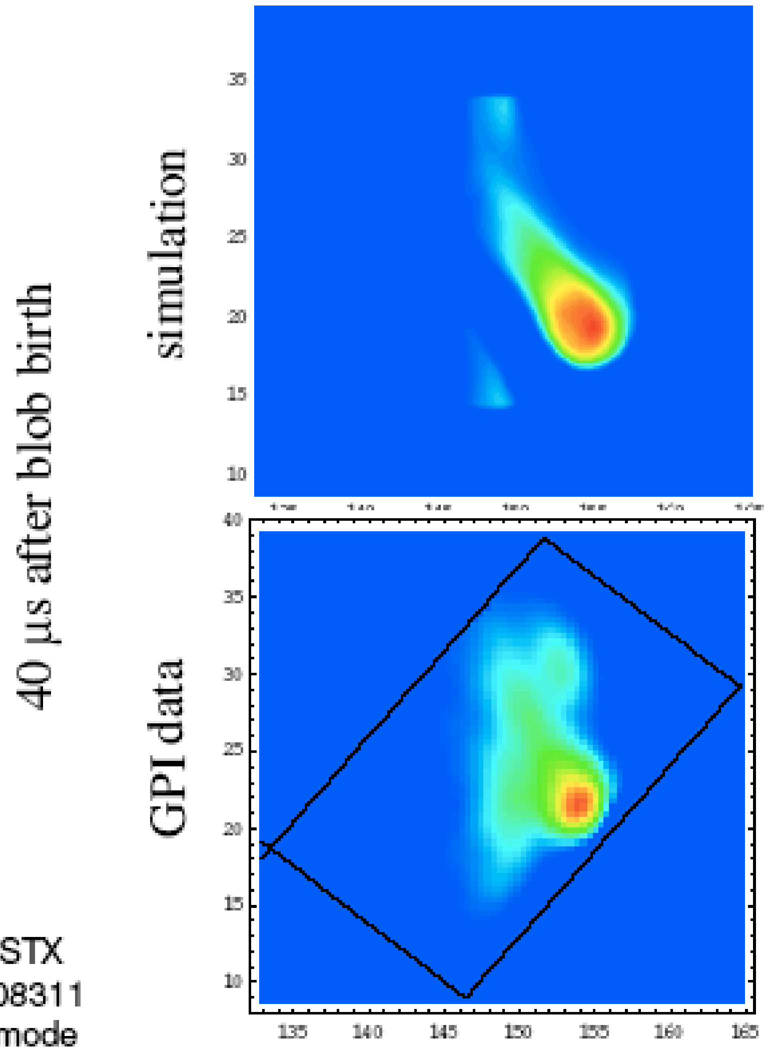
- H-L transitions generally appear as high-n poloidal modes which evolve into radially moving blobs

- Transient periods of H-like quiescence occur ≤10 msec before the main L-H transition

Questions on L-H Transition

- Is there an increase in poloidal flows (shear or zonal) just before the L-H transition (as in theory) ?
- How much does the turbulence “dither” from L- to H-type as a function of time before the main L-H transition ?
- Is there a consistent instability pattern leading from H-L ?
- How do the transitions seen in GPI compare with those in the reflectometer, Firetip and probe diagnostics ?

Comparisons with Theory

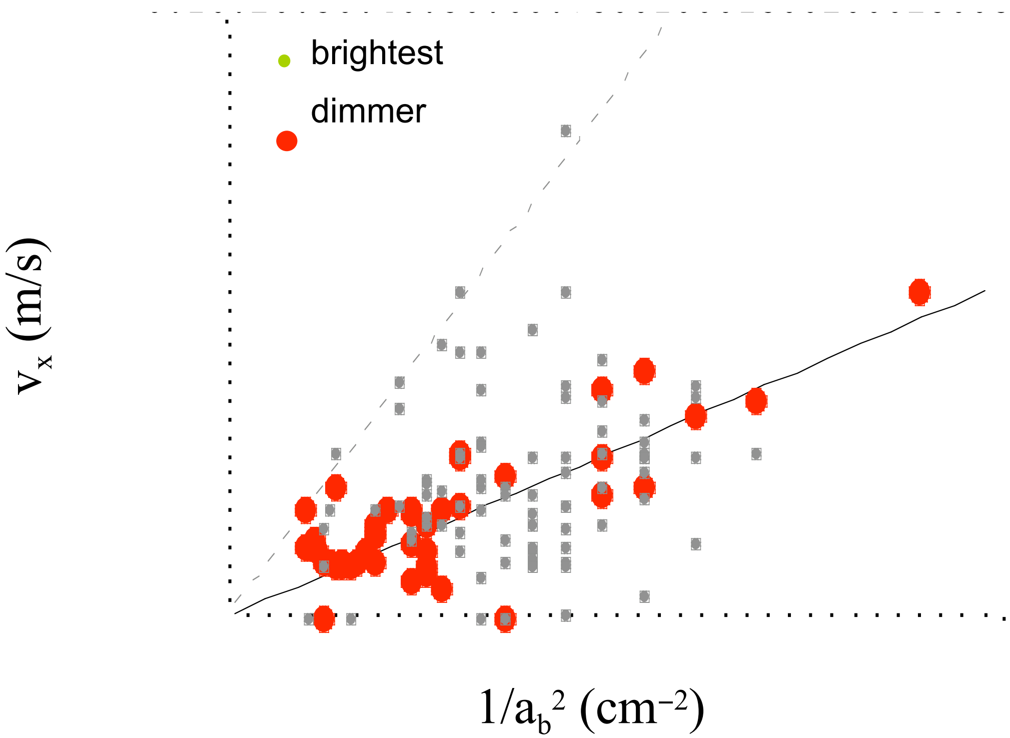


NSTX
#108311
H mode

- simulations of blob dynamics, emission patterns [2D fluid code + DEGAS-2 (Stotler)] reproduce dynamical features
  - convective velocity & wake
- passive convection assumption also allows inverse mapping: n_e, $T_e \leftarrow I$
  - blobs born at region of max γ_{linear}

(Myra, D'Ippolito, Russell)

Blob database allows comparison of convective velocity with theory



Expt. Analysis: wavelet & feature tracking defines blobs
Theory: delineates several blob regimes & scalings, e.g. sheath-connected regime:

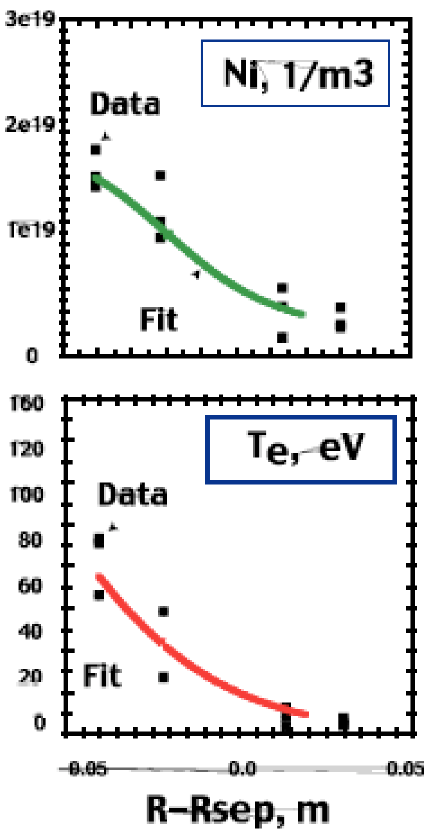
$$v_x \sim \frac{qT_e^{3/2}}{a_b^{\,2}B^2}$$

NSTX shot
#112825

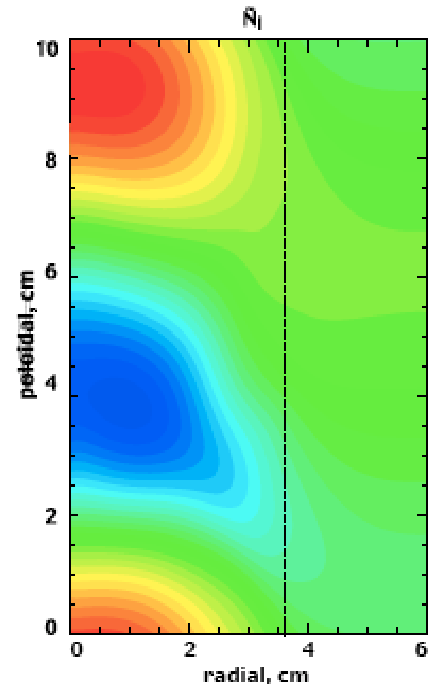
Lodestar Research Corp.

BOUT Simulations are in Progress

Modeling of NSTX presents a challange to BOUT due to the relatively weak B field (=> numerical difficulties)



- δN_i at the level ~10%
- δT_{ei} at the level a few eV
- $\delta\phi$ at the level ~10 V
- Spatial scale ~ 2 cm
- Frequency f ~ 1e5 s^{-1}



Umansky

Summary

- 2-D Imaging data looks interesting
  - similar to usual edge turbulence
  - but some new features seen in 2-D
  - need to compare with other diagnostics
- Considerable analysis is needed to:
  - quantify what we see in images
  - relate it to edge turbulence modeling
  - test modeling with dedicated experiments