Structure and Motion of Edge Turbulence in NSTX and Alcator C-Mod

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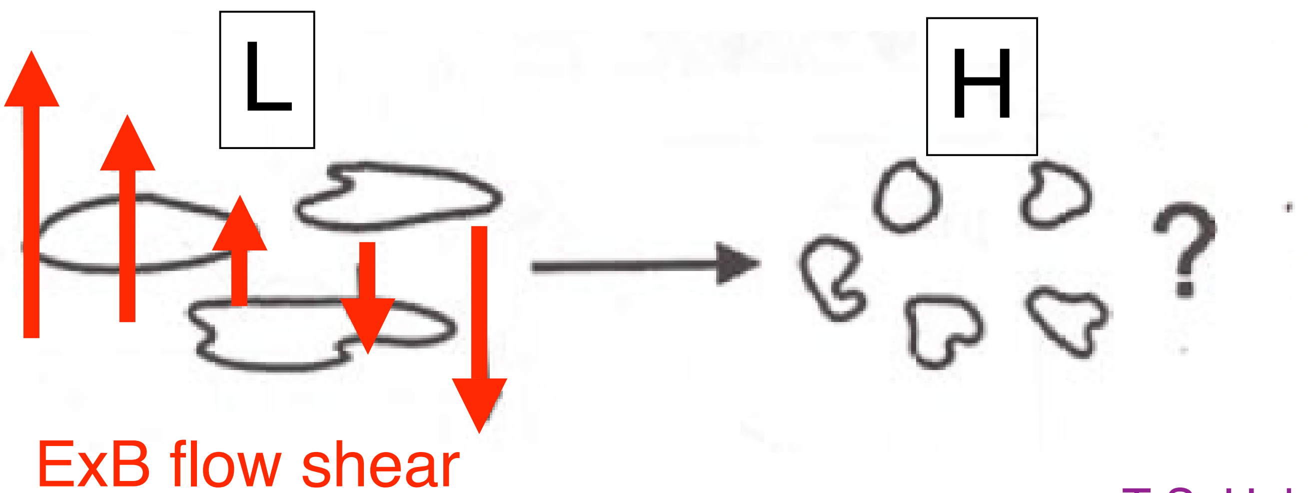
NSTX

JET 12/08/05

Alcator C-Mod

Motivations

- Edge turbulence affects location of plasma-wall interaction
- Edge turbulence influences global tokamak confinement
- Cause of L-H transition is not yet completely understood

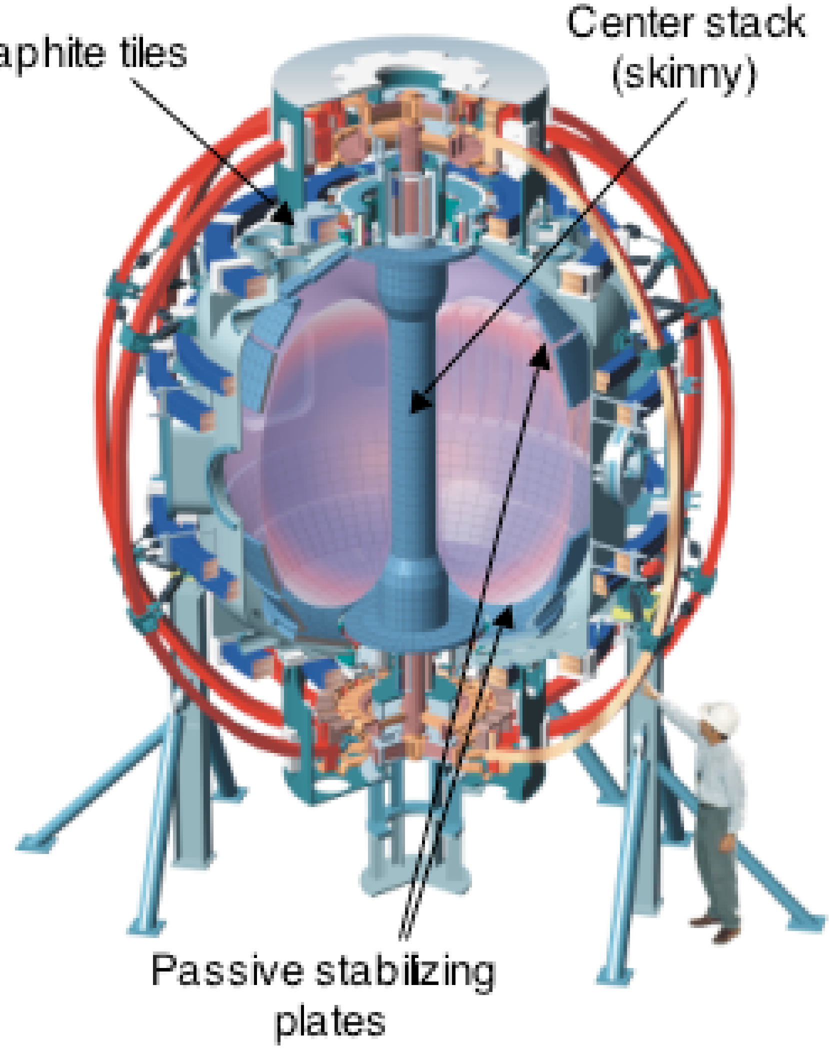


T.S. Hahm

Outline

- Gas puff imaging diagnostic
- NSTX GPI images (L, L-H and H)
- Analysis of Structure and Motion
- Comparison with Alcator C-Mod
- Initial comparisons with theory
- Open questions and directions

National Spherical Torus Exp't (NSTX)



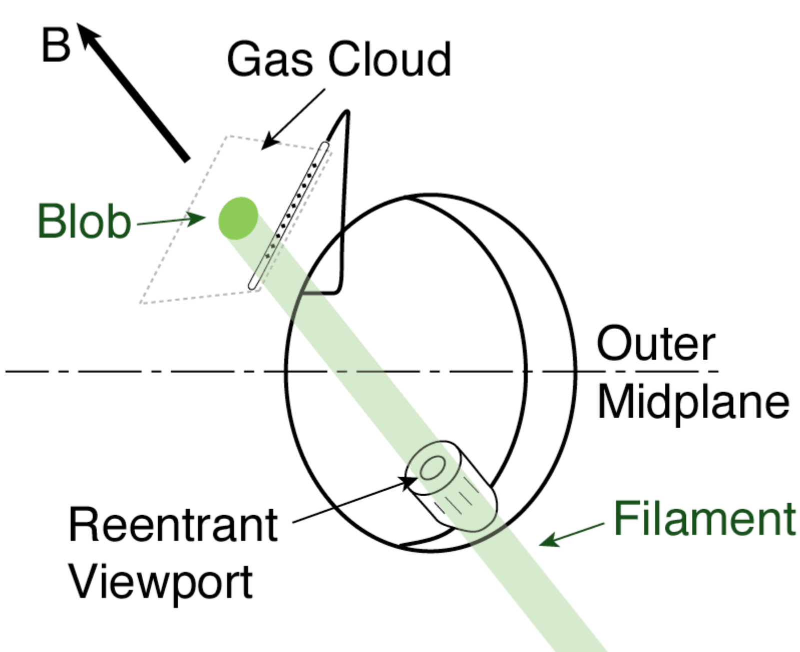
typical parameters for this talk

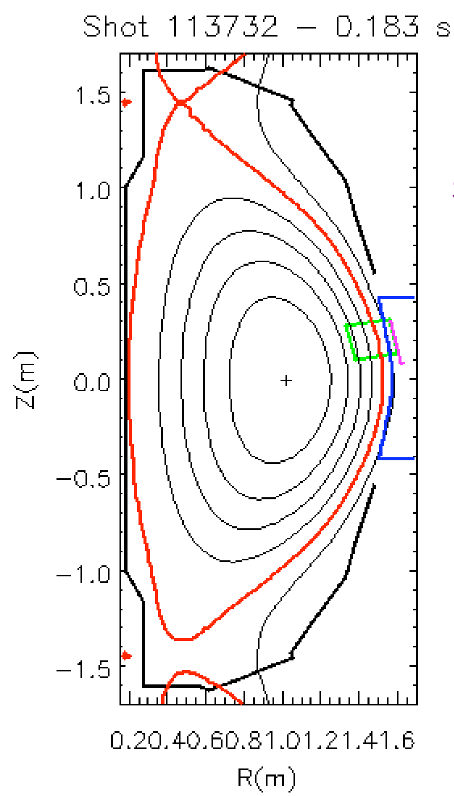
$R = 0.85$ m
$a = 0.68$ m
$B = 0.3$ T
$I \approx 0.8$ MA
$P_{NBI} \approx 2\text{-}4$ MW
$\beta_T \approx 10\%$

Gas Puff Imaging (GPI) Diagnostic

- Looks at D_α line of neutral deuterium from a gas puff
- View ≈ along B field line to see 2-D structure ⊥ B

view from center column

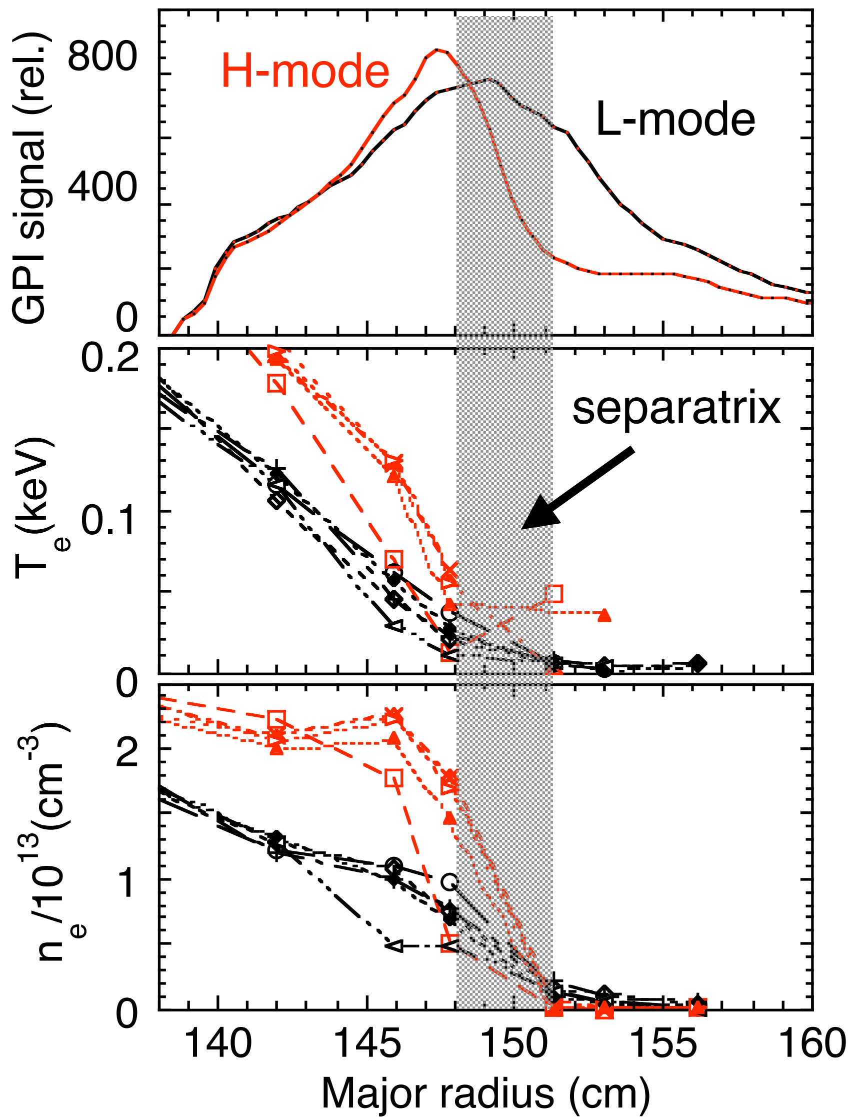




viewing area
≈ 25x25 cm
spatial resolution
≈ 1-2 cm

see: R.J. Maqueda et al, Rev. Sci. Inst. 2003

Location of GPI Light Emission



- D is unexcited @ $T_e < 5$ eV
- D is ionized @$T_e > 100$ eV

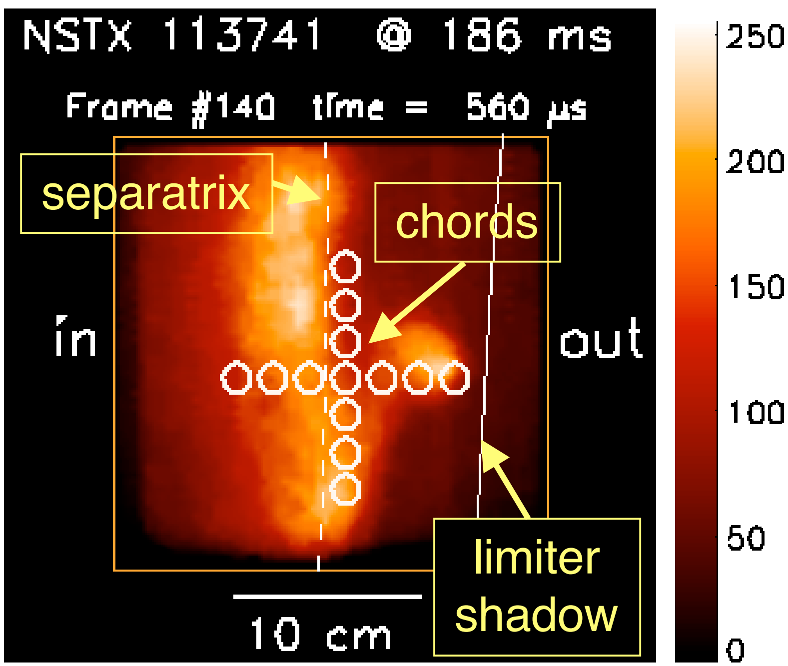
NSTX Edge Parameters

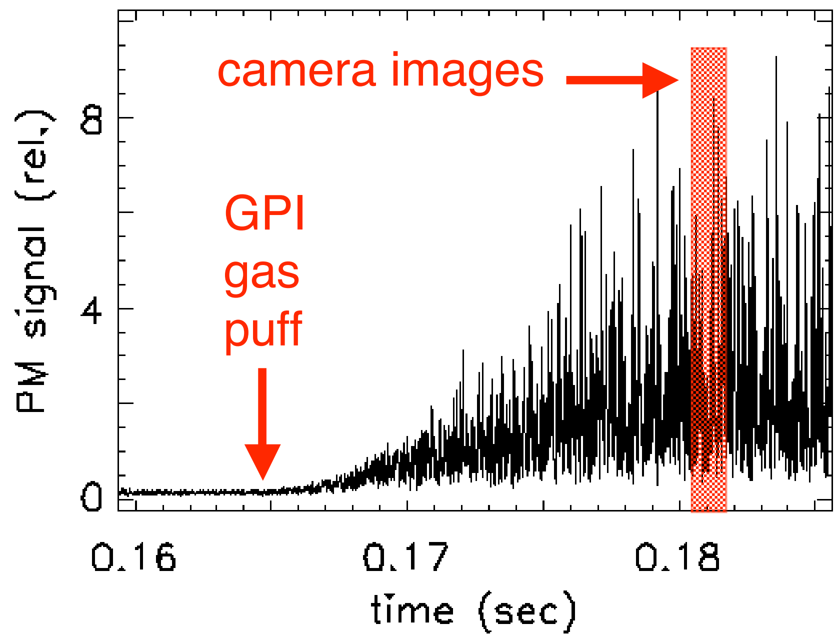
n ~ 0.2-2 $\times 10^{13}$ cm^{-3}
T_e ~ 5-50 eV
$L_\perp$ ~ 2-5 cm
$L_{||}$ ~ 5 m
ρ_s ~ 0.2 cm
β_e ~ 10^{-3}

~ similar to many tokamak edge plasmas

GPI Fluctuation Data in NSTX

- PSI-5 camera records 300 frames at ≤ 250,000 frames/sec with 64x64 pixels / frame => 1.2 msec of data per shot
- Additional PM tube array digitized radial vs. poloidal array at 500,000 Hz => 64 msec of data per shot





Interpretation of GPI Fluctuations

- Line emission signal levels $\propto n_e^{\alpha} T_e^{\beta}$ with $0.5 < \alpha, \beta < 2$, so measured signals are nonlinear functions of n and T_e [see Stotler et al, Cont. Plasma Phys. **44**, 294, 2004]

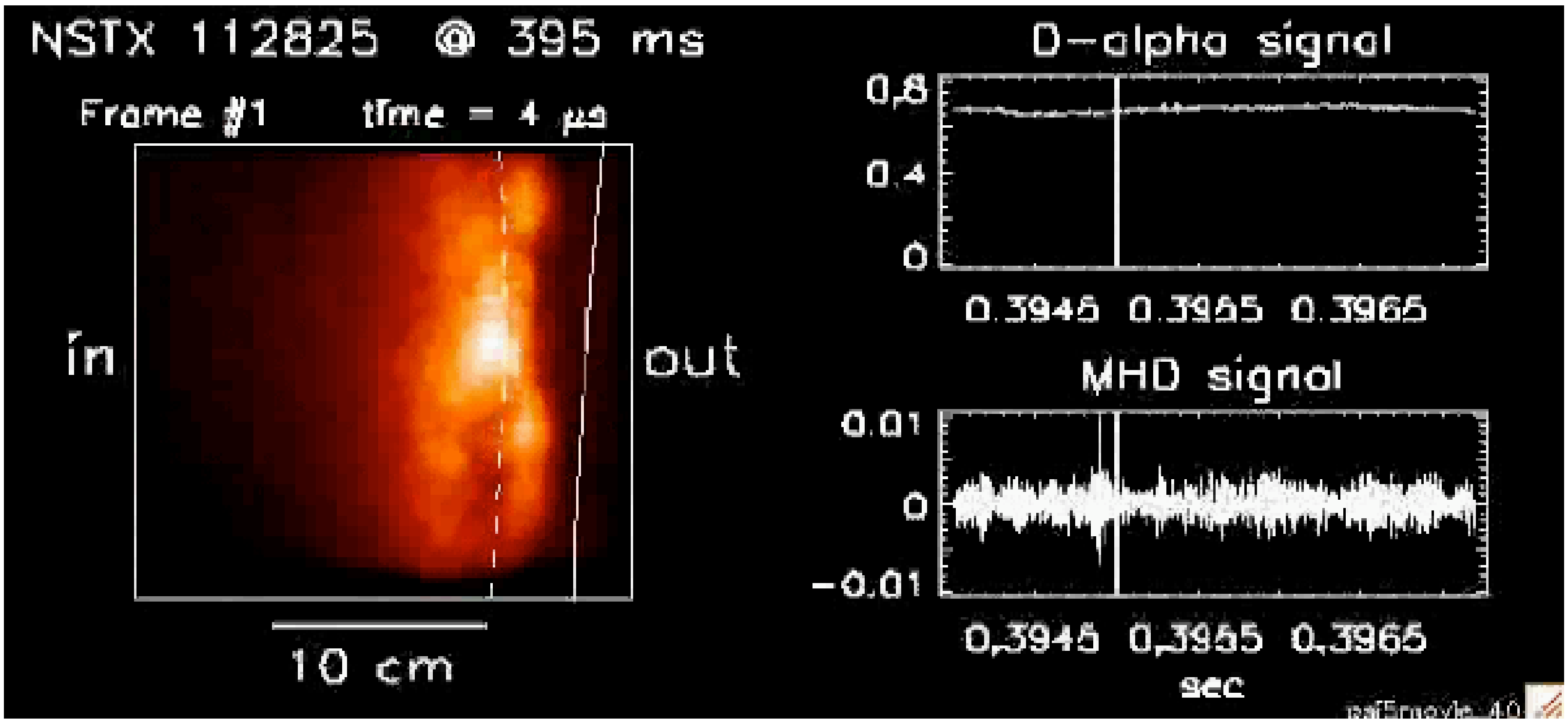
- However, turbulence structure and motion are approximately independent of these nonlinearities and also nonlinearity in camera intensifier (nonlinearity acts like “contrast knob”) [see S.J. Zweben et al, Nucl. Fusion **44**, 134, 2004]

=> *Assume that structure and motion of GPI light fluctuations represents structure and motion of the turbulence (not necessarily the same as the fluid motion)*

- Gas puff imaging diagnostic
- **NSTX GPI images (L, L-H and H)**
- Analysis of Structure and Motion
- Comparison with C-Mod
- Comparisons with theory

Images During L-mode

- color scale the same for all images in each shot



movies at: http://www.pppl.gov/~szweben/

Images During L-H Transition

L-H Transition

NSTX #113732

B=3.0 kG, I=780 kA, 2.0 MW NBI

$\langle n \rangle = 2.2 \times 10^{13}$ cm^{-3}

250,000 frames/sec

Images During H-Mode

H-mode

NSTX #113745

B=3.0 kG, I=810 kA, 4.0 MW NBI

$\langle n \rangle = 2.7 \times 10^{13}$ cm^{-3}

250,000 frames/sec

Analysis of Structure and Motion

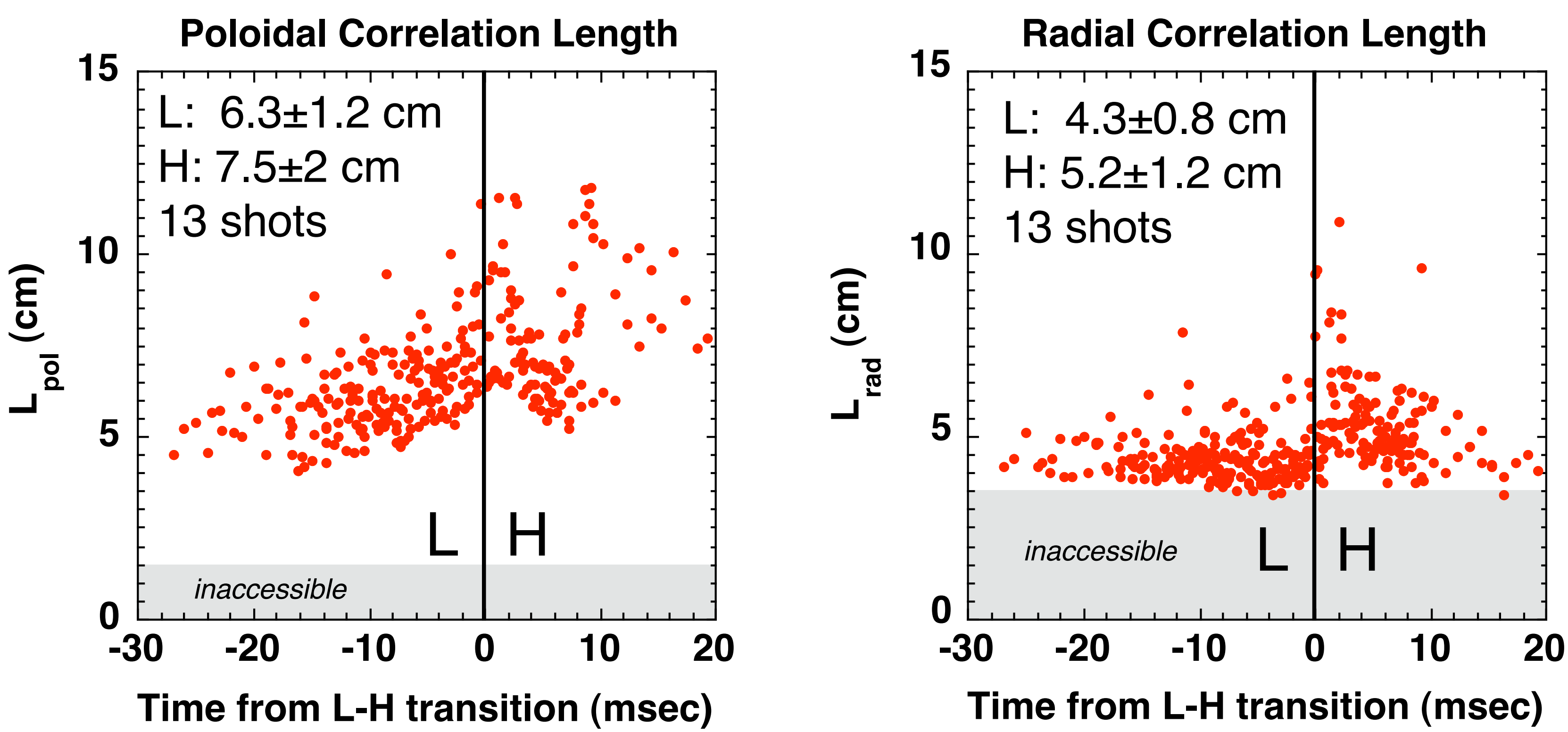
- Use simplest analysis via 2-point cross-correlation function of fluctuations in GPI light signals vs. space and time:

$$C(\Delta x, \Delta t) = \sum_{t} \tilde{S}_0(t)\, \tilde{S}_{\Delta x}(t+\Delta t)$$

- Correlation length from FWHM of $C(\Delta x, 0)$ [$\approx 1.6 \times \sigma_{Gaussian}$]
- Velocity from time the delay of the peak in $C(\Delta x, \Delta t)$ vs. Δx
- $C(\Delta x, \Delta t)$ averages over space and time spectrum of signals

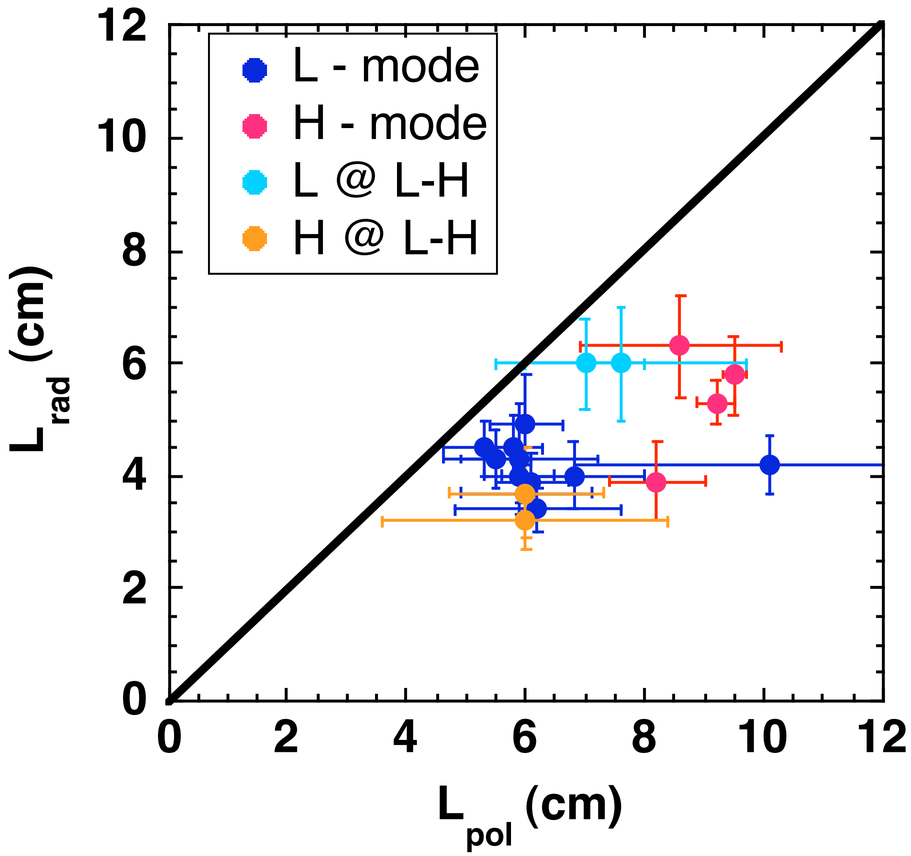
2-D Structure from Chords

- No significant changes from L- to H-mode (13 shots)
- Maybe some increase in L_{pol} over ~ 30 msec before L-H



2-D Structure from Images

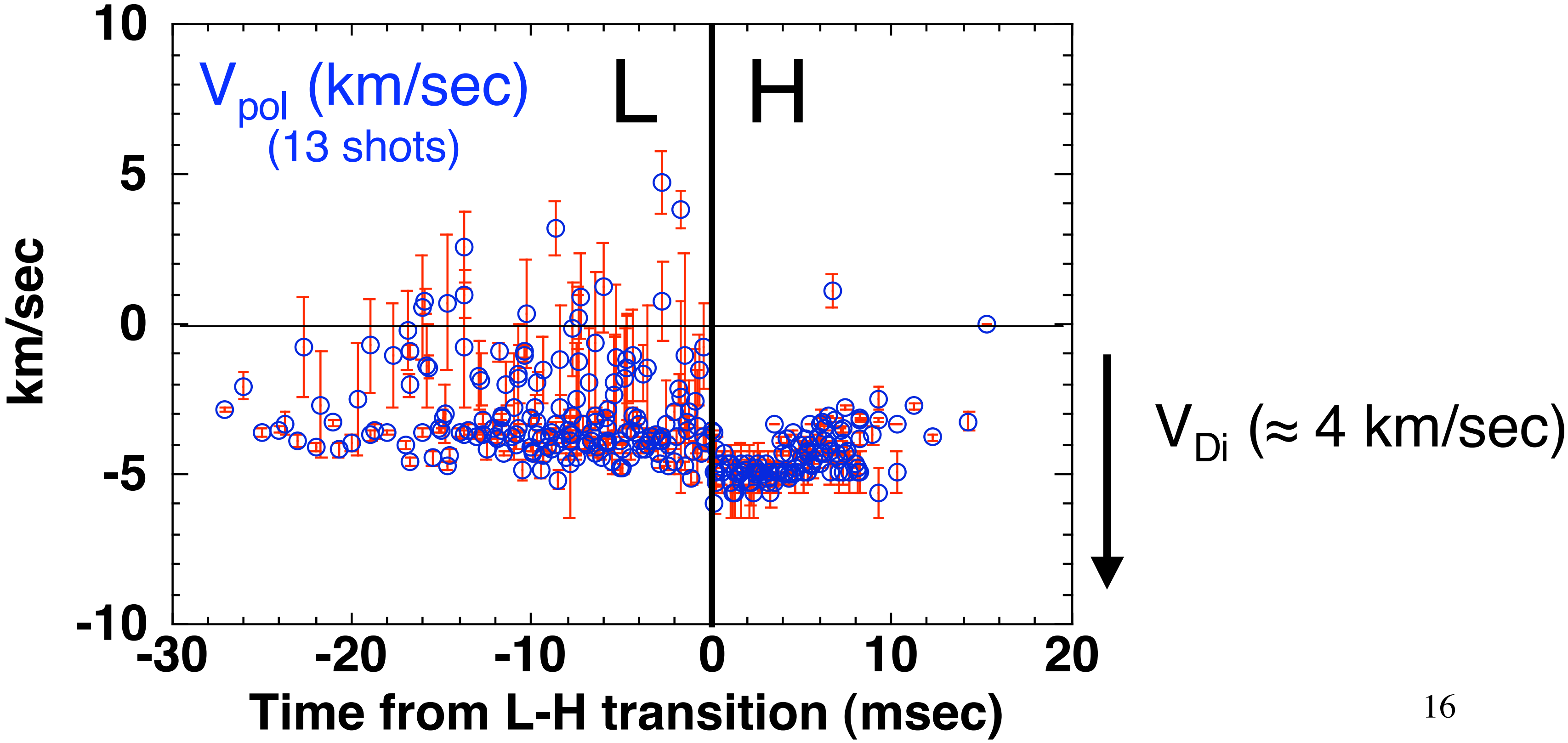
- Evaluated near radial peak of GPI signal ~ separatrix
- No statistically significant changes from L- to H-mode



	L_{rad} (cm)	L_{pol} / L_{rad}
L	4.2±0.4	1.5±0.4
H	5.3±1.0	1.9±0.4

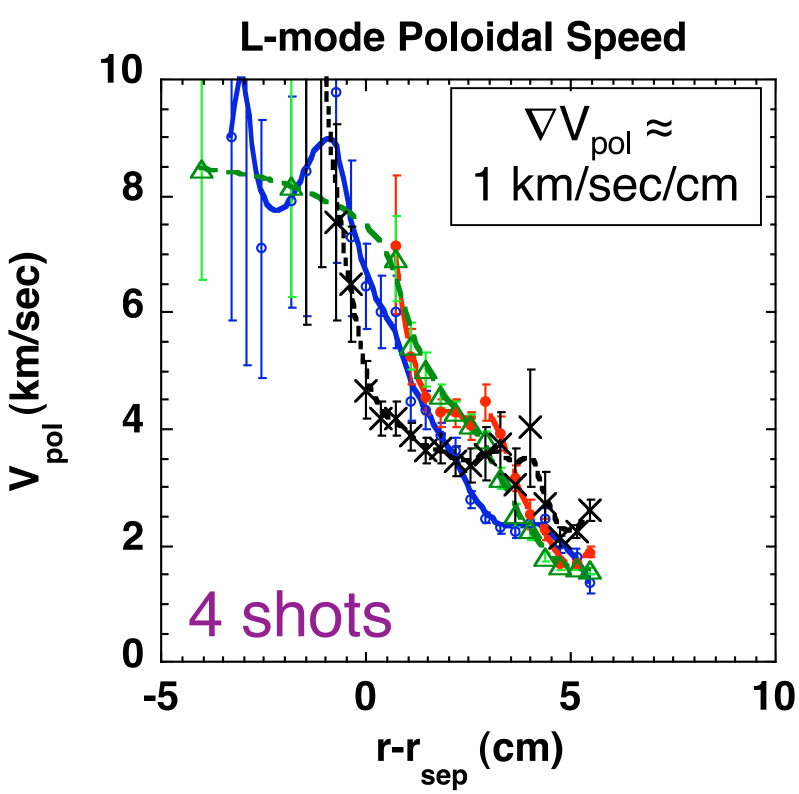
Poloidal Motion from Chords

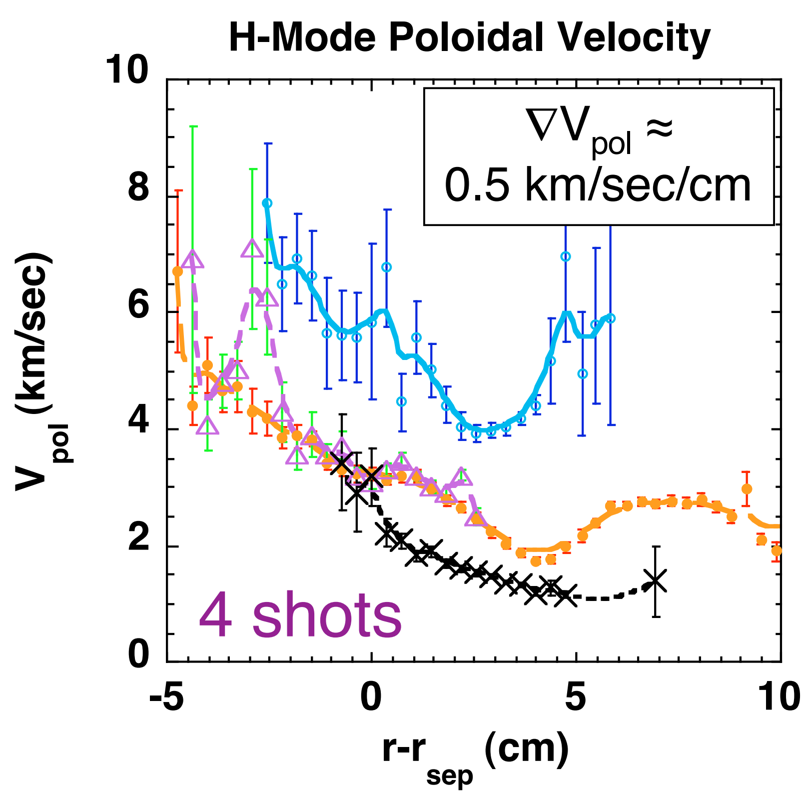
- Poloidal motion generally in ion diamagnetic drift direction
- Poloidal flow more “frozen” in H-mode than L-mode (ρ ~ 0)



Poloidal Motion from Images

- Average flow is generally in ion diamagnetic drift direction
- V_{pol} gradient tend to be lower for H-mode than L-mode





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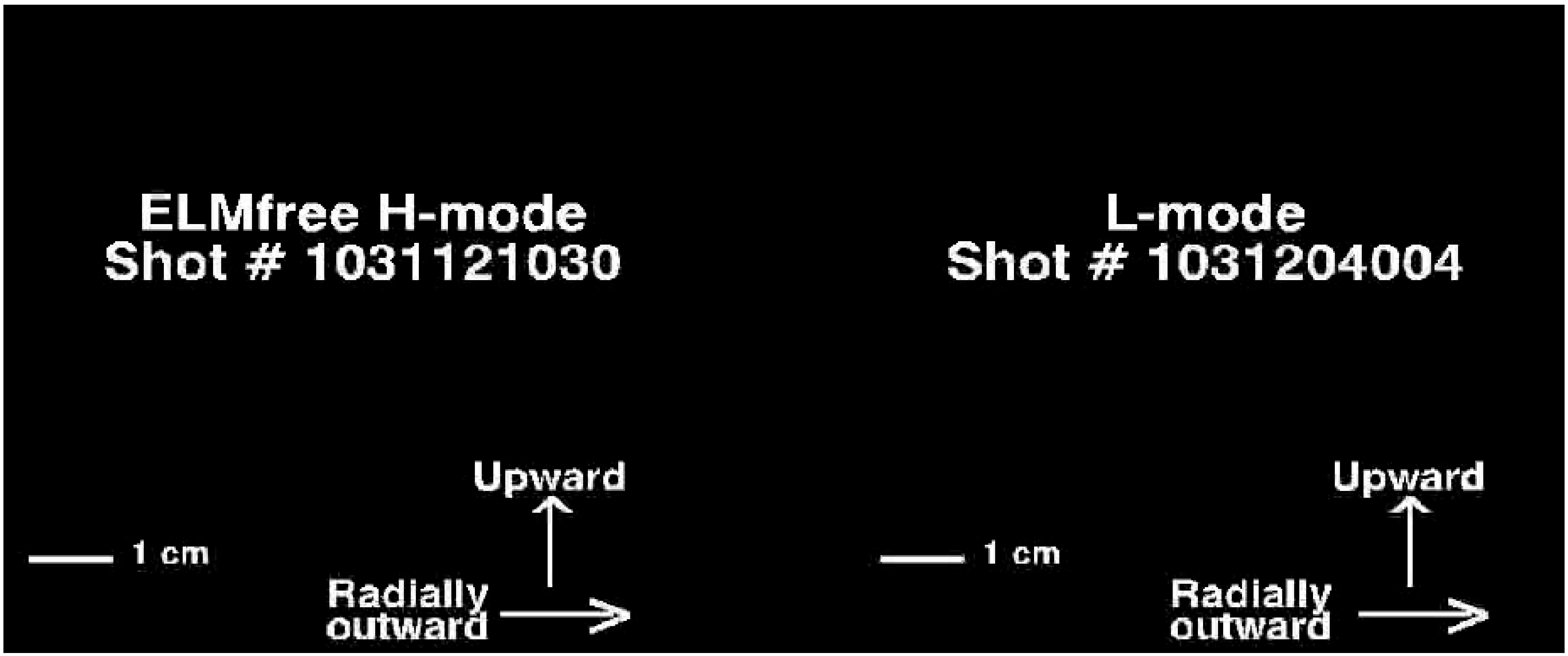
Images from Alcator C-Mod

H-mode

L-mode



Terry et al, J. Nucl. Mater. ‘04

NSTX vs. C-Mod (L-Mode)

	NSTX *	Alcator C-Mod**
B_{edge}	2-3 kG	40 kG
n_{edge}	0.2-2x10^{19} cm^{-3}	2-20x10^{19} cm^{-3}
$T_{e,edge}$	5-50 eV	20-80 eV
L_{pol}	5-9 cm	0.6-1.0 cm
L_{rad}	2-6 cm	0.7-1.5 cm
V_{pol}	≤ 5 km/sec	≤ 1 km/sec
V_{rad}	≤ 1-2 km/sec	≤ 1.5 km/sec

* S.J. Zweben et al, Nucl. Fusion 44, p. 134 (2004)

** J.L. Terry et al, submitted to Fusion Science and Technology (2005)

- Gas puff imaging diagnostic
- NSTX GPI images (L, L-H and H)
- Analysis of Structure and Motion
- Comparison with C-Mod
- Initial comparisons with theory
    - L-H transition
    - blob model
    - NLET model
    - ESEL model

Comparison with L-H Transition Model

- Transition doesn't look like standard ExB flow shear picture
  - little or no decrease in radial correlation length
  - little or no increase in poloidal shear flow

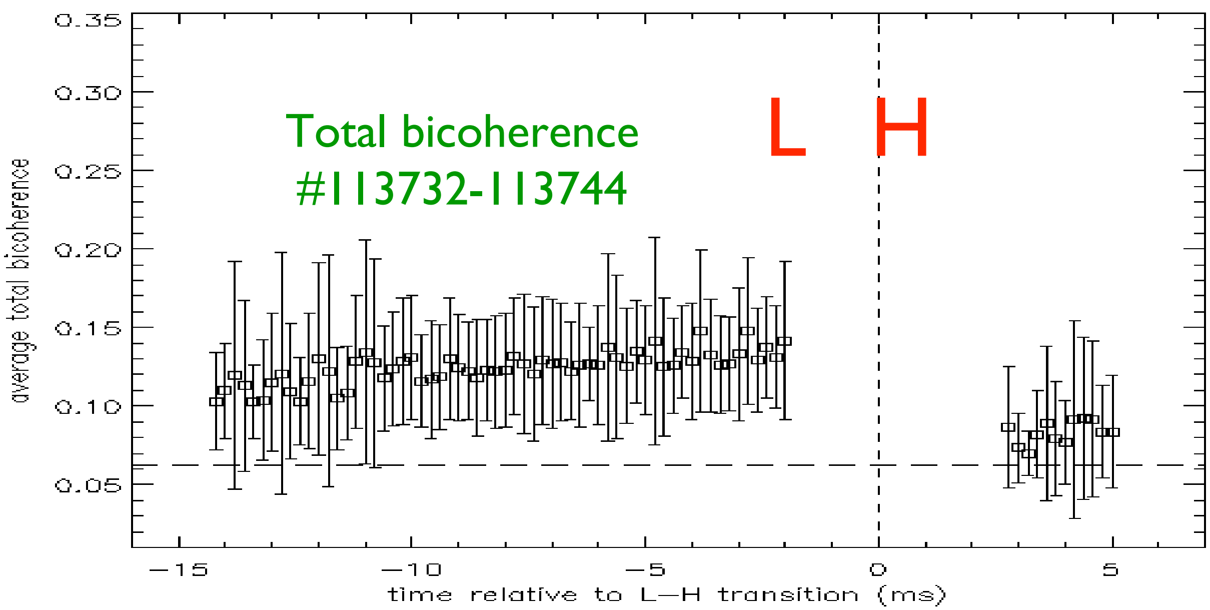
- Yet flow shear is near the usual stabilization criterion for L-H
  - $\nabla V_{pol}(L_{rad}/L_{pol}) \approx$ 30-40 kHz $\approx 1/\tau_{auto}$

Caveats:

- region causing transition may be outside GPI view
- poloidal velocities averaged over ~ 1 msec
- no actual simulation of L-H transition
- relatively small data set

Bichoherence at L-H Transition

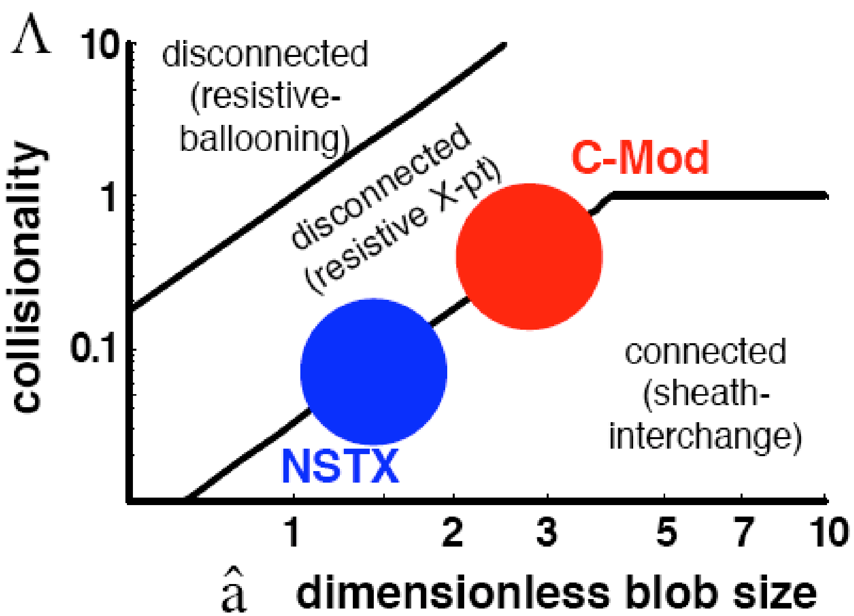
- An increase in total bicoherence, suggesting an increase in coupling between low frequency flows and high frequency turbulence, was seen at L-H transition DIII-D (Moyer 2001)
- The same analysis was applied to NSTX chord data, but no significant increase in bicoherence was observed at L-H.



Anne White (UCLA)
APS DPP '05

Comparison with "Blob" Model

- Model for dynamics of isolated density structures in SOL
- Various regimes depending on blob size and collisionality



theoretical bounds on blob radial velocity

$$\frac{1}{\hat{a}^2} < \frac{v_x}{v_0} < \hat{a}^{1/2}$$

sheath

resistive bal.

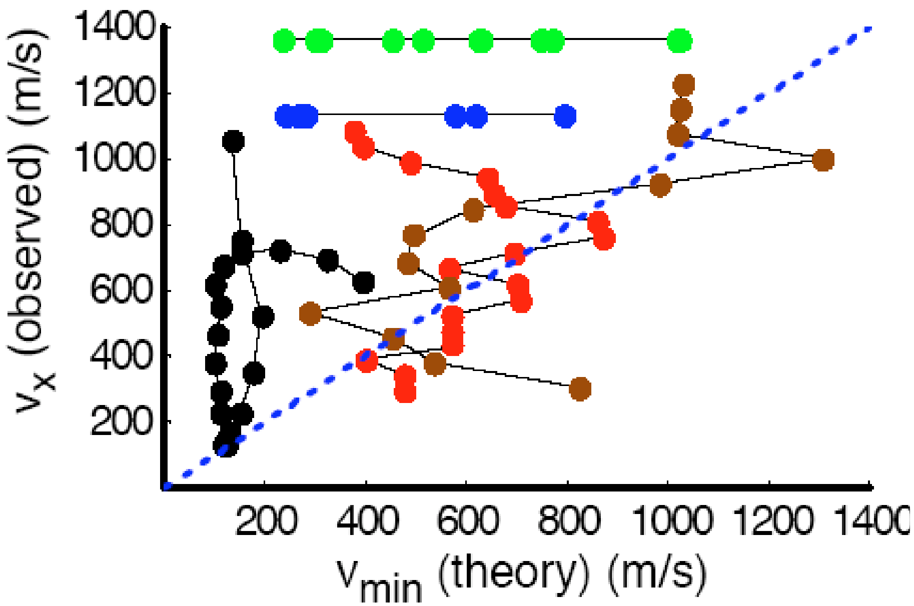
Jim Myra et al, APS DPP '05

Lodestar

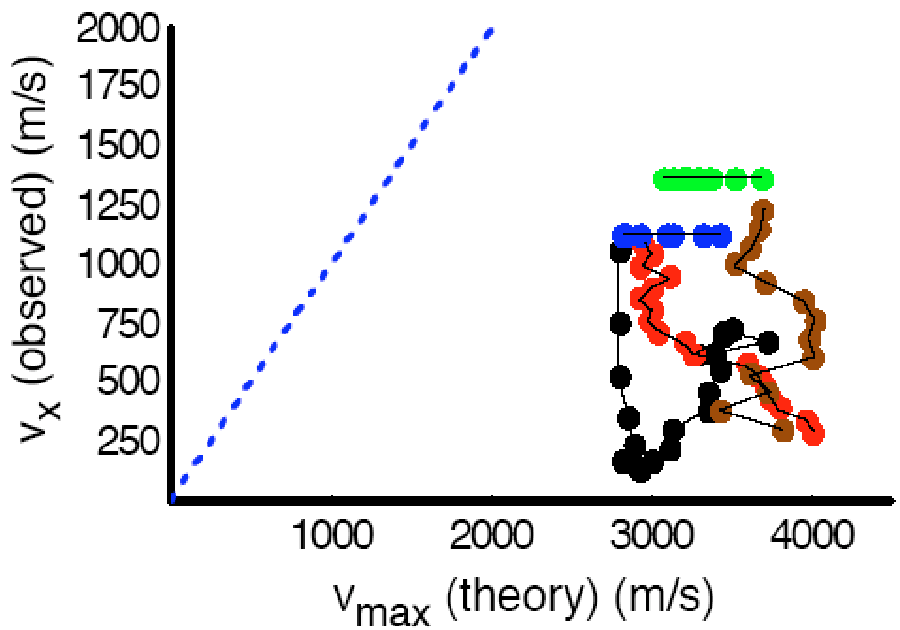
Comparison with NSTX Data

- Measure radial blob speed vs. time for one typical NSTX shot
- Compare with theory using some assumptions (Myra APS '05)

sheath-connected regime

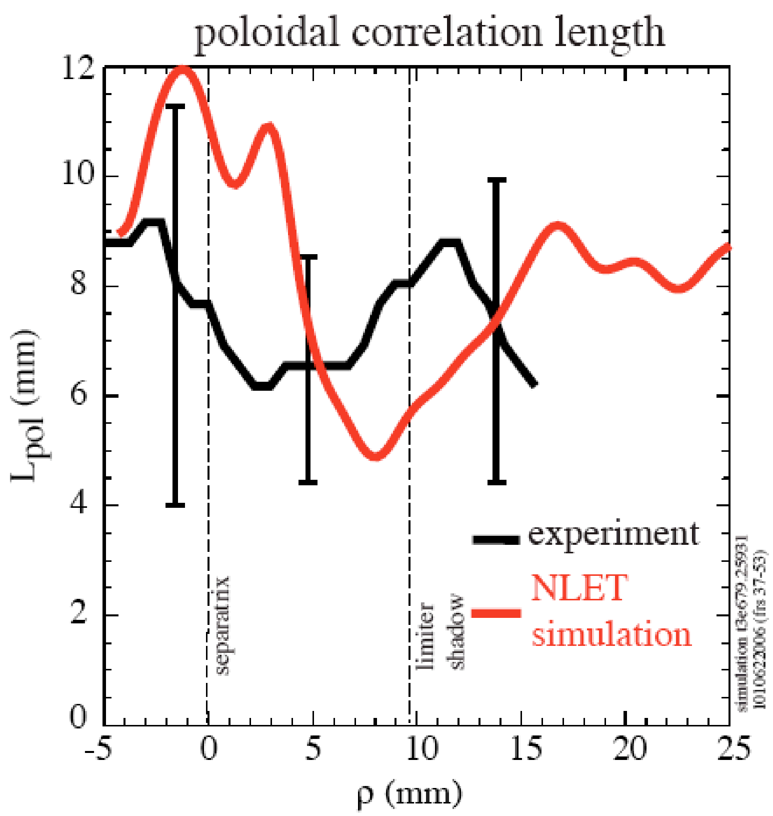


resistive ballooning regime



NLET (nonlinear EM turbulence) Model

- Klaus Hallatschek compared his 3D NLET code (an offshoot of Maryland's DBM model) with C-Mod L-mode data

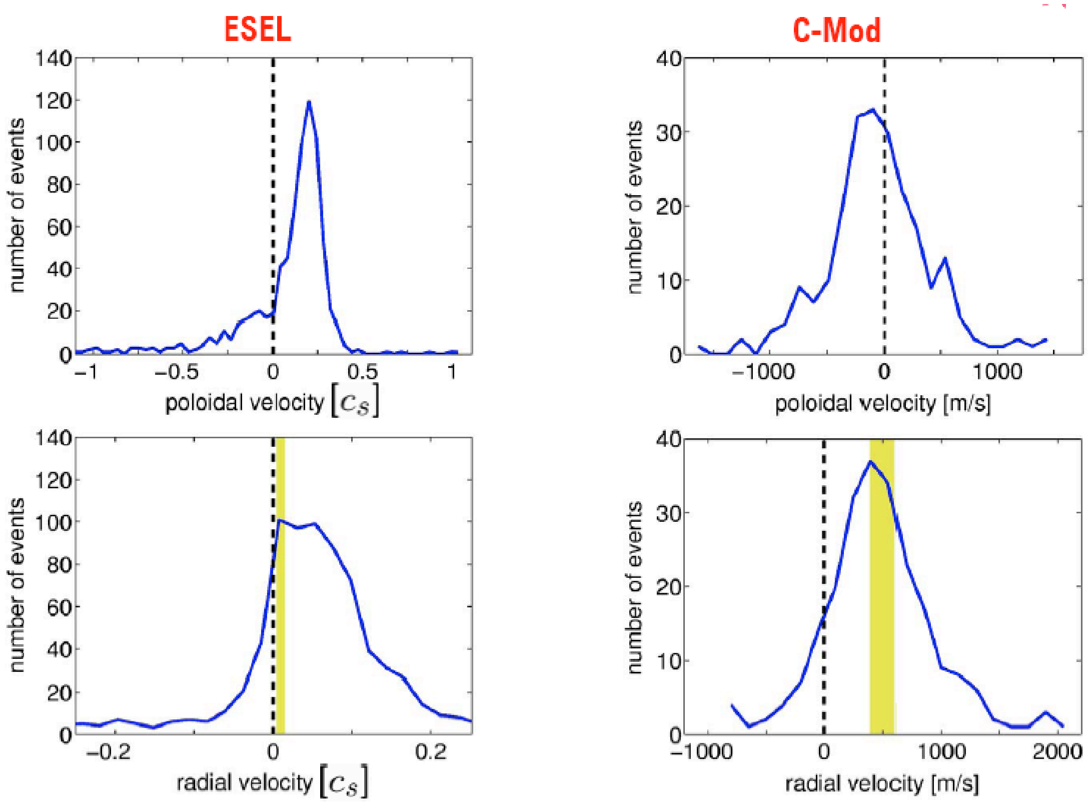


- L_{pol} agreed fairly well
- Γ_n agrees to within ~ x2
- τ_{auto} x2 too small in code

Jim Terry et al, Phys. Plasmas 10, 1739 (2003)

ESEL (edge SOL ES turbulence) Model

- Olaf Grulke compared the 2D interchange model of Garcia and Naulin (Phys. Plasmas 12, 2005) to blob speed distributions in C-Mod L-mode plasmas



- track blob motion with same method in C-Mod and code
- radial blob speed is higher in code by x5
- further analysis in progress

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Some Open Physics Questions

- What is the minimal physics needed to explain L-mode edge turbulence ? (2D or 3D ? ES or EM ? fluid or kinetic ? local or nonlocal ? radiation/neutrals ?)
- Do zonal flows affect L-mode edge turbulence ?
- What causes the H-mode ?
- What forms blobs ?
- Can edge/SOL transport be predicted for ITER ?
- How can edge turbulent transport be controlled ?

Some Experimental Directions

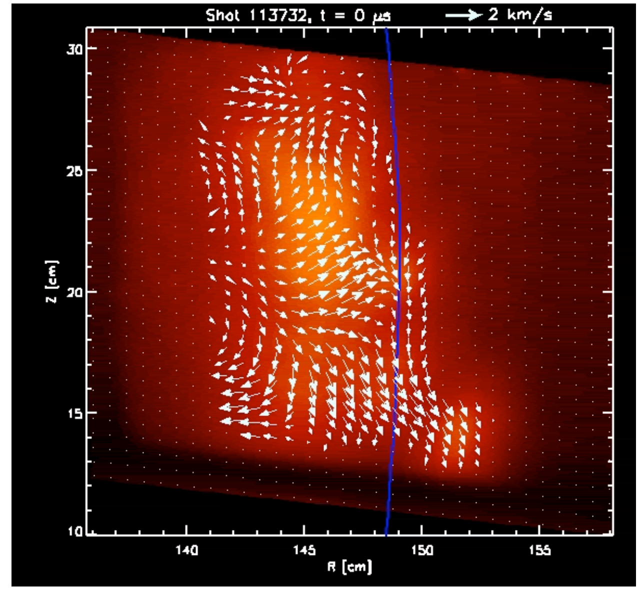
- Analyze higher-order spatial structure

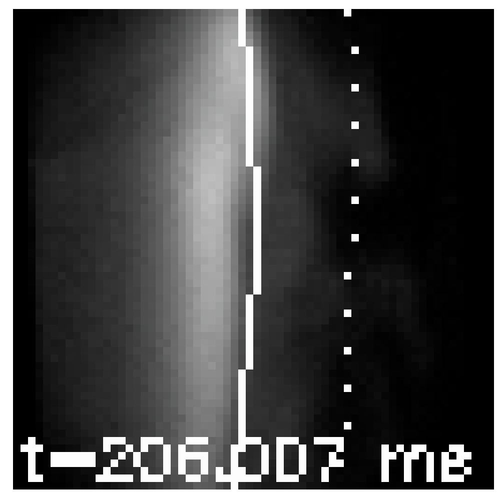
- Analyze 2-D velocity fields vs. time
  - optical flow (Munsat APS '05)
  - PCA (Stoltzfus-Dueck APS '05)

- Try imaging at other locations
  (X-point, inner wall, core ?)

- Acquire image data for longer times
  to see L-H and ELMs better

- Compare results on different devices
  (TJ-II stellarator, JET, LAPD, etc)





Some Theoretical Directions ?

(Apparently a large code will be needed to explain this data)

- Use 3D codes such as BOUT (Xu, Umanksy) and GEM (Scott) to simulate NSTX and/or Alcator C-Mod

- Understand physics of code results with analytic models

- Develop more comprehensive edge codes (NYU, LLNL)

=> verify and validate codes with present data
=> use codes to develop possible control methods
=> test these control methods in existing machines
=> control L-H transition and SOL transport in ITER