Investigating small-scale edge turbulence with the NSTX-U GPI diagnostic

N. Mandell, S. Zweben, W. Guttenfelder, Y. Ren, S. Sabbagh

APS DPP
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Abstract

The Gas Puff Imaging (GPI) diagnostic on NSTX has previously been used to measure medium-scale edge turbulence with correlation lengths $L_{pol}, L_{rad} \sim 2$ - 20 cm, corresponding to $k_{\perp}\rho_s \sim .1$ - 1. Some smaller-scale structures down to ~ 1 cm were occasionally observed, but not very clearly. Therefore the GPI optics have been upgraded using a new zoom lens system to investigate smaller-scale structures down to a scale length of 1 mm for NSTX-U. We present the previous best measurements of small-scale structure in GPI, and compare them with prior observations from the high-k scattering diagnostic on NSTX, and with calculations of ETG modes in NSTX. We also present details on the new optics, and describe the effects of field line curvature on limiting the spatial resolution of the GPI system.

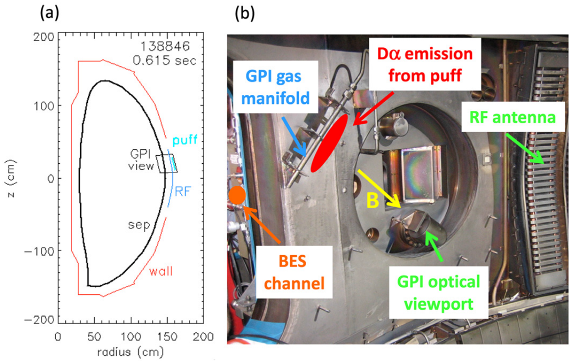
Motivation: Why is turbulence important?

- Turbulent fluctuations cause transport of heat and particles, which degrades confinement

$$\tilde{\Gamma}_e = \langle \tilde{n}_e \tilde{V}_{E_r} \rangle, \qquad \tilde{Q}_e = \frac{3}{2} \langle \tilde{p}_e \tilde{V}_{E_r} \rangle \qquad \text{(quasilinear)}$$

- Turbulence can arise from drift wave microinstabilities:
  - Ion Temperature Gradient (ITG), Trapped Electron Mode (TEM), and Electron Temperature Gradient (ETG), etc
- Understanding structure and dynamics of turbulence is critical to developing methods for turbulent transport reduction
- Core turbulence is somewhat well understood from theory/simulation, but edge region is more complicated
  - Sources and sinks, plasma-wall interactions, more neutrals/impurities, large fluctuation levels ($\tilde{n}/n \sim 0.3$)
- Edge turbulence affects edge profiles and pedestal, which then affects core

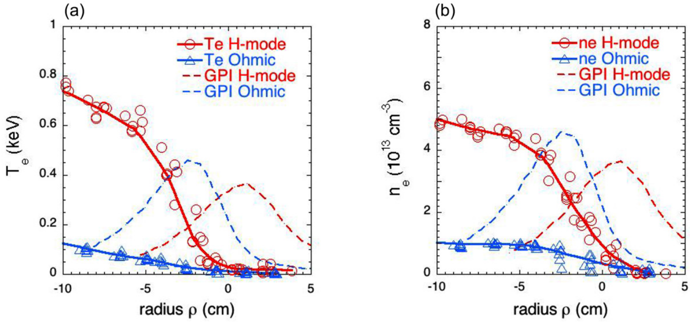
GPI Setup



- Neutral deuterium gas puffed at edge (3-6 Torr-$\ell = 2$-4×10^{20} atoms)
- Interactions with electrons produce visible D_α emission (656.2 nm)
- View angle aligned with local B ($k_\perp \gg k_\parallel$)

Zweben et al, Plasma Phys. Control. Fusion 56 (2014)

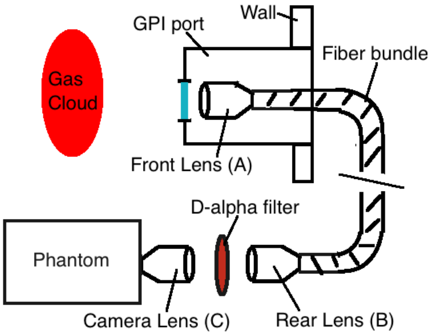
GPI Signal Location



- GPI signal (dotted) peaks within ± 2 cm of separatrix
- Usable data over ± 4 cm around sepatrix
  $\rightarrow$ bottom of pedestal in H mode

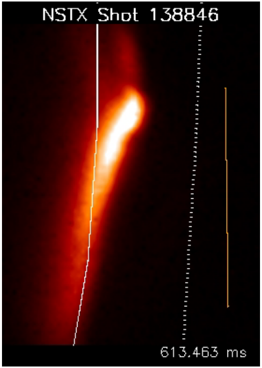
Zweben et al, Nucl. Fusion 55 (2015)

Optics Setup



- Schott Fiber Optic Image Bundle:
  - Coherently transfers 8x10mm image
  - 800x1000 array of 10μm elements
- Phantom v710 camera:
  - $\sim$400,000 fps for 80x64 pixel image

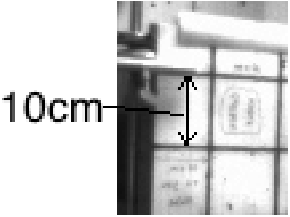
2010 Optics Setup



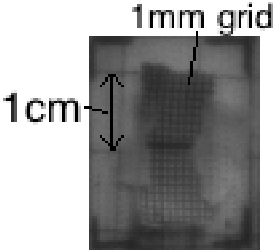
- Imaged region: 24 x 30 cm
- Front Lens (A): 25mm f/1.3 (fixed focal length)
- Rear Lens (B): 50mm f/1.4 (fixed focal length)
- Camera Lens (C): 50mm f/1.2 (fixed focal length)

2015 Zoom Optics Upgrade

- Goal of zoom upgrade: achieve resolution on order of 1 mm (ETG scale)
- Use zoom lens (f=8-48mm) for Front Lens (A) and Camera Lens (C)



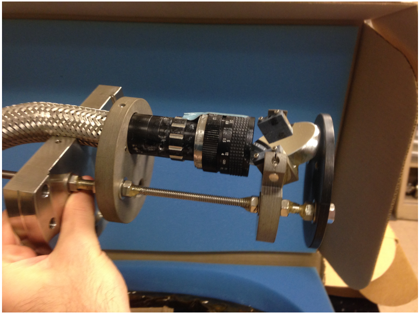
$f_A = 8,\ f_C = 25$
Imaged region: 25 x 30 cm
Reproduces 2010 view



$f_A = 48,\ f_C = 48$
Imaged region: 2 x 2.5 cm
~ 12x zoom

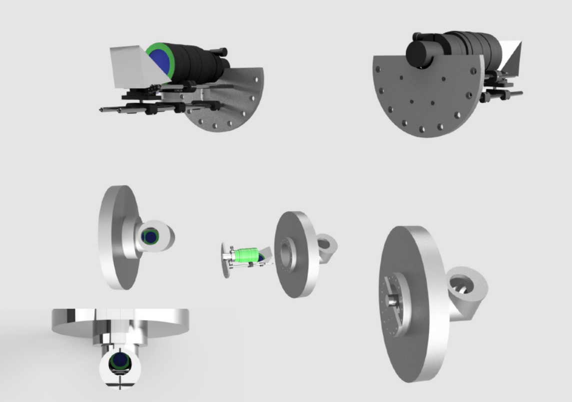
*** Max zoom setting (right) allows resolution of $\lesssim 1$ mm ***

Front end optics



- Left: 2010 front end optics, with fixed focal length lens, f=25mm
- Right: 2015 front end optics, with new zoom lens, f=8-48mm

CAD prototypes for zoom optics mounting



- Can adjust zoom manually without removing optics from port
- Adjustable mirror angle allows view to be shifted radially

What are we measuring with GPI?

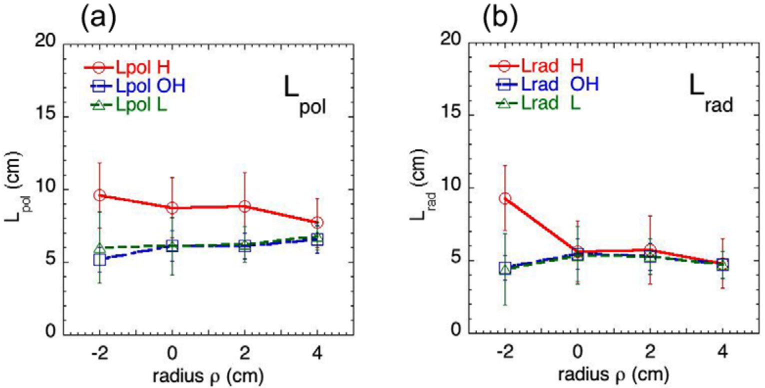
- Intensity of D_α emission from $n = 3 \rightarrow 2$ transition given by

$$S(photons/s\ m^3) \sim n_0 f(n_e, T_e)$$

- $n_0 =$ local neutral density
- $f(n_e, T_e) =$ density ratio between neutrals in upper state of transition ($n = 3$) to those in lower state ($n = 2$)
- We assume that fluctuations dominated by local electron density and temperature fluctuations
- If we take $f(n_e, T_e) \sim n_e^\alpha T_e^\beta \Rightarrow \delta S/S \sim \alpha \delta n_e/n_e + \beta \delta T_e/T_e$

$\Rightarrow$ Intensity fluctuations correspond to fluctuations in the electron density and/or temperature

Correlation Length Measurements



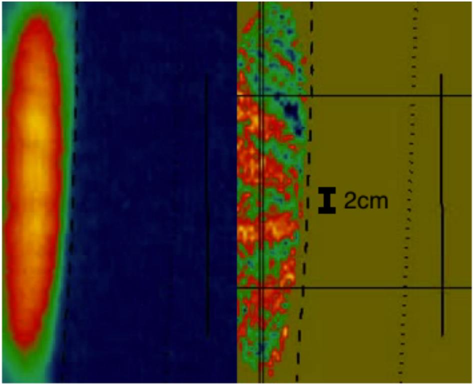
- Turbulence seem so far is well above resolution of 2010 optics
- Correlation lengths inside separatrix ~ 2x larger for H-mode

Zweben et al, Nucl. Fusion 55 (2015)

Isolating small(ish)-scale fluctuations from 2010

- Some small-scale structure ~ 1 cm seen in 2010 data

Raw intensity data S(x,y)

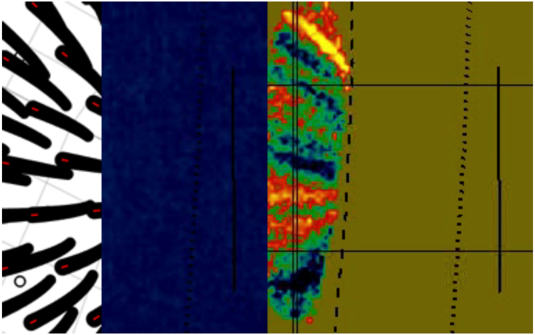


Fluctuating intensity $\tilde{S}$(x,y)

$S(x,y) = \overline{S(x,y)} + \tilde{S}(x,y)$, where $\overline{S(x,y)}$ is averaged over .2 ms (80 frames)

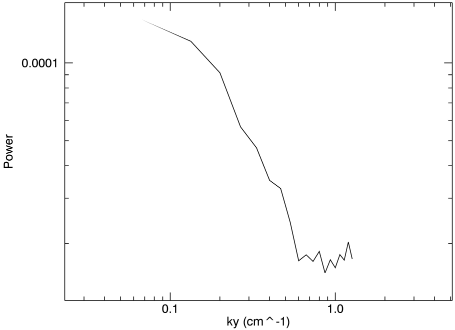
$$\Rightarrow \tilde{S}(x,y) = S(x,y) - \overline{S(x,y)}$$

Field line curvature limits radial resolution



- Left: EFIT reconstruction of field lines extending through puff region (~ 20 cm along field line)
- Angles of elongated bands on right consistent with angles of field lines on left
- $\Rightarrow$ Bands indicate elongation along field lines, not radial elongation
- Limits radial resolution to $\sim 1 - 2$ cm; also limits poloidal resolution away from midplane of image

Poloidal fluctuation spectra



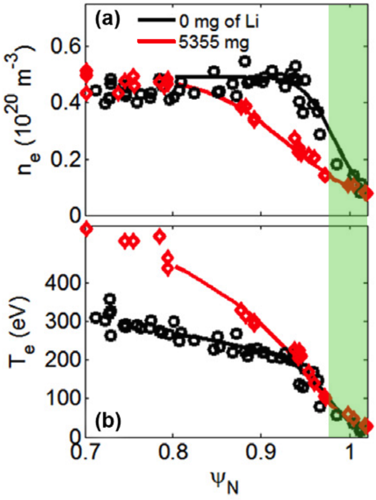
- Poloidal (y) spectrum taken over narrow boxed region
- $k_{pol} \gtrsim 0.5\ cm^{-1}$ not well resolved
- With zoom upgrade, hope to be able to resolve up to $k_{pol} \sim 5\ cm^{-1}$

Electron transport in NSTX $\rightarrow$ ETG

- In NSTX, ion thermal transport is near neoclassical levels; thermal losses from electrons dominant
- ETG modes are a candidate for explaining electron transport in NSTX: e.g. Mazzucato et al, PRL 101 (2008); Ren et al, PRL 106 (2011); etc.
- High-k microwave scattering diagnostic has shown evidence of ETG
- ETG turbulence: $\rho_s^{-1} < k_\perp \lesssim \rho_e^{-1} \Rightarrow \boxed{2 < k_\perp < 200\ cm^{-1}}$

$\Rightarrow$ Need zoom upgrade to see ETG modes with GPI

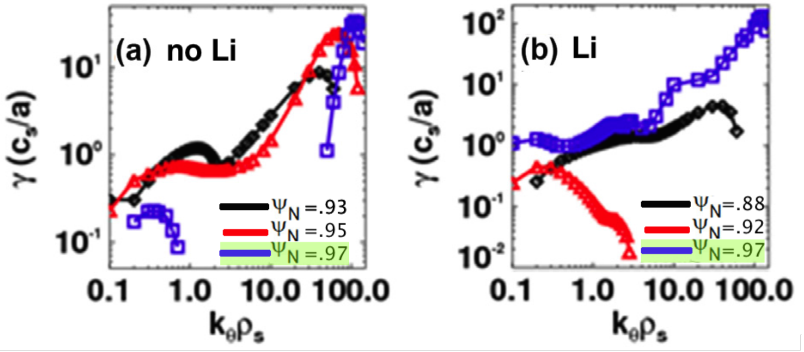
Effect of Lithium PFCs on Pedestal



Canik et al, Nucl. Fusion 53 (2013)

- Profiles from Thomson scattering
- Black pre-lithium
- Red with 5355 mg lithium
- Lithium reduces ∇n_e in pedestal by $\sim 50\%$, consistent with reduction of recycling
- Near edge (in GPI region), ∇T_e is stiff
- Green indicates approximate expected GPI signal region

Effect of Lithium PFCs on Microinstabilities



- Growth rates from GS2 (a) without lithium, (b) with lithium
- Blue curves at radius of $\Psi_N = .97$, which is approx. GPI location
- ETG modes in range $1 < k_\theta \rho_s \lesssim 50$ predicted to be unstable only with lithium

Canik et al, Nucl. Fusion 53 (2013)

ETG as mechanism for ∇T_e stiffness

- Proposed mechanism:
  - Without lithium, ETG transport may be negligible compared to ion scale (low-k) transport
  - As lithium is added, ∇n_e decreases $\rightarrow$ ETG transport becomes stronger
  - Strong ETG prevents ∇T_e from increasing, keeping T_e profile stiff near edge
- Important because stiffness of ∇T_e $\rightarrow$ lower bootstrap current $\rightarrow$ less drive for peeling-ballooning modes $\rightarrow$ less ELMs

We plan to investigate this mechanism with zoom-upgraded GPI by comparing high-k fluctuation spectra with and without lithium PFCs

Summary & Future Work

- Edge turbulence must be better measured and understood to improve performance
- GPI diagnostic has produced good results for measurements of medium-scale turbulence
- GPI diagnostic has been upgraded with zoom capabilities, with the goal of measuring small-scale structure in NSTX-U edge turbulence
- Experiment planned to investigate small-scale structure with and without lithium PFCs, to assess role of ETG in stiffness of T_e profile
- Plan to scan B field tilt to optimize view alignment and resolution
- Develop new analysis techniques for movies
- Implement synthetic GPI diagnostic in turbulence simulations