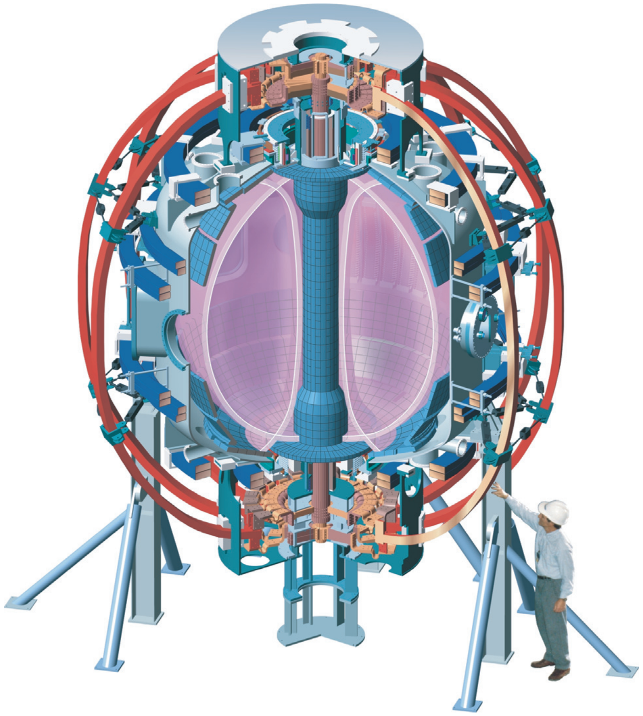
NSTX and DIII–D Boundary Particle and Energy Transport

by
J.A. Boedo
for
the DIII–D and NSTX Teams



Presented at the
21st IAEA Fusion Energy Conference
Chengdu, China

October 16–21, 2006

Abstract

J.A. Boedo 1), R.J. Maqueda 2), D.L. Rudakov 1), G.R. McKee 3), H. Kugel 4), R. Maingi 5), N. Crocker 6), R.A. Moyer 1), V.A. Soukhanovskii 7), J. Menard 4), J.G. Watkins 8), S.J. Zweben 4), D.A. D' Ippolito 9), T.E. Evans 10), M.E. Fenstermacher 7), M. Groth 7), E.M. Hollmann 1), C.J. Lasnier 7), J.R. Myra 9), L.A. Roquemore 4), W.P. West 10), and L. Zeng 6) (see institution List at the end)

Abstract. The far scrape-off layer (SOL) radial transport and plasma-wall contact is mediated by intermittentand ELM-driven transport. Experiments to characterize the intermittent transport and ELMs have been performed in both DIII-D and NSTX under similar conditions. Both intermittent transport and ELMs are comprised of filaments of hot, dense plasma (ne ne~1×10^{13} cm^3 , Te ~ 400 eV) originating at the edge, transport both particles and heat into the SOL by convection, increasing wall interaction and causing sputtering and impurity release. Both intermittent filaments and ELMs leave the pedestal region at speeds of ~0.5-3 km/s, losing heat and particles by parallel transport as they travel through the SOL. The intermittency shows many similarities in NSTX and DIII-D, featuring similar size (2-5 cm), large convective radial velocity, "holes" inside and peaks outside the LCFS which quickly decay and slow down with radius. Whereas in DIII-D the intermittency decays in both intensity and frequency in H-mode, it chiefly decays in frequency in NSTX. In the low collisionality ($\nu^* = \pi R q95 / \lambda_C$) ($\nu^* \sim 0.1$, $N_G \sim 0.3$) case, the ELMs impact the walls quite directly and account for ~90% of the wall particle flux, decreasing to ~30% at ($\nu^* \sim 1.0$, $N_G > 0.6$).

Two Main Transport Vehicles: Intermittency and ELMs

Two main vehicles of radial transport have been identified in the edge/SOL; intermittency and ELMs.

Intermittent transport is the only mechanism in L-mode. It increases with density/collisionality/Greenwald fraction (N_G). $N_G = n_e \pi a^2 / I_p$

In H-mode ELM-mediated and inter-ELM (intermittent) transport play a role. ELMs become smaller (grassier) with increased collisionality/density while intermittency increases. What is the final relative weight?

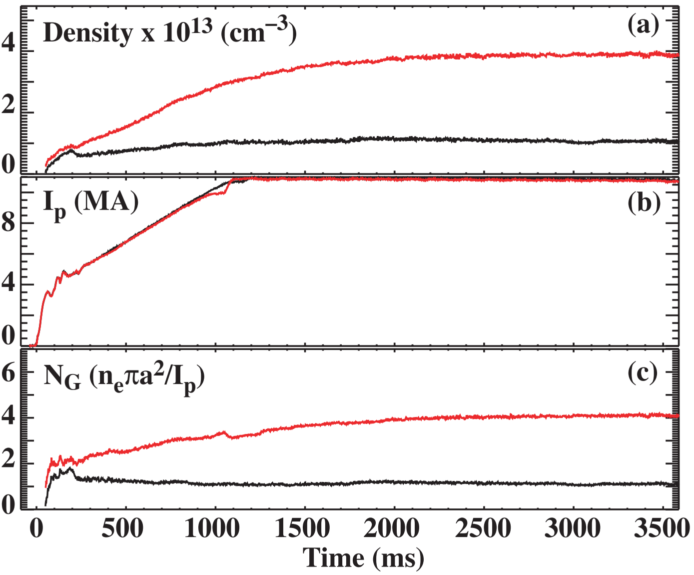
Finally, (N_G) has been used as a parameter to vary to control intermittency. Is this real? What if we compare various ranges of (N_G) in two different machines (NSTX and DIII-D)?.

Experimental Setup: Density Scan

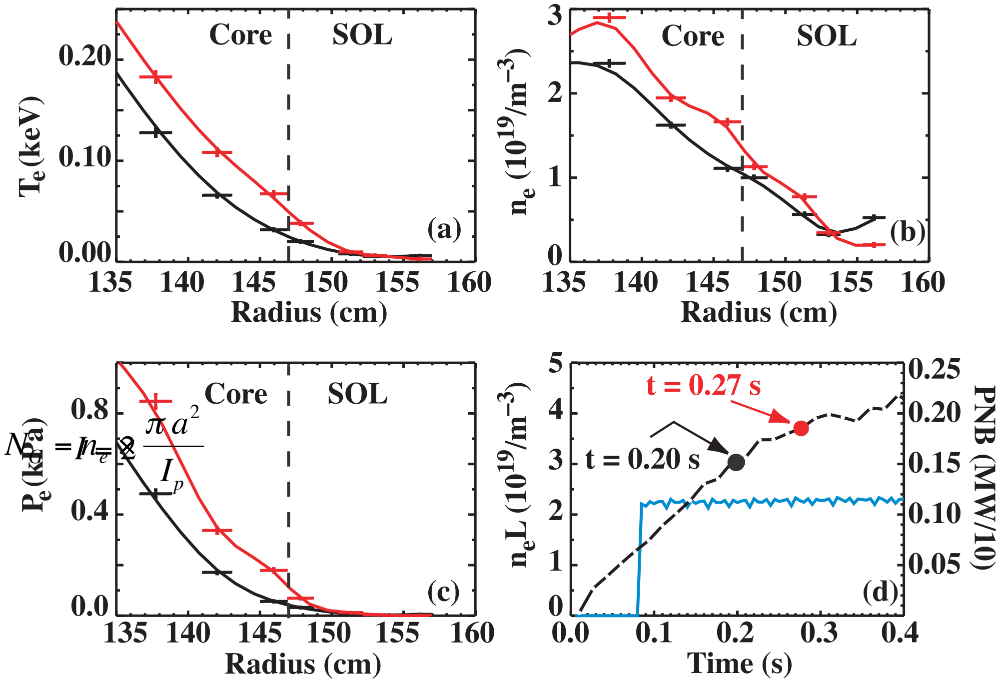
DIII-D

NSTX

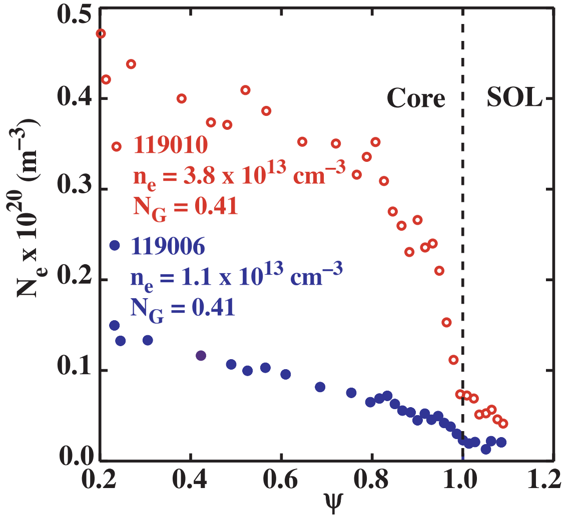
DIII-D Discharges
119006 ($N_G = 0.12$) and 119010 ($N_G = 0.40$)



NSTX Discharge 115571



DIII-D Thomson Scattering



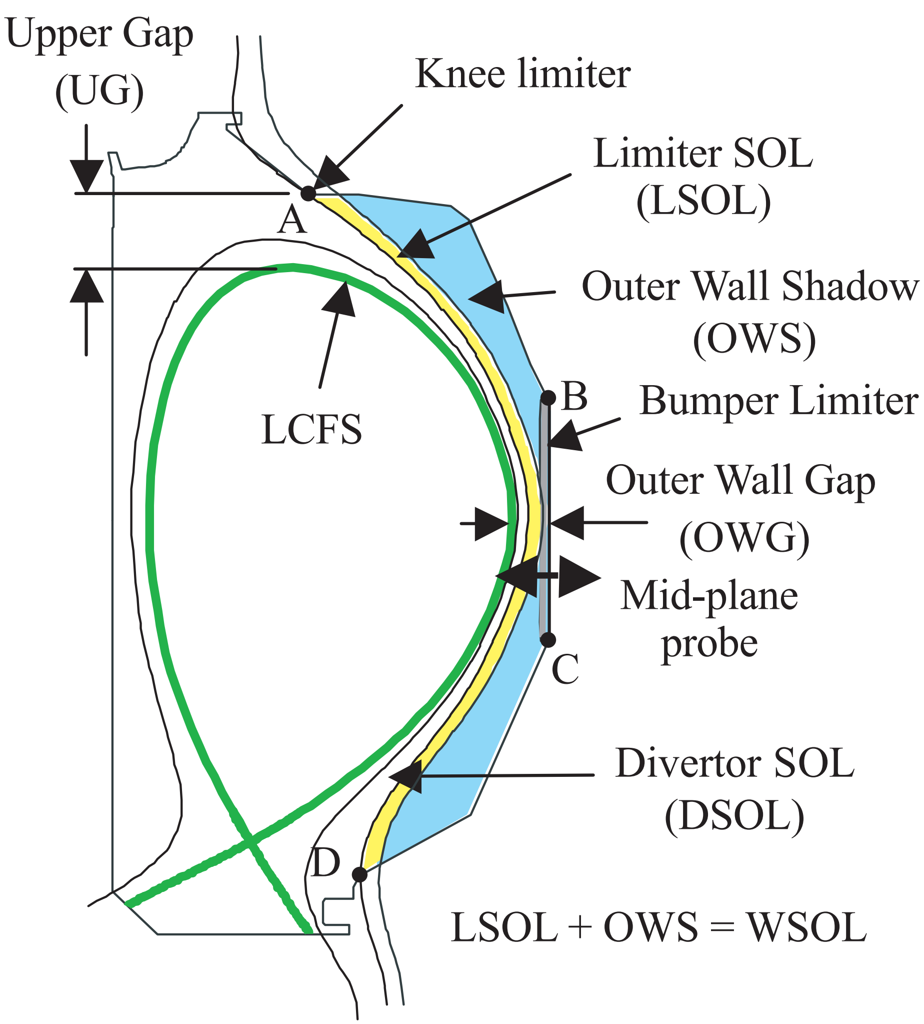
The goal is to scan the collisionality/Greenwald fraction

$$N_G = n_e \pi a^2 / I_p$$

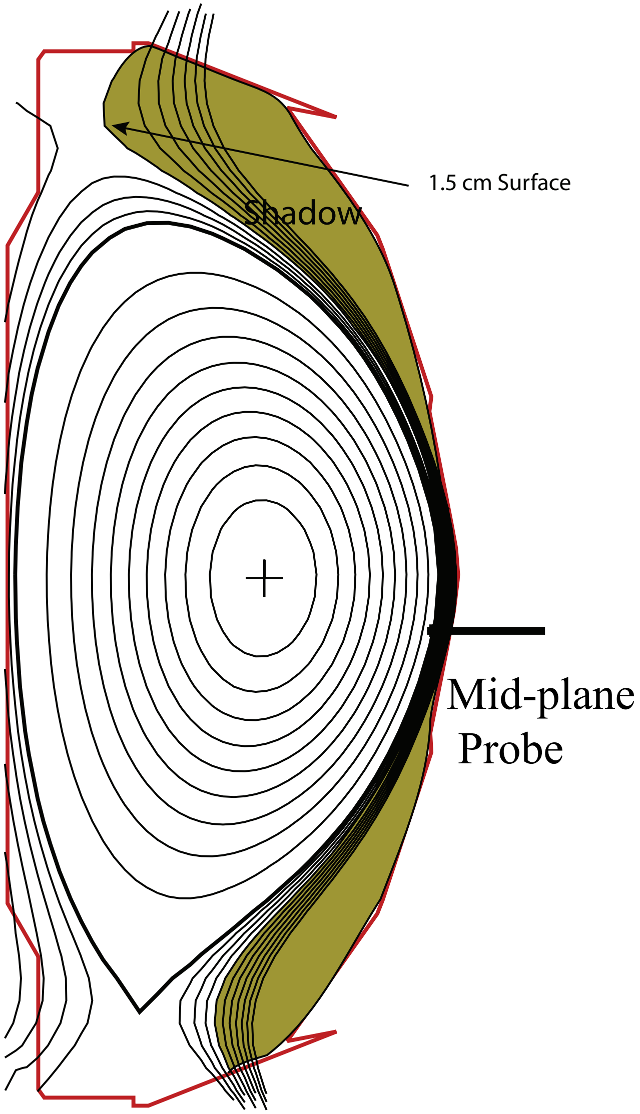
In DIII-D the density is scanned shot to shot.

In NSTX a density ramp is used and measurements taken at various times.

Experimental Setup: Discharge and Shapes Utilized



LSOL + OWS = WSOL



NSTX: Ip=0.80 MA, Bt=0.45 T, Pin=1 MW, q95=7, W=0.2 MJ, V=11 m^3

DIII-D: Ip=1 MA, Bt= 2 T, Pin= 1 MW, q95= 4.6, W=0.16 MJ, V=18.7 m^3

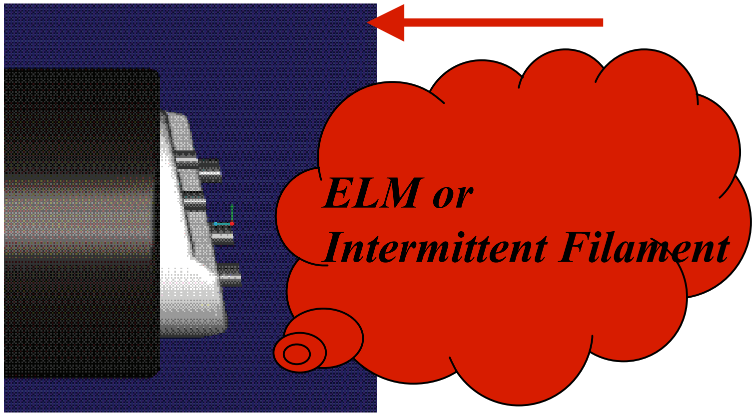
Diagnostics: Fast Probe

To perform this work we have used:

NSTX	**DIII-D**
Fast scanning probe	*Fast scanning probe*
Gas puff imaging (fast camera based)	*Beam Emission Spectroscopy*
Fast diode array	*Fast diodes*

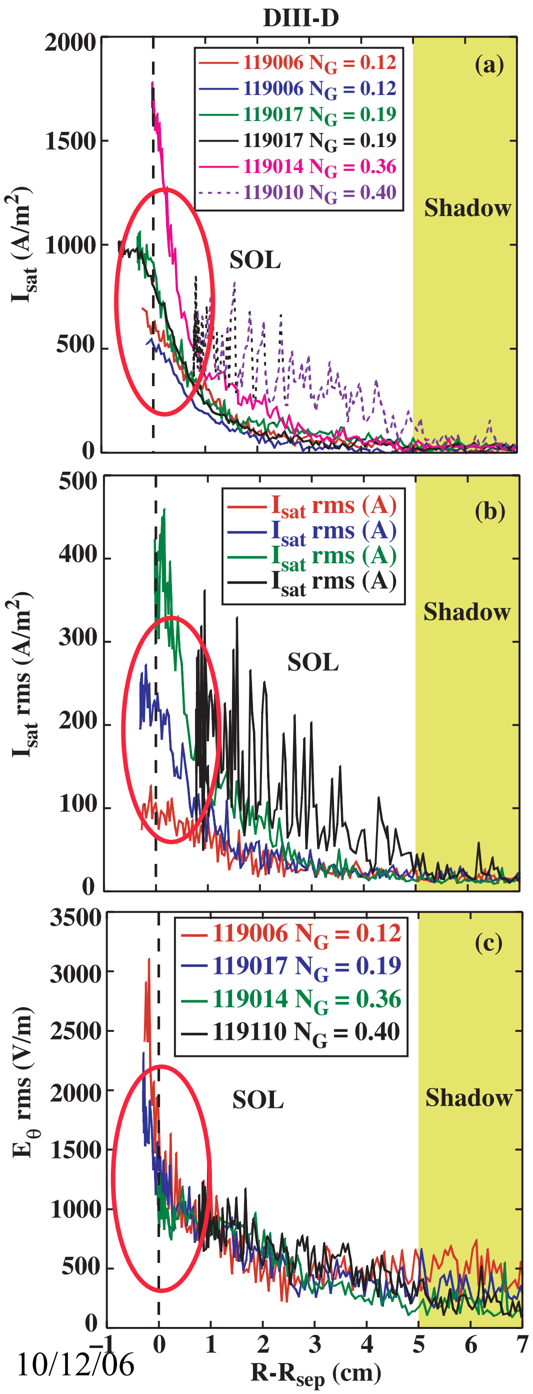
Probe measures Isat, Ne, Te, Eq, Er DIRECTLY
(no further analysis beyond Langmuir theory)

Velocity can be inferred as: $V_r = E_\theta / B_T$



J. Watkins, RSI 1997
J. Boedo, RSI 2006

Intermittency present at DIII-D and NSTX

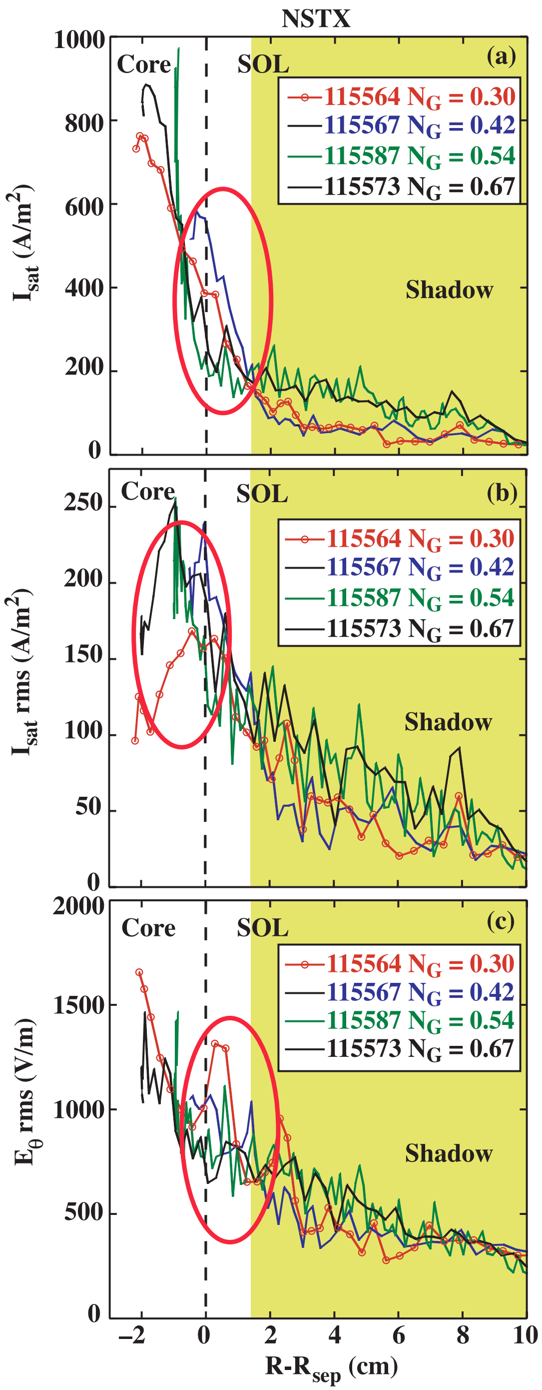


Changes seem to occur mostly at higher N_G in both devices. However, the N_G is ***different*** in each machine. **No universality of N_G**

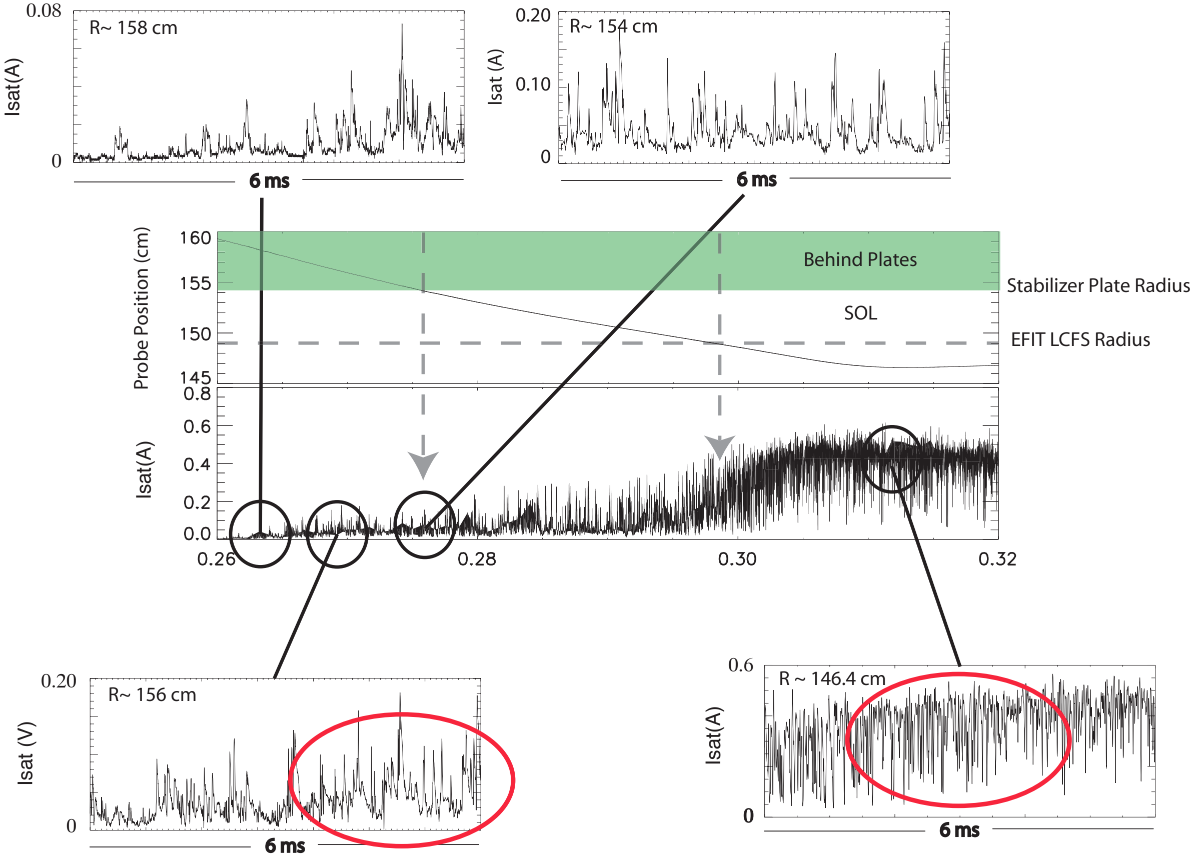
SOL profiles flatten at higher N_G in both machines

I_{sat} rms levels (fluctuations) increase in both machines with N_G

Radial velocity behaves differently. No changes in DIII-D, changes by the LCFS in NSTX

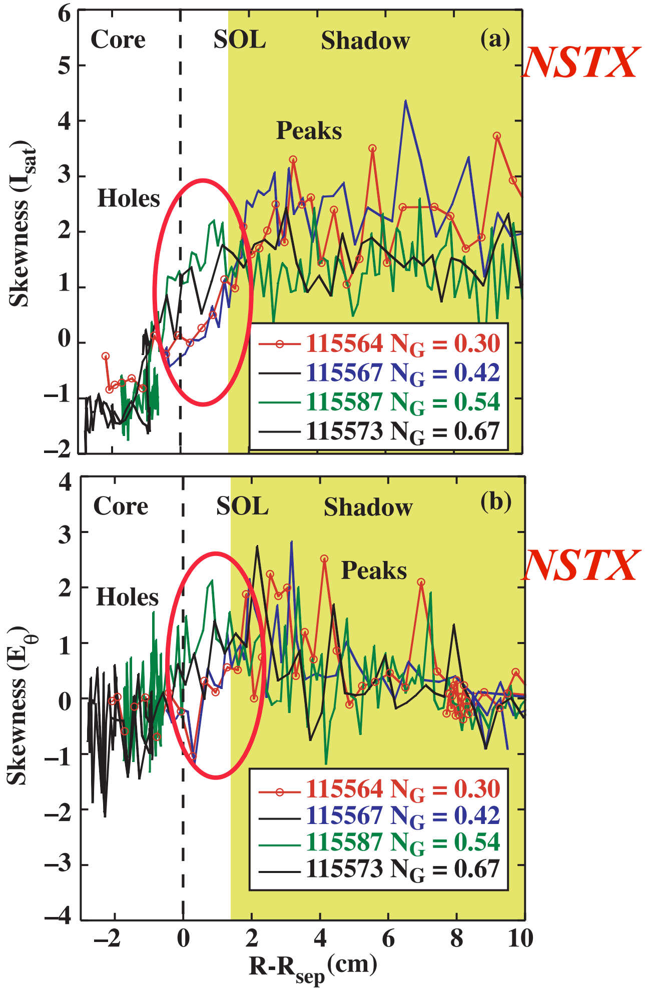


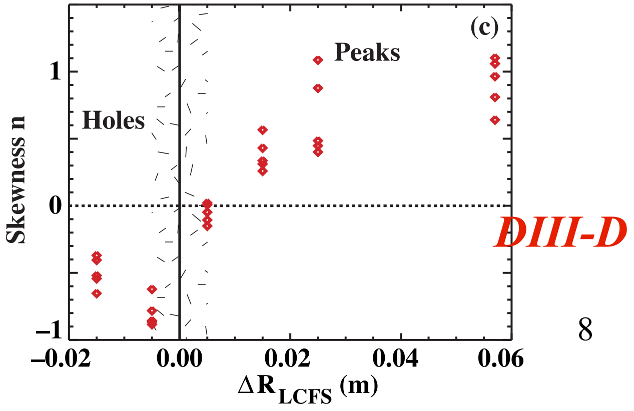
Skewness Profile is Universal and Indicates Interchange Source



Peaks in SOL

Holes in core





In *both* NSTX and DIII-D skewness changes across LCFS from negative (I.e. holes) to peaks.

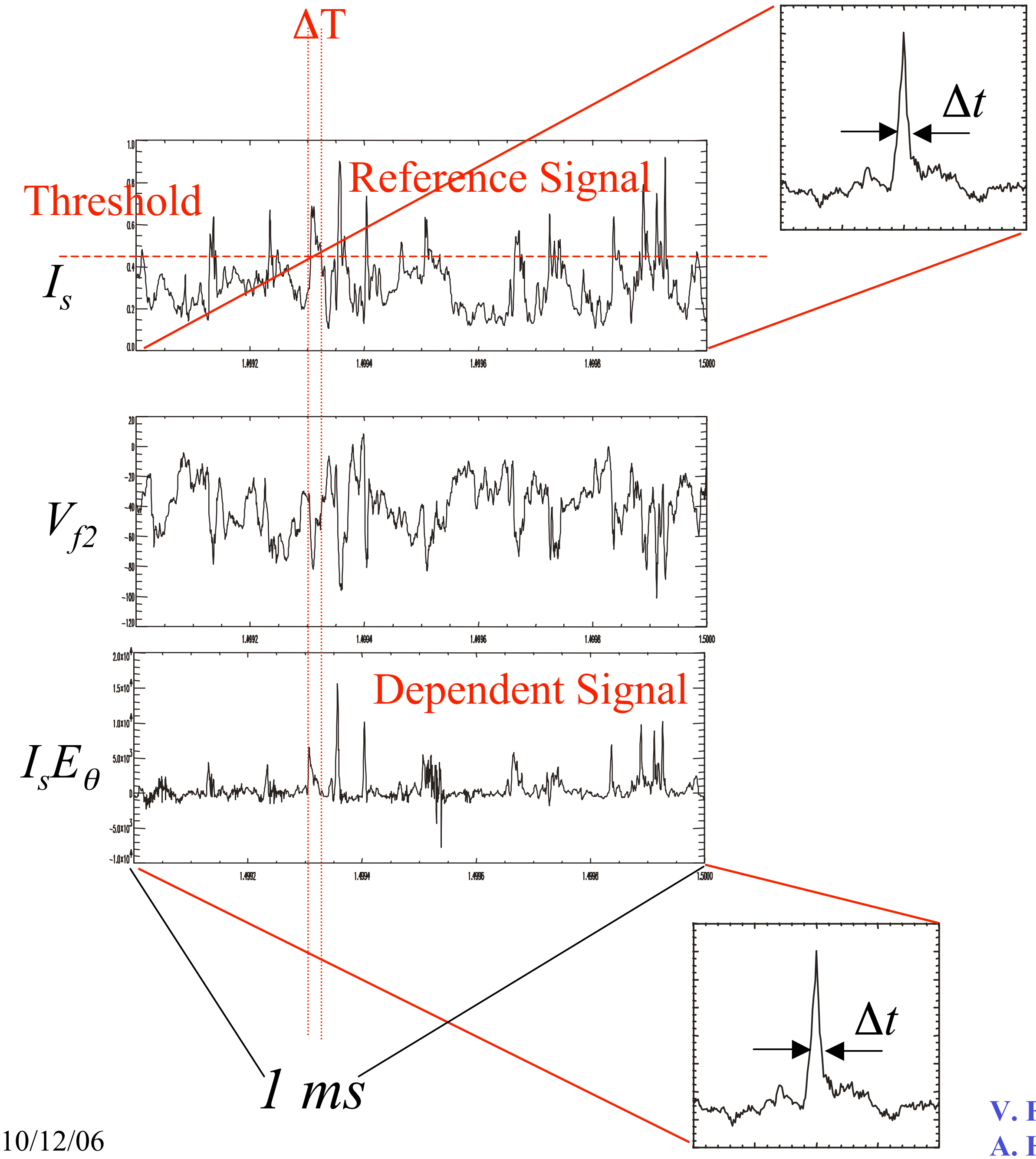
if s=standard deviation,

$$Skewness = \sum_{i=1}^{N} (Y_i - \overline{Y})^3 / (N-1)s^3$$

Data consistent with Interchange instability at LCFS (ref)

Y. Sarazin, PoP 1998, P. Ghendrih, Nuc. Fus., 2004, J. Horacek, PPCF 2006

Conditional Averaging (CA) Extracts Intermittent Events



- Conditional averaging tools allow us to extract pulsed or intermittent information from a signal

- One signal is the reference.

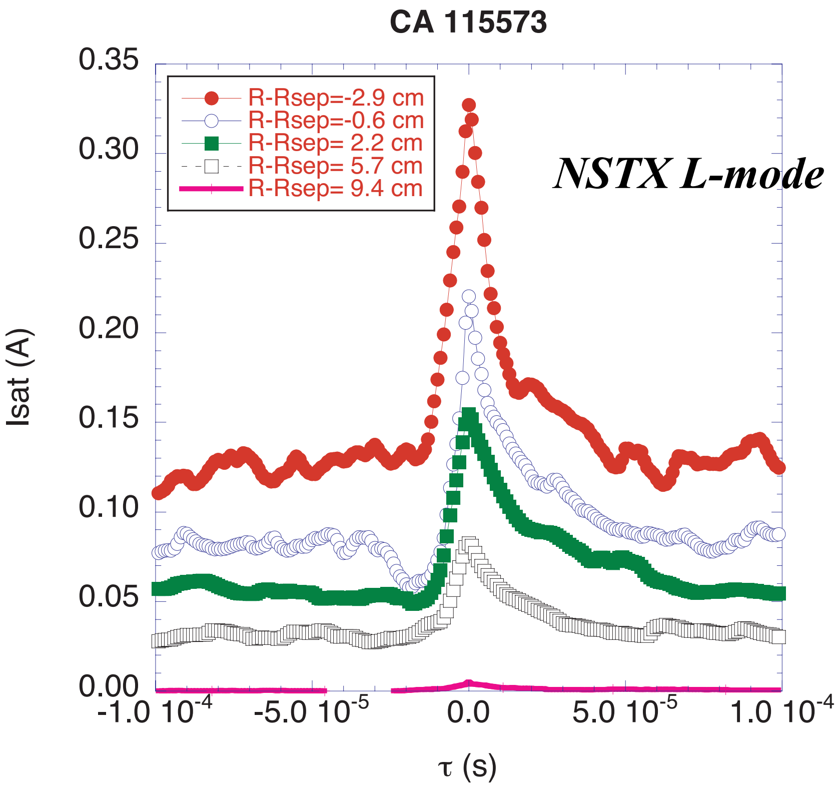
- The rest of the signals are sampled as per the reference one.

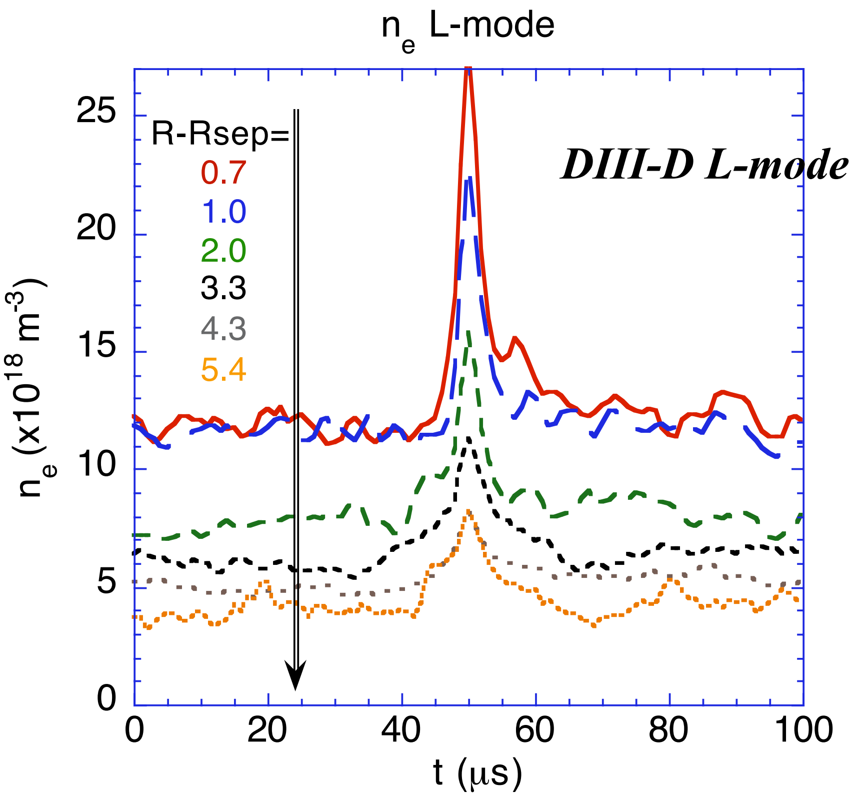
- Correlated features are brought out

- Data processed in 5 ms slices, threshold of 2.5 rms

V. Filippas, et al (TEXT 95), A. H. Nielsen et al (96), A. Heller (CASTOR 99)

Intermittent Events Similar in DIII-D and NSTX

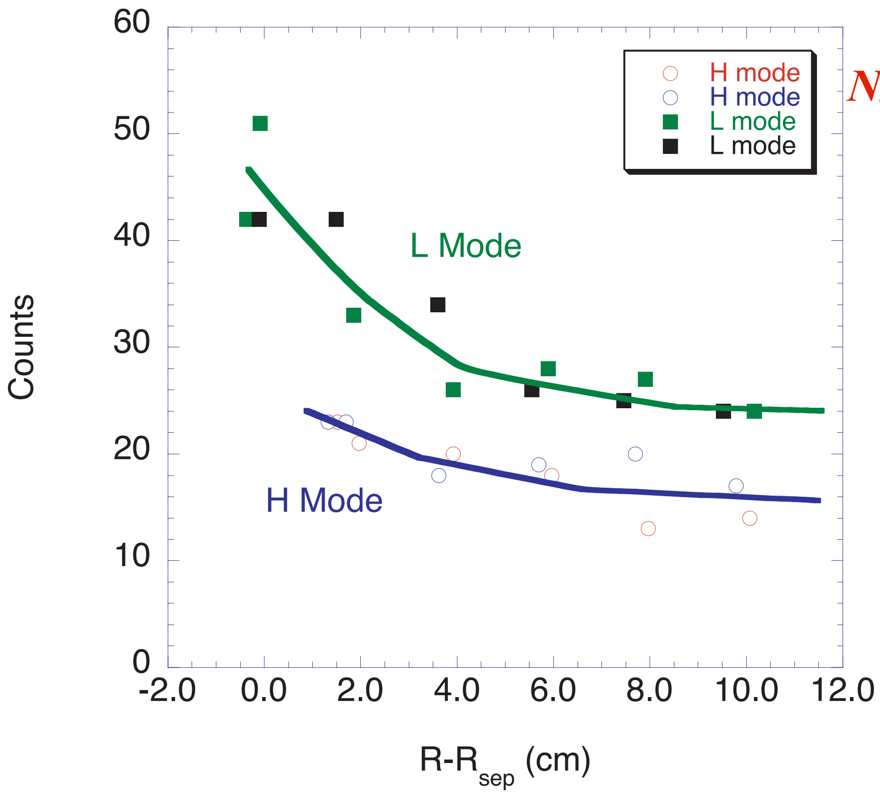




- The intermittent objects look identical in NSTX and DIII-D
- 50 μs wide pulses, 2-5 cm in radius
- Decay with R-Rsep in amplitude (ne and Te)
- Velocity ($V_r=E_\theta/B_T$) starts at 600-1000 m/s at the LCFS and decays with R-Rsep

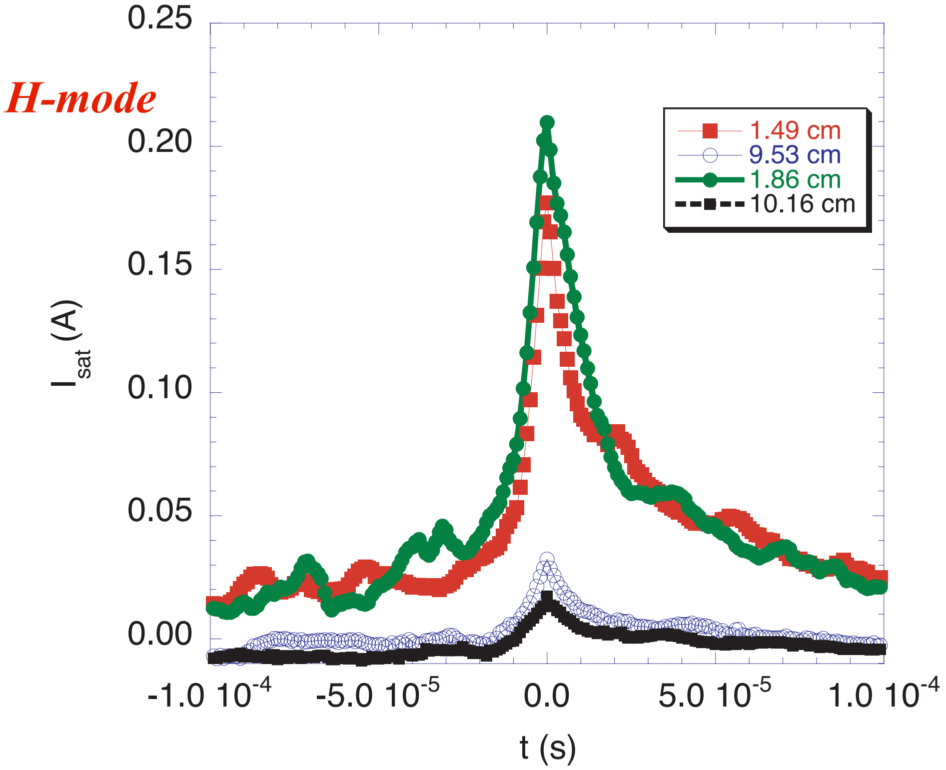
H-mode Intermittency different in NSTX and DIII-D

I_{sat} Events > 2.5 rms vs $R\text{-}R_{sep}$ H and L Mode



NSTX L and H-mode

H-mode I_{sat} at $R\text{-}R_{sep}$ ~1.4 cm and ~10 cm

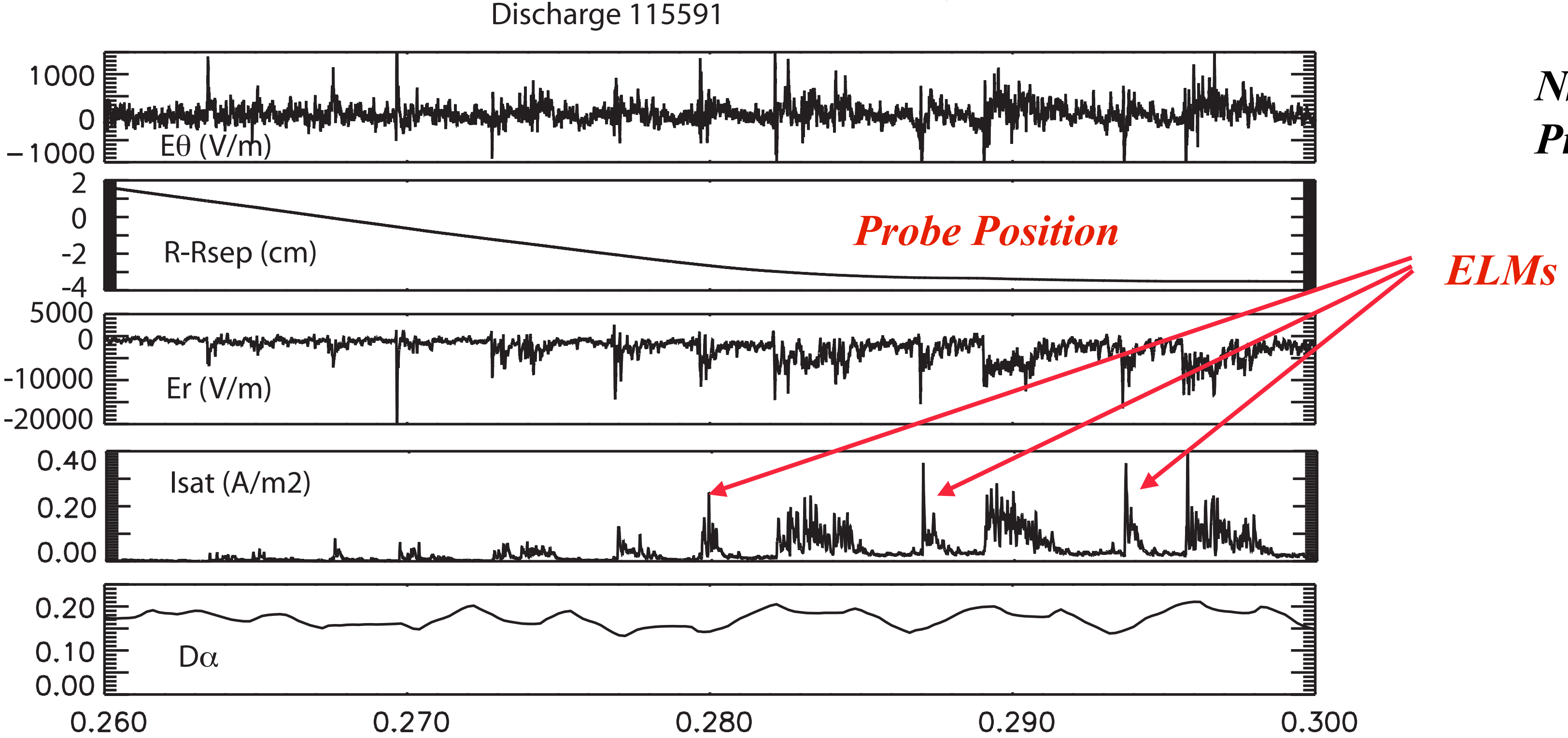


- In DIII-D, L and H-mode events differ in two ways
  - –Amplitude at LCFS is larger in L-mode by x2.5
  - –Number of events per time larger in L-mode

–In NSTX L and H-mode decay different only on event frequency

  - –L-mode almost 2x H-mode frequency
  - –L and H-mode amplitudes very similar with R-Rsep

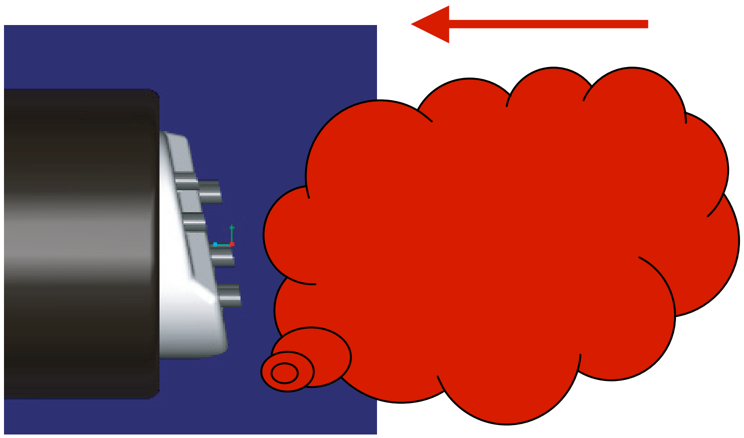
ELMs also Characterized by Probes in NSTX and DIII-D



Probe Position

ELMs

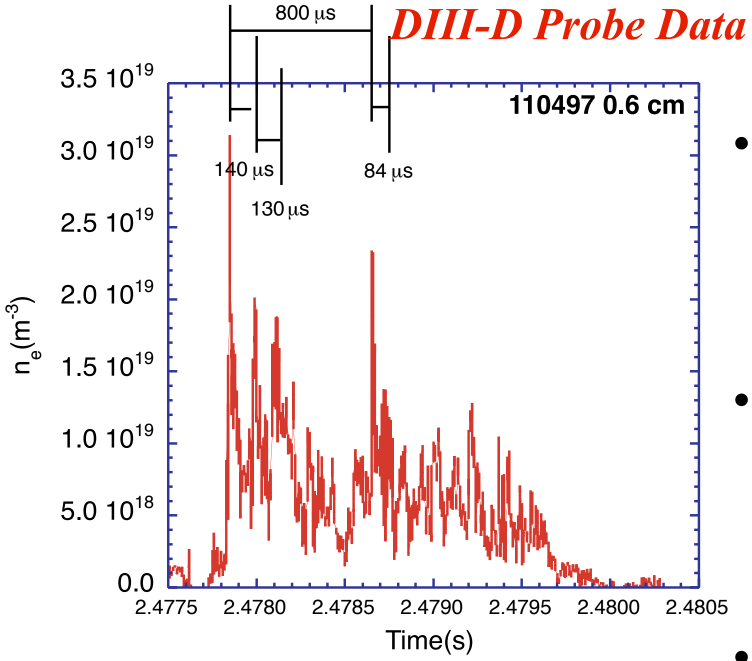
NSTX H-mode
Probe signals

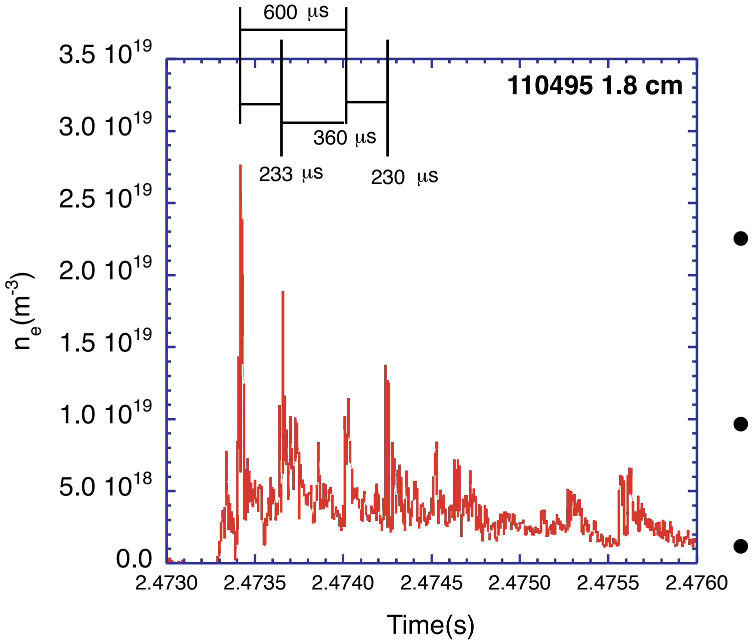


- As probe plunges, various ELMs strike
- Thus ELM properties variation vs R-Rsep studied
- Probe reveals structure not seen in lower resolution diagnostics (Dα at bottom)

ELMs are microscopically similar in DIII and NSTX

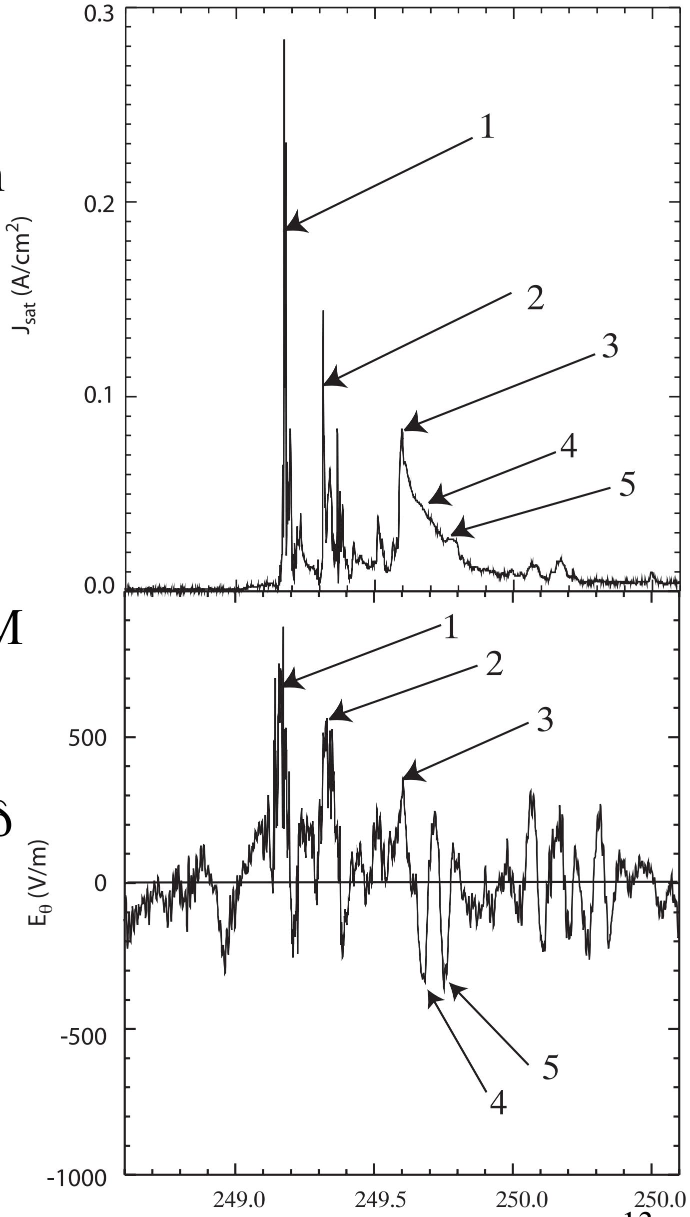
DIII-D Probe Data





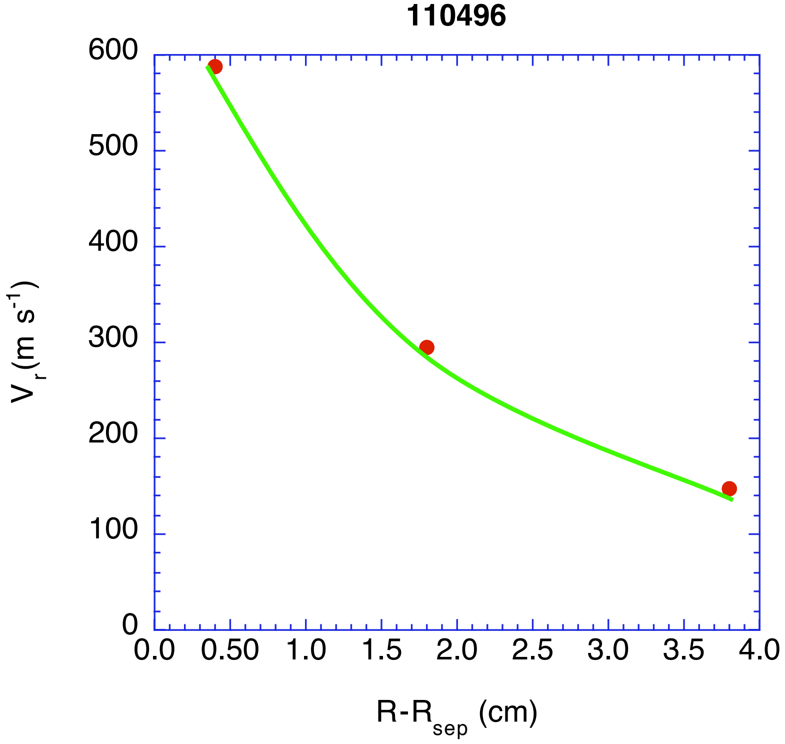
- ELM is comprised of various short (~10 µs) bursts in rapid succession (~20-50 µs)
- ELM radial velocity can be high ~ 500 m/s near LCFS and slows down (~200 m/s) in the SOL.
- Near wall, negative Vr (4,5) is seen in some ELM components (reflected plasma?)
- Using measured V_r then δ r~3-5 cm (see BES) per burst!
- Density matters; longer, grassier bursts at high ne
- Pulses reach wall ~ 100-300 µs

NSTX Probe Data



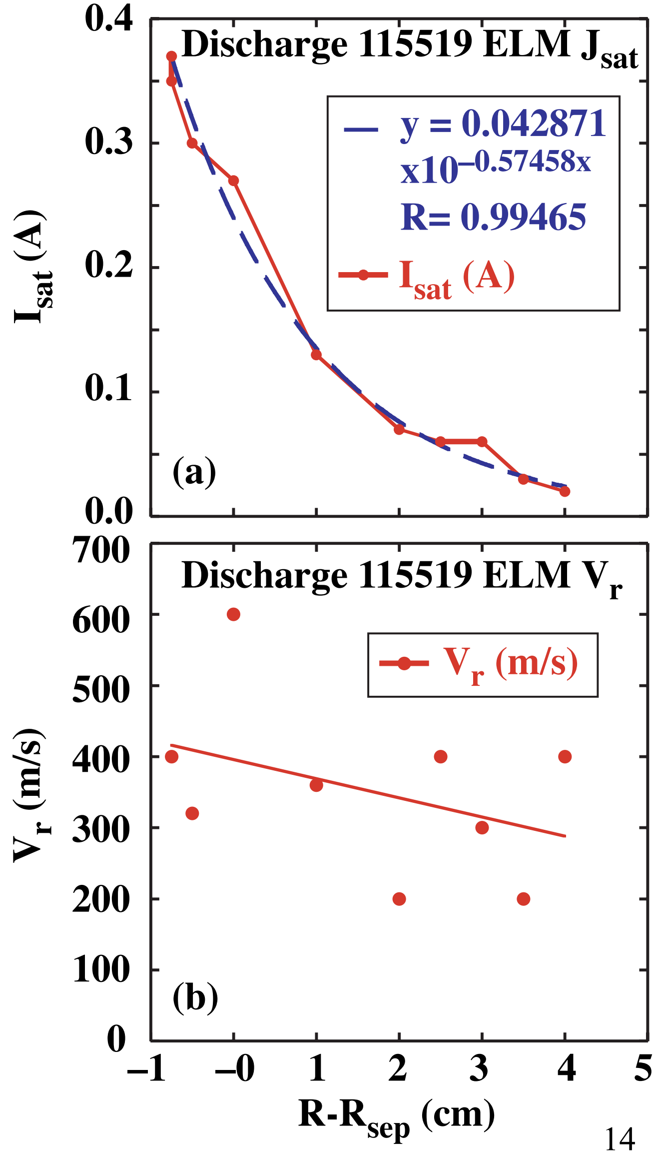
ELM decay radially in DIII and NSTX. Transport in CONVECTIVE

DIII-D Probe Data



$$V_r = \frac{E_\theta \times B_\phi}{B^2}$$

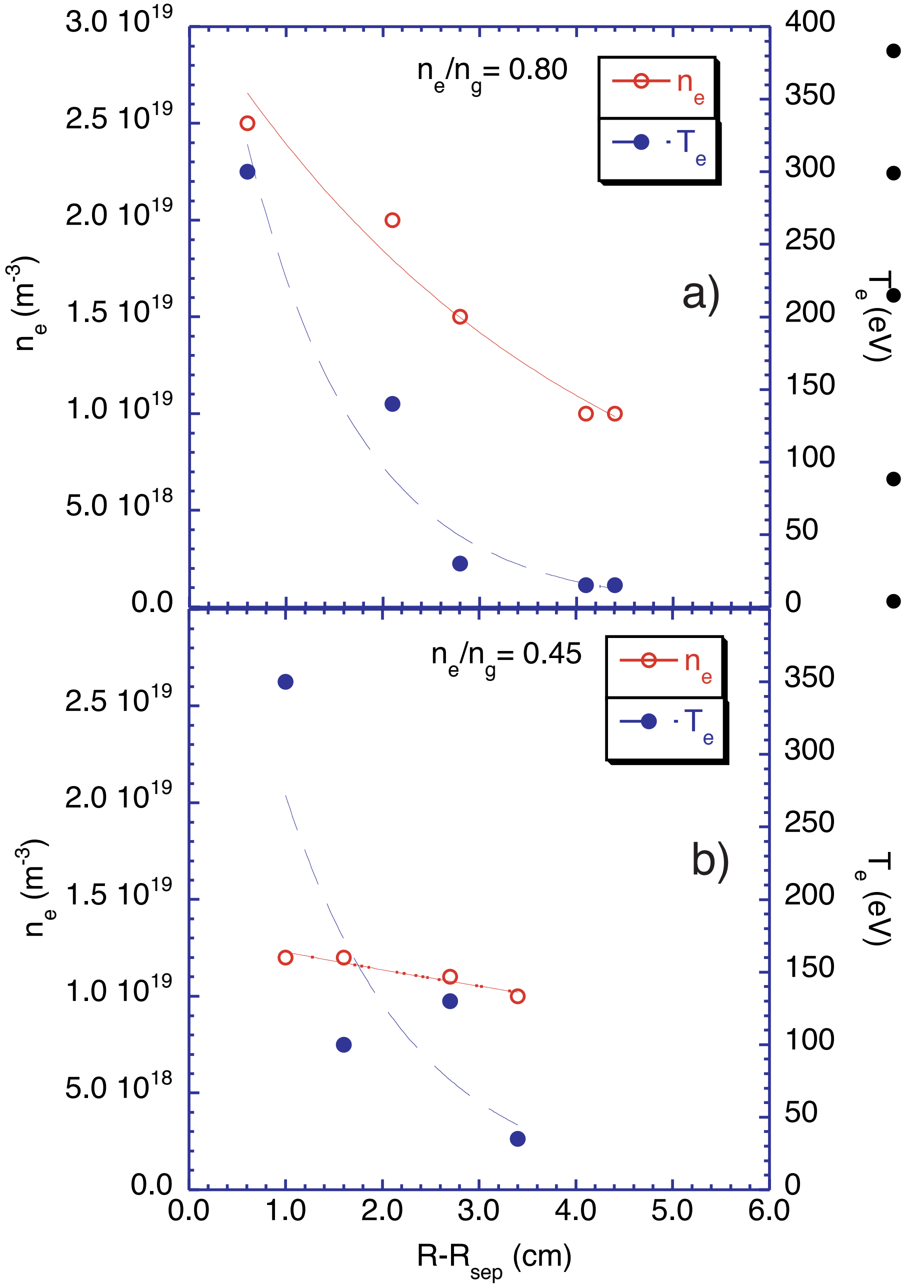
NSTX Probe Data



- ELMs decay by parallel transport as they move radially
- Type I ELM **amplitude and velocity** decay ~exponentially in DIII-D
- In NSTX, amplitude decays exponentially BUT **velocity decays linearly.**

10/12/06

ELM Heat and Particle Transport are Decoupled and Ne dependent


DIII-D Probe Data

- In DIII-D, density dependence of decay length

- High Ne: L_N=3.8 cm
  L_T= 1.2 cm
- Low Ne: L_N=13 cm
  L_T=1.3 cm

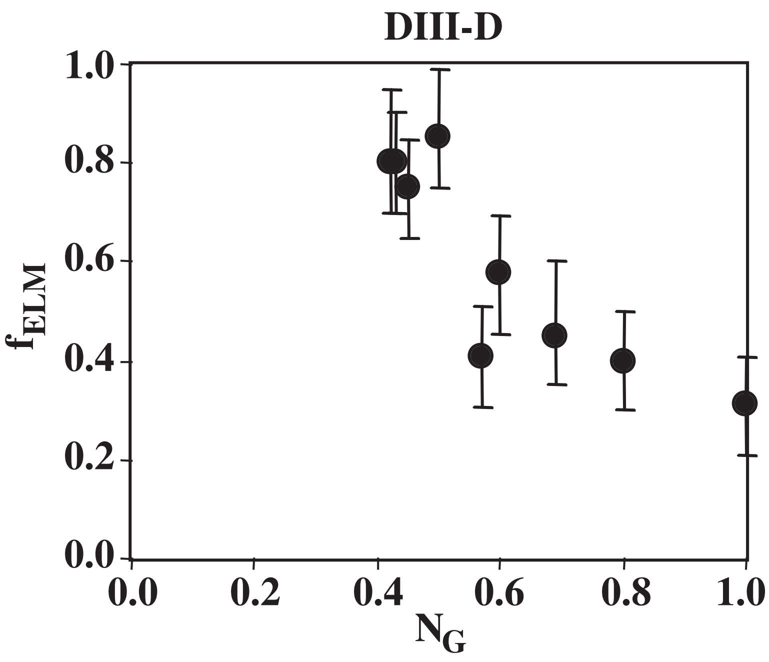
- Particles strike wall unhindered at low Ne

- Heat decays quickly in every case

$<n_e>/n_{GW}$= 0.8	Γ_r^{ELM} (m^{-2} s^{-1})	Q_r^{ELM} (J m^{-2} s^{-1})
LCFS	1.0 10^{22}	1,800,000
Wall	1.5 10^{21}	21,600

$<n_e>/n_{GW}$= 0.45	Γ_r^{ELM} (m^{-2} s^{-1})	Q_r^{ELM} (J m^{-2} s^{-1})
LCFS	5.6 10^{21}	1,323,000
Wall	1.8 10^{21}	27,000

ELMs vs Intermittency, who is the winner?



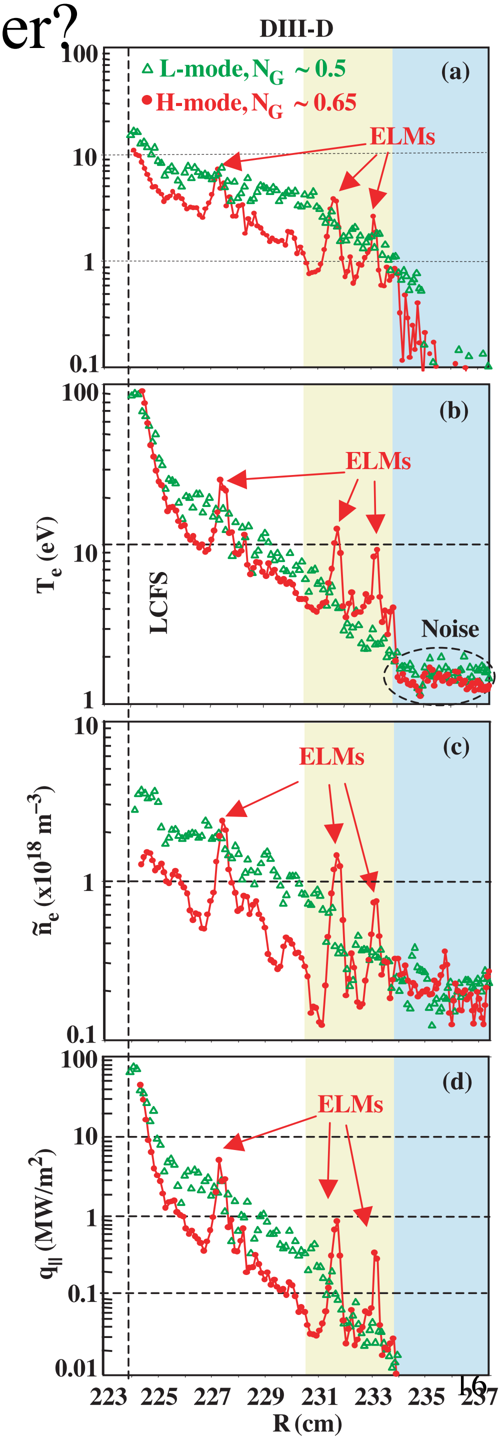
These are ITER relevant collissionalities!

D. Rudakov, UCSD

- ELM-mediated transport can (momentarily) exceed L-mode transport (right). How does this compare to inter-ELM transport?
- ELM fraction of ion flux to the wall has been evaluated as:

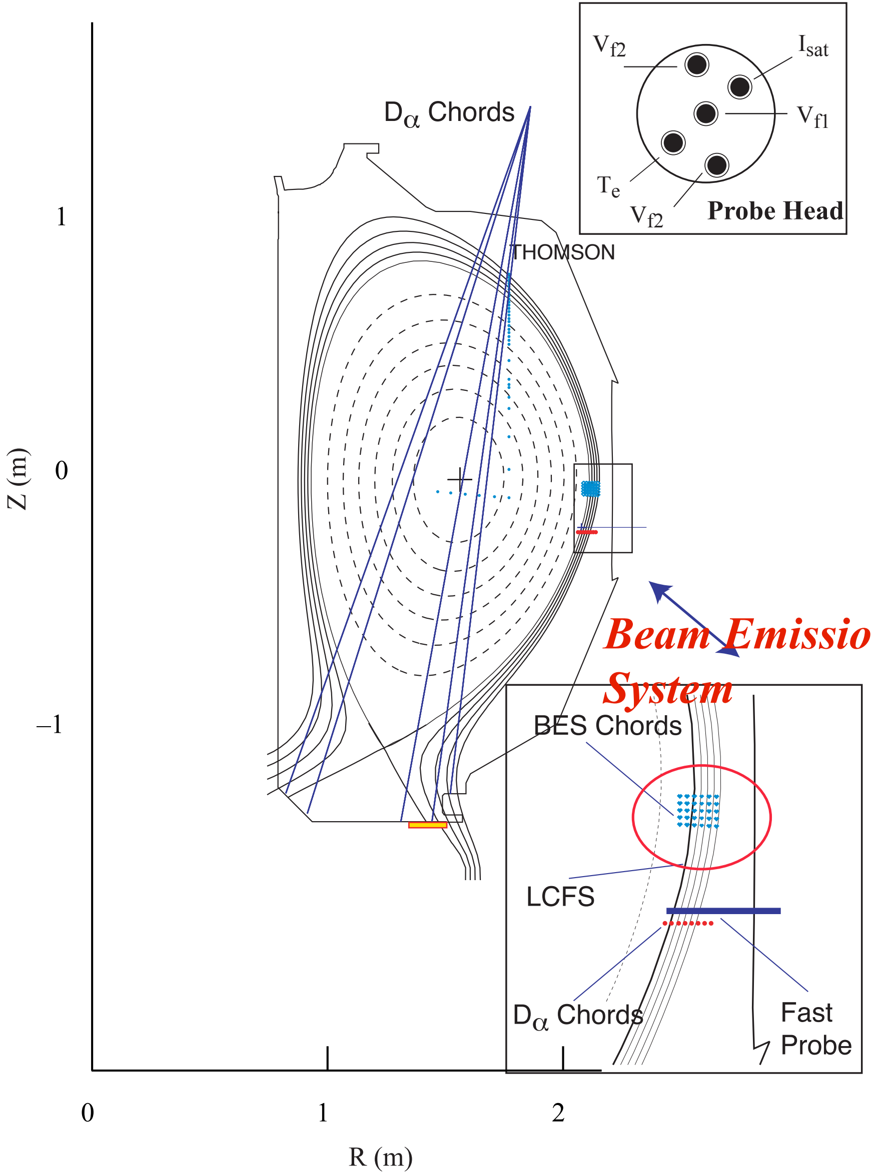
$$f_{ELM} = \int_{ELM} I_{si}\,dt \Big/ \int_{Total} I_{si}\,dt$$

- Discharge density/collissionality scanned as Greenwald fraction (N_G) from 0.4 to ~1.0.
- ELM-mediated transport decreases with N_G as intermittent transport increases.



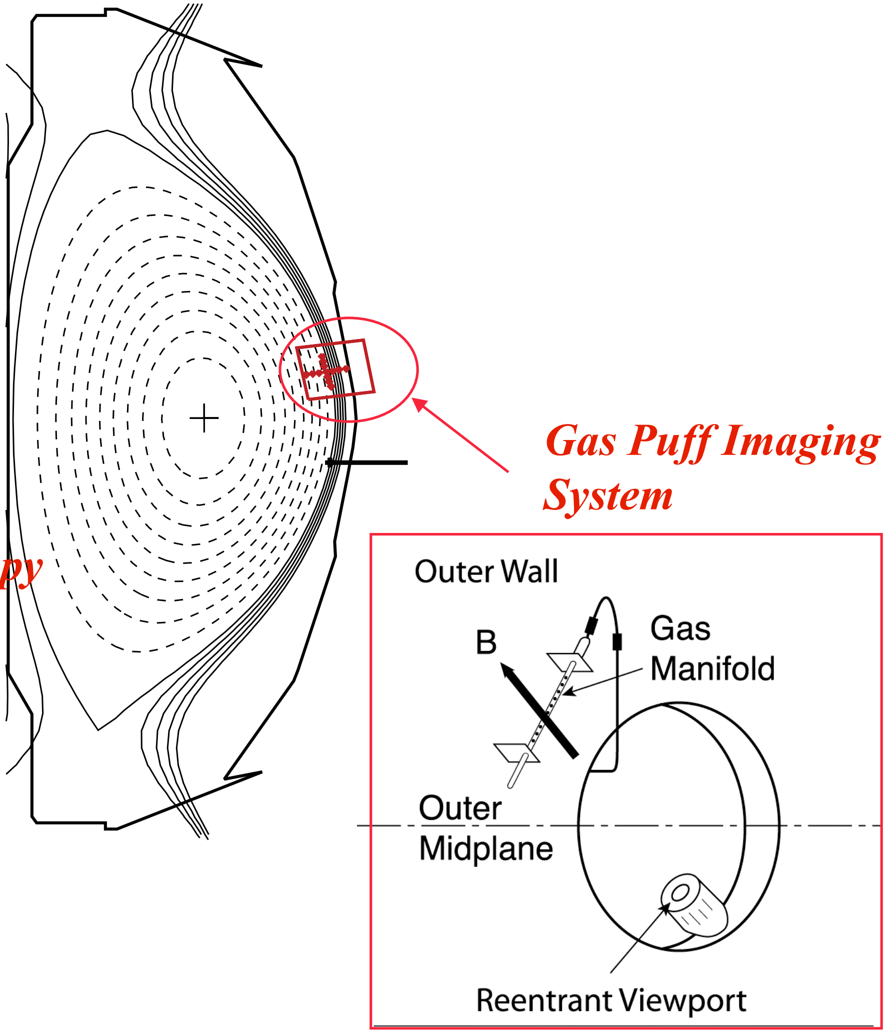
Imaging of Intermittency and ELMs in DIII-D and NSTX

DIII-D



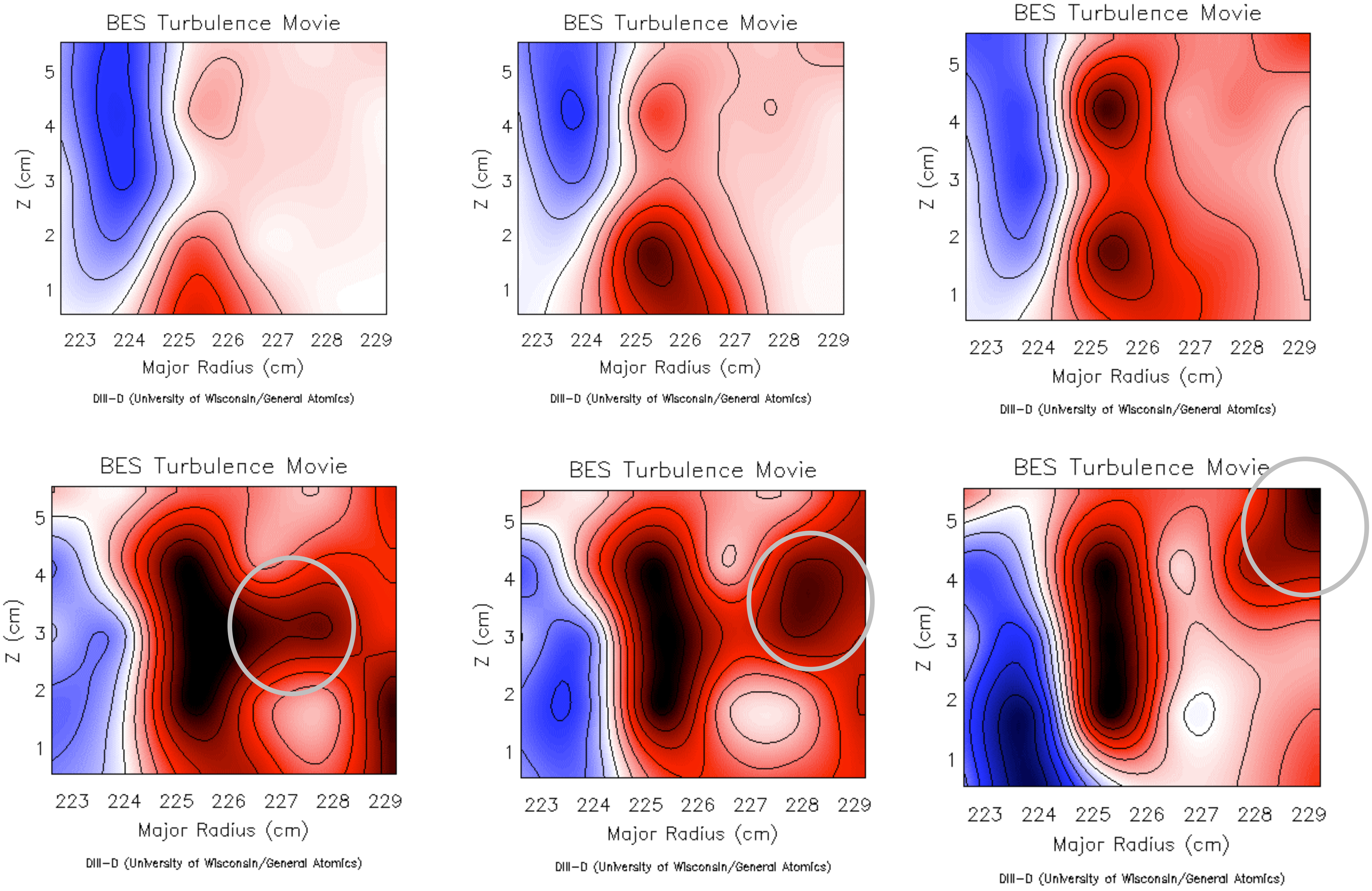
Beam Emission Spectroscopy System

NSTX



Gas Puff Imaging System

ELM detail over a total of ~20 μs from BES frames



GPI Diagnostic in NSTX

- Camera used to view visible emission from edge just above midplane.

- Gas puff is injected to increase image contrast and brightness. Gas puff does not perturb local (nor global) plasma.

- Emission filtered for D_α (He) light from gas puff:

  $I \propto n_o n_e f(n_e, T_e) \quad (\propto n_e^{\alpha} T_e^{\beta})$

  with $0.5 < \alpha, \beta < 2$

- D_α (He) emission only seen in range

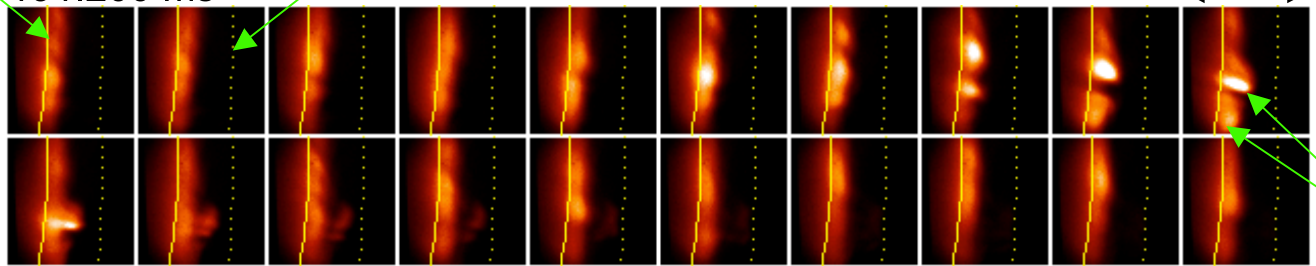
  $\sim 5 \text{ eV} < T_e < 50 \text{ eV}$

- View aligned along B field line to see 2-D structure ⊥ B. Typical edge phenomena has a long parallel wavelength, **filament structure**.

R.J. Maqueda et al., Rev. Sci. Instrum. 74(3), p. 2020, 2003.

Gas Puff Imaging: Intermittency regimes in NSTX

Ohmic
(L-mode)



Separatrix

191.200 ms

Antenna limiter shadow

23 cm radial

23 cm poloidal

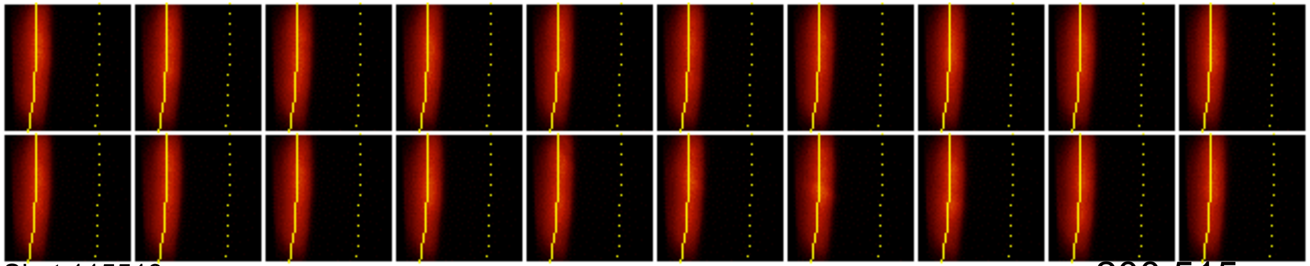
Intermittent events

Shot 115513

191.357 ms

Quiescent
H-mode

200.358 ms

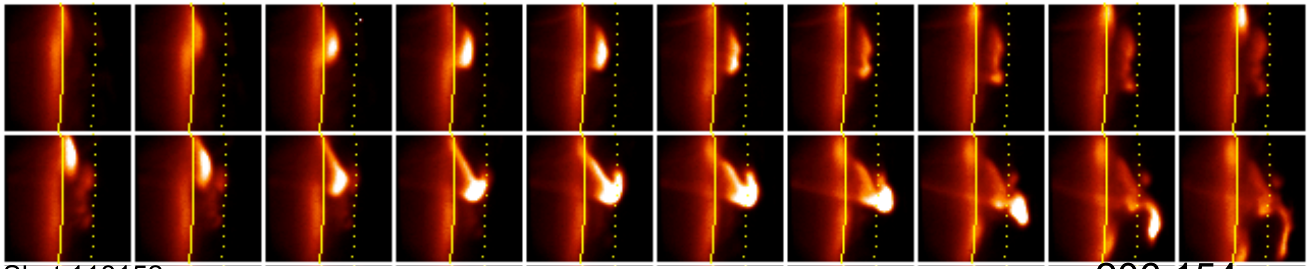


Shot 115513

200.515 ms

Active
H-mode

206.007 ms



Shot 118152

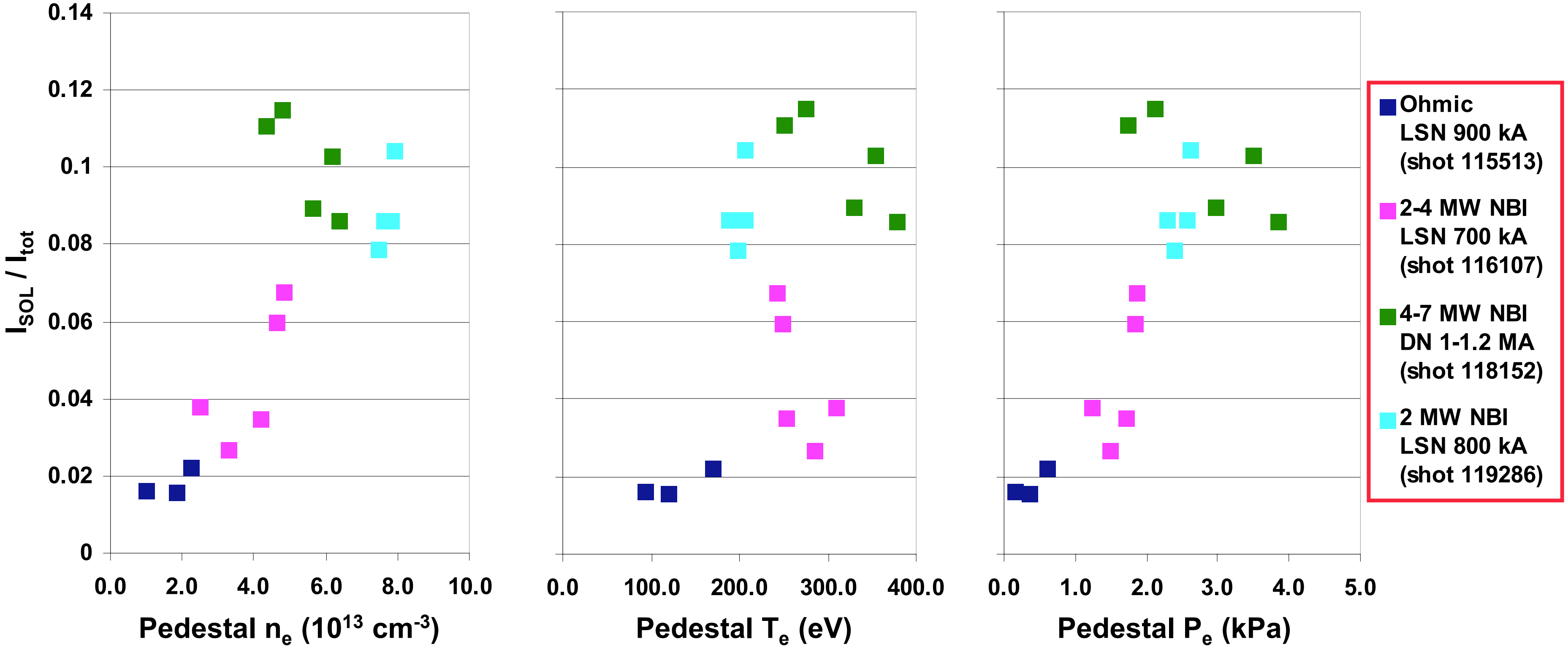
206.154 ms

~8 μs between frames
0.16 ms mosaics
D_2 puff - D_α filter

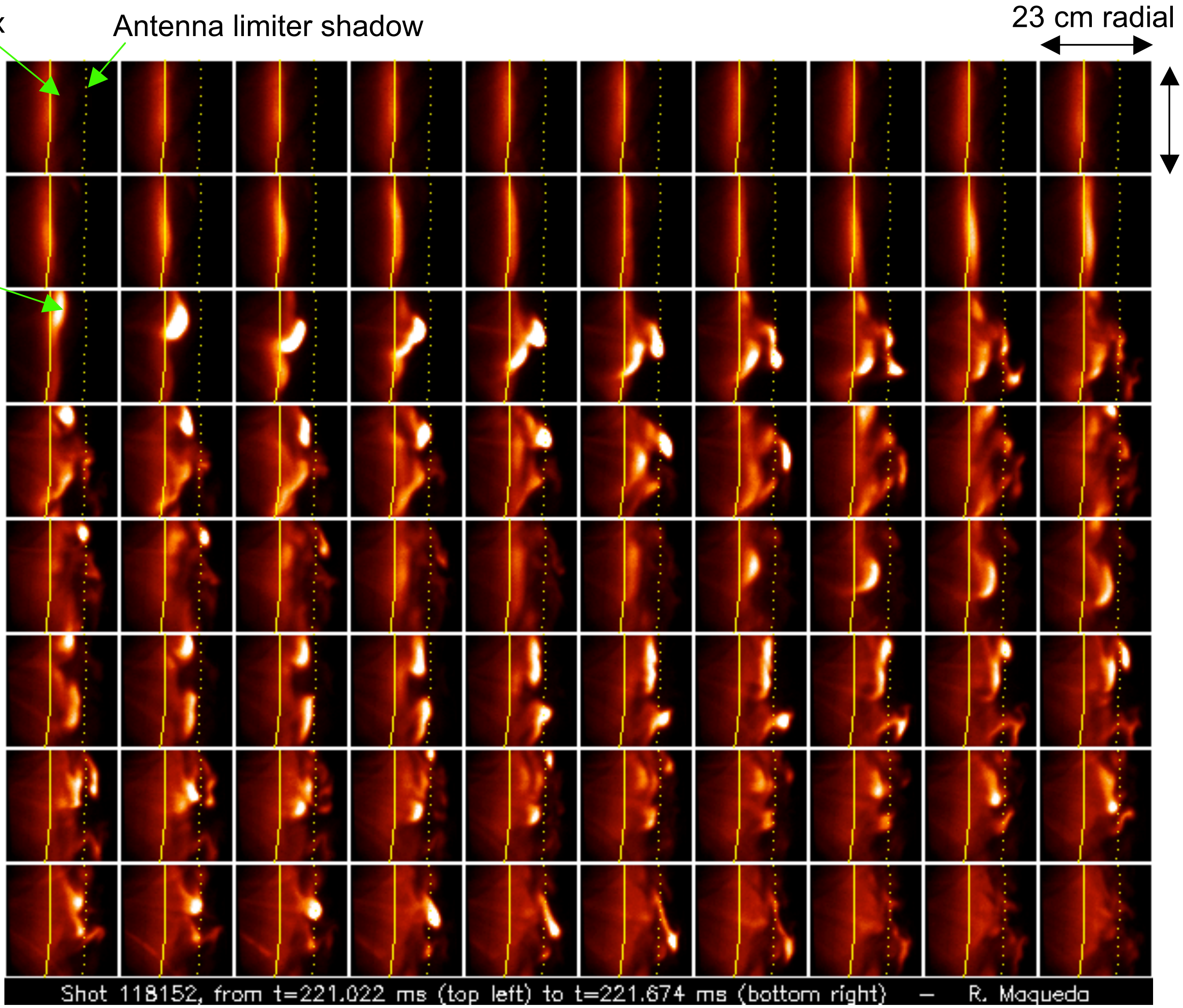
NOVA PHOTONICS

H-mode activity correlates well with n_e

- The characteristics of the H-mode turbulence and intermittency present a **continuum** from a turbulence level just above that measurable (a "quiescent" H-mode) to that approaching L-mode level (an "active" H-mode), at least for brief periods of time.
- The level of activity correlates well with the pedestal n_e or P_e. Similar to probe data



After large ELMs edge similar to L-mode-like edge



H-mode edge

Primary ELM filament

Turbulent edge

multiple secondary filaments

4.5 MW NBI

~8 μs between frames

0.65 ms mosaic

D_2 puff

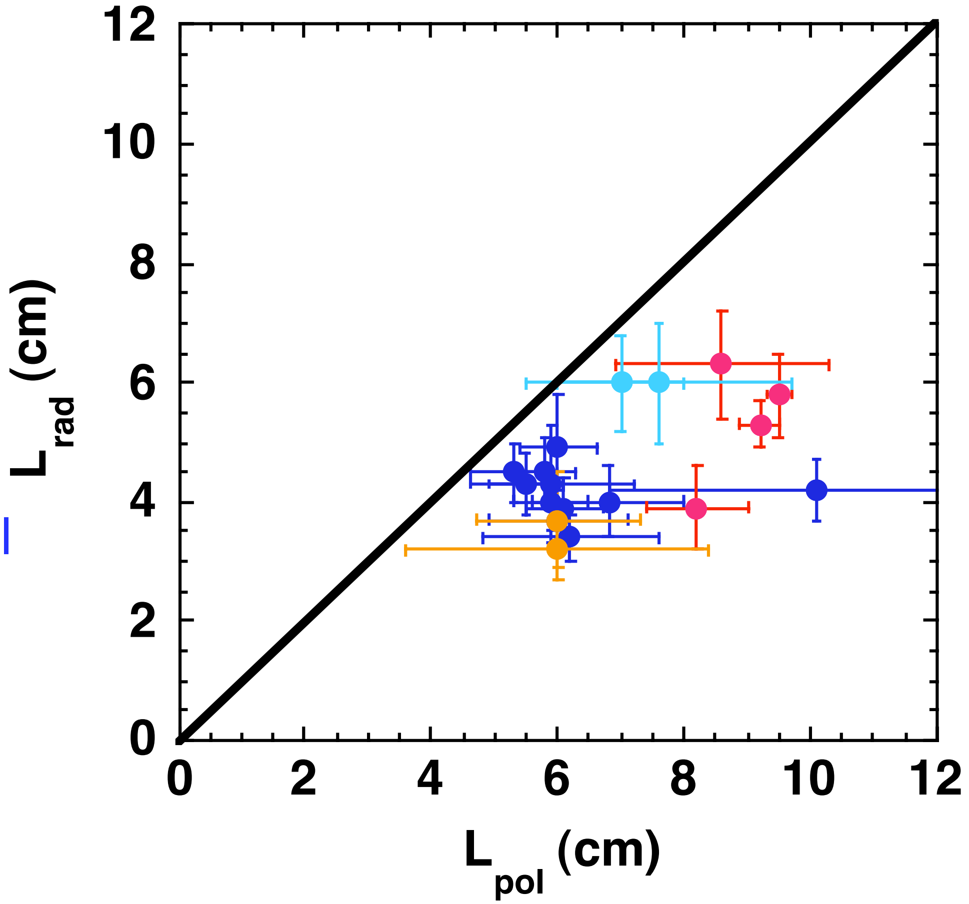
D_α filter

ELM transport reaching L-mode levels also seen on probe data, page 16

Comparison with L-H Transition Model

- L-H transition doesn't look as expected from standard model
  - little or no decrease in radial correlation length
  - little or no increase in poloidal shear flow

- Yet the flow shear is near the usual ExB flow-shear-stabilization threshold
  - $\nabla V_{pol} \approx$ (4 km/s)/10 cm $\approx$ (25 μs)$^{-1} \approx 1/\tau_{auto}$



	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

S. Zweben *et al*, Phys. Plasmas, 2006

Summary and Conclusions

- Intermittency is microscopically similar in DIII-D and NSTX

  GPI and probes show that in NSTX although the edge turbulence and intermittent frequency is much reduced in H-mode compared to L-mode, there is no significant change in the structure of the turbulence (correlation lengths)

  GPI shows that a significant change between L-mode and H-mode is a decrease in the fluctuations in the poloidal velocity of the turbulence, as if there were better defined ('frozen') flows patterns in H-mode.

  Intermittent activity in H-mode correlates well with the pedestal electron density (and pressure). See below.

- Type I ELMs are microscopically similar in NSTX and DIII-D.

  Formed by multiple bursts of dense, hot plasma originating in the pedestal

  Convecting plasma from the LCFS to the wall

  However, velocity profile is flat in NSTX and decays exponentially in DIII-D

- ELMs and intermittency compete for radial transport dominance depending on local collisionality

Institution List

1) University of California-San Diego, La Jolla, California, USA
2) Nova Photonics, Princeton, New Jersey, USA
3) University of Wisconsin-Madison, Madison, Wisconsin, USA
4) Princeton University, Princeton, New Jersey, USA
5) Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
6) University of California-Los Angeles, Los Angeles, California, USA
7) Lawrence Livermore National Laboratory, Livermore, California, USA
8) Sandia National Laboratories, Albuquerque, New Mexico, USA
9) Lodestar Research Corp, Boulder, Colorado, USA
10) General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA