Theory and Experimental Analysis of Blobs in the NSTX Boundary Plasma*

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Introduction

Background & Motivation

- Both theory and experiment from many devices suggest that convective "blob" transport in the SOL can compete with and/or dominate diffusion.
- Convective "blob" transport in the SOL is important:
  - controls density in far SOL ⇒ main chamber recycling
    - chemical erosion, wall particle content (tritium inventory)
  - may impact energy flow in SOL (ELMs) ⇒ influence divertor heat loads and possibly short circuit divertor (heat goes across not along B)
- Fundamental understanding of SOL transport is badly needed.
  - predictive models of SOL width for divertor design (ITER)
  - SOL environment for RF antennas
  - H-mode formation and control
- Gas Puff Imaging (GPI) diagnostic enables 2D visualization of edge/SOL turbulence
  - blob-like objects observed on GPI
  - unique opportunity for analysis and comparison with basic theory models

Outline of the poster

I. Extracting n_e and T_e of a blob from GPI intensity data

II. Statistical blob model and comparison with GPI data

III. 2D fluid simulation comparison with GPI data

I. Extracting n_e and T_e of a blob from Gas Puff Imaging (GPI) intensity data

for GPI experiment see Lowrance et al., poster LP1.006

Procedure

Theory

- Intensity of light emission I is related to the neutral density n_0, the plasma density and temperature n_e and T_e, and an atomic physics function F by

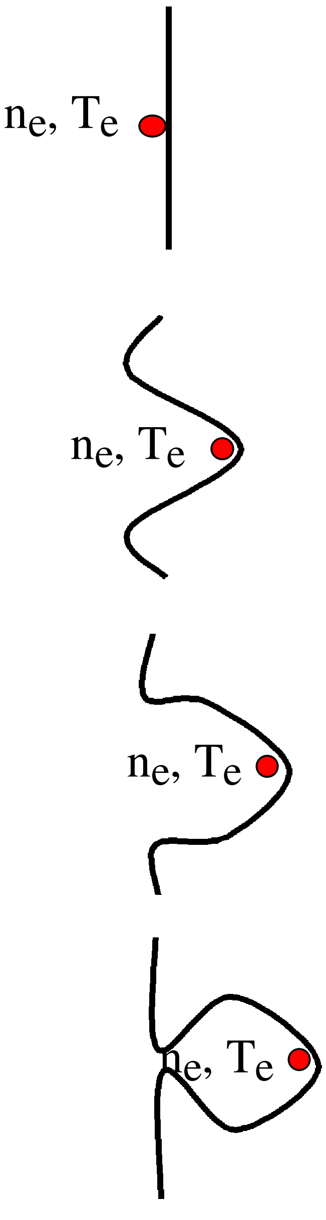
$$I = n_0 F(n_e, T_e)$$

- If n_0 is known and the 2D image of intensity I is measured by the GPI camera, then F can be inverted for n_e and T_e if we assume that $T_e = T_e(n_e)$.
- $T_e = T_e(n_e)$ is justified for interchange turbulence when $E \times B$ turbulent motion passively convects n_e and T_e together. [Meier (2001), Rudakov (2002)]
- The mapping $F^{-1}(I/ n_0)$ to n_e and T_e is determined from the equilibrium frame using the Thompson Scattering (TS) data to calibrate I.
- On the time and space scales of the turbulence we assume n_0 = constant, i.e. calculate n_0 for the equilibrium and use it for the turbulence
- caveat: parallel plasma losses are neglected. Applies for fast moving plasma blobs with $\tau_{convection} < \tau_{||}$

basic idea: measure I and map to n_e and T_e from a knowledge of n_0

Schematic of inversion procedure I ↔ n_e , T_e

nonlinear interchange mode and blob formation



$I = n_0 \, F(n_e, T_e)$

equilibrium:

TS ⇒ n_e, T_e

DEGAS ⇒ n_0

passive convection assumption

$T_e = T_e(n_e)$

$\Rightarrow$

$I = n_0 \, F(n_e)$

$\Rightarrow$

given n_0 we can map

$I \leftrightarrow n_e$

in turbulent state

Equilibrium calibration

Goal

- Use the calculated neutral density (not absolutely calibrated), the TS data and an equilibrium GPI frame to construct the mappings I → n_e,T_e that will be used to interpret the turbulent GPI images.
- Here *equilibrium* means quiescent background plasma on which intermittent *blobs* propagate.

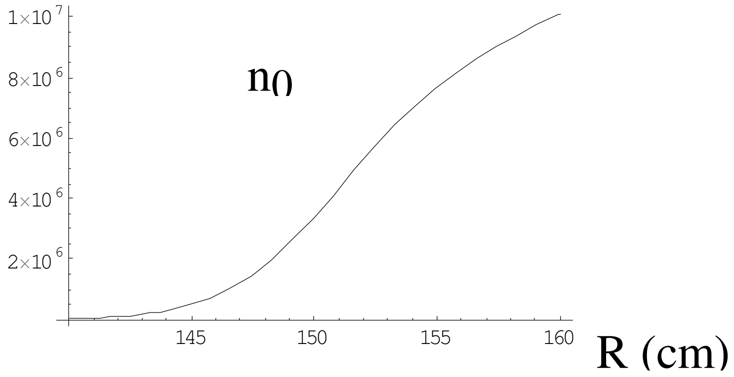
Neutral density

- calculated from DEGAS-2 using TS profiles and geometry as input
  - *see Stotler et al., poster LP1.007*
- shifted and rotated so that the calculated emission pattern aligns with the GPI emission image
- fit to a separable function of pseudo-flux coordinates (x, y) = (radial, poloidal)

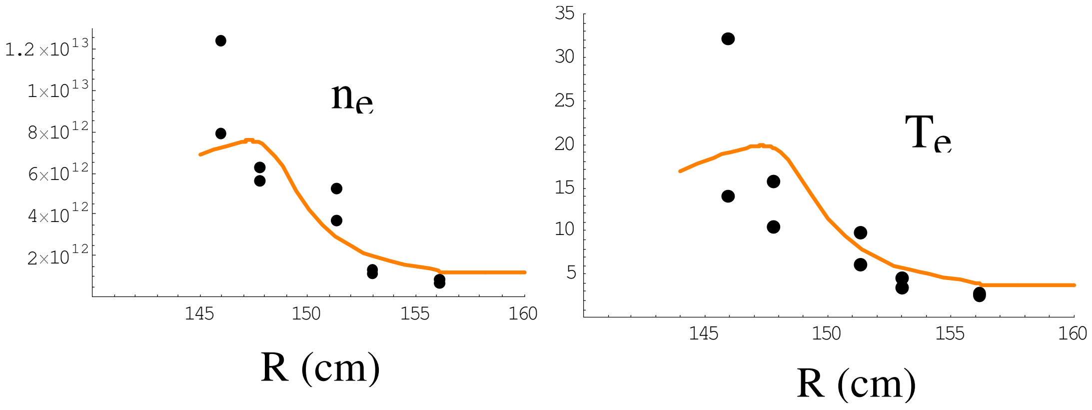
Equilibrium

- take the time *median* over the 28 frames of the GPI movie as the equilibrium GPI frame
  - median eliminates intermittent objects (blobs) from the equilibrium
- use smooth fits to the TS data projected along field lines to construct the *equilibrium* $n_e(x)$,$T_e(x)$ profiles

Sample equilibrium reconstruction



Radial dependence of neutral profile $n_0(R)$ from DEGAS-2 (arbitrary normalization). R values are flux mapped to the midplane.

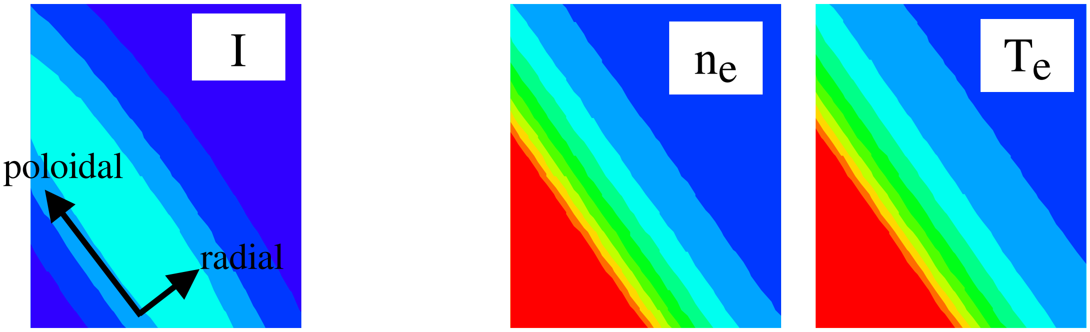


Comparison of reconstructed profiles with TS data. black dots: TS data; orange curve: reconstructed profiles using our procedure on the equilibrium frame.

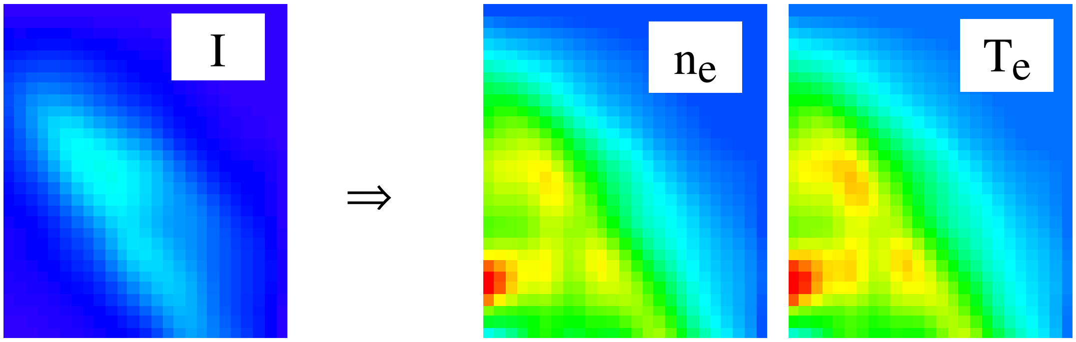
Reconstruction is not accurate into the core where both I and n_0 become small. (i.e. one gets $F = 0/0$)

Compare equilibrium & turbulent frames

DEGAS equilibrium (pseudo-frame)

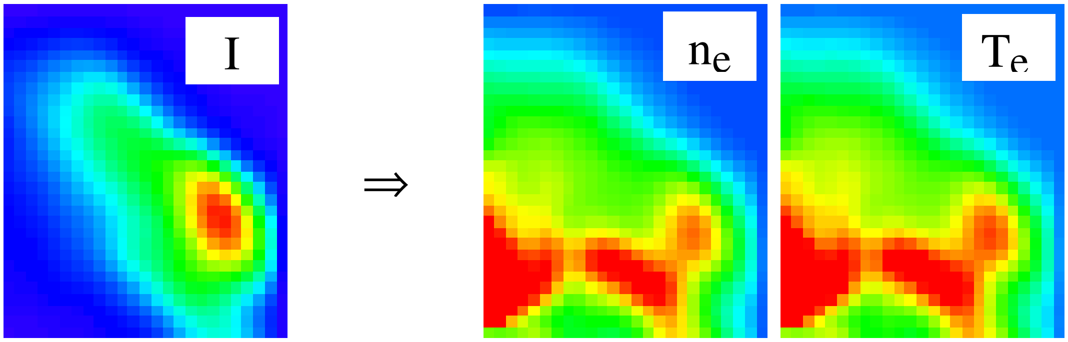


median frame

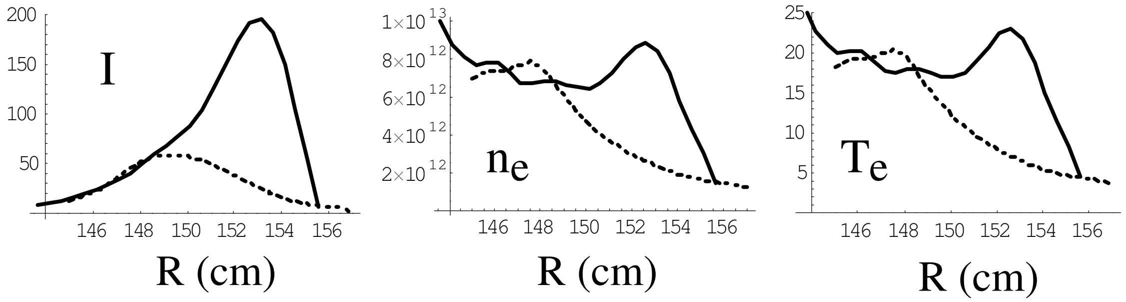


Upper portion of the image plane of the GPI camera. Reconstruction is poor to the lower left (I and n_0 small)

turbulent (blobby) frame



comparison of cuts across the frame



equilibrium dashed, blobby solid

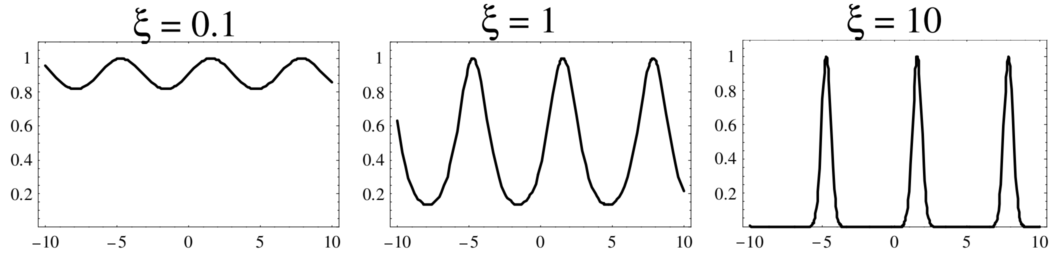
notes

- cuts normal to the flux surfaces (also see 2D images) suggest that the blob is not completely detached, and has somewhat of a radial streamer character
- intensity appears detached because n_0 increases strongly to the right
- the blob or radial streamer in this H-mode data (NSTX #108311) has a characteristic
  - $n_e \sim 10^{13}/cm^3$
  - $T_e \sim 20$ eV.

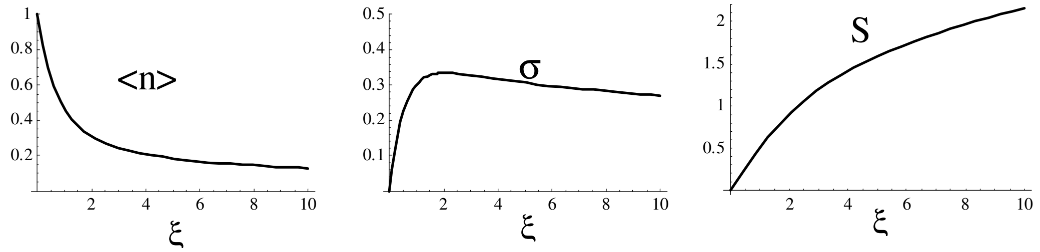
II. Statistical blob model and comparison with GPI data

Model: blob train passing a probe

$$n(t) = n_0 \exp\left[\xi\left(\sin\frac{2\pi t}{\tau} - 1\right)\right]$$

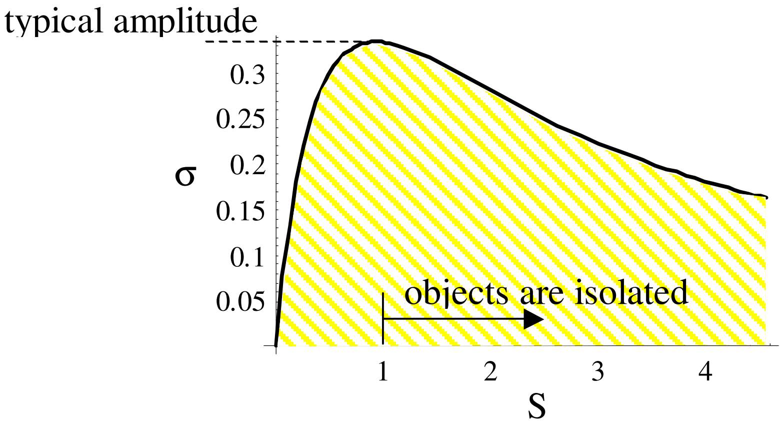


Above: n(t) for various values of ξ



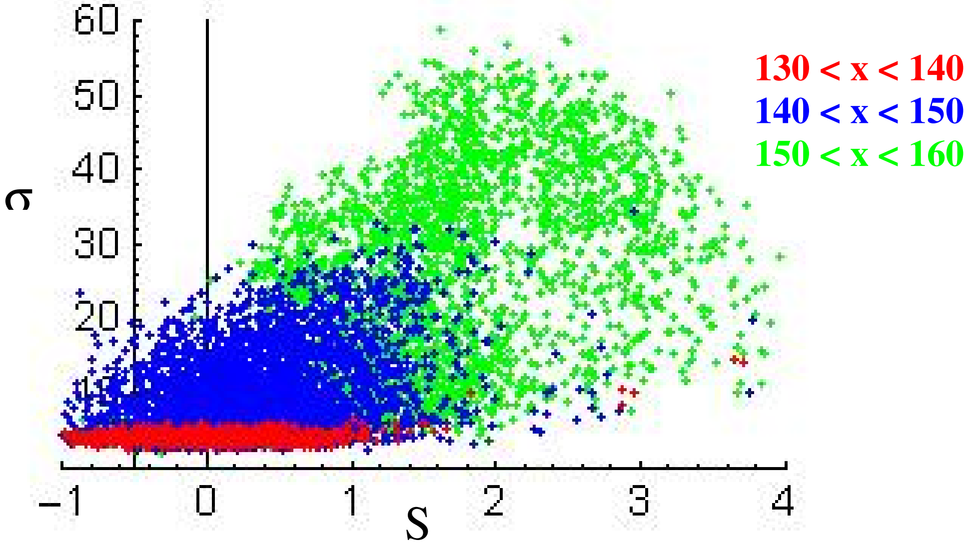
Statistic moments obtained by analytic calculations:

$< n >= n_0 e^{-\xi} I_0(\xi)$; $\sigma = n_0 e^{-\xi}\sqrt{I_0(2\xi) - I_0(\xi)^2}$ etc.



GPI Data

- use the 28 GPI movie frames and assumed statistical invariance in y to perform statistical averages
- movie of H-mode shot shows one large blob, several smaller, less obvious ones, and some fluctuations
- analysis is based on statistics of intensity I
    - ○ statistics of n_e is similar but noisier due to errors in inversion process
- distribution of blob amplitudes and impact parameters fills in shaded area below characteristic curve of model
- skewness S increases with x (distance into SOL)
- characteristic event amplitude σ increases with x
- these features are similar to what has been reported from probe data: here we can see the 2D patterns that go with the statistics



Statistics of emission from GPI movie for NSTX H-mode data. The s vs. S plot is insensitive to nonlinearities in $I(n_e,T_e)$.

III. 2D nonlinear fluid simulation comparison with GPI data

- compare the properties of a blob observed with GPI (e.g. radial and poloidal velocity, shape and size, spin …) with analytical theory and numerical simulations
  - ○ S.I. Krasheninnikov, Phys. Lett. A 283, 368 (2001).
  - ○ D.A. D'Ippolito, J.R. Myra, S.I. Krasheninnikov, Phys. Plasmas 9, 222 (2002).

2D nonlinear simulation code

ion polarization drift

sheath potential

curvature drift

viscosity

$$\cancel{\frac{d}{dt}\nabla^2\Phi} = \alpha(\Phi - \Phi_B) - \frac{\beta}{n}\frac{\partial p}{\partial y} - \nu\nabla^2\Phi$$

diffusion

$$\frac{dn}{dt} = D\nabla^2 n$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla$$

ExB convection

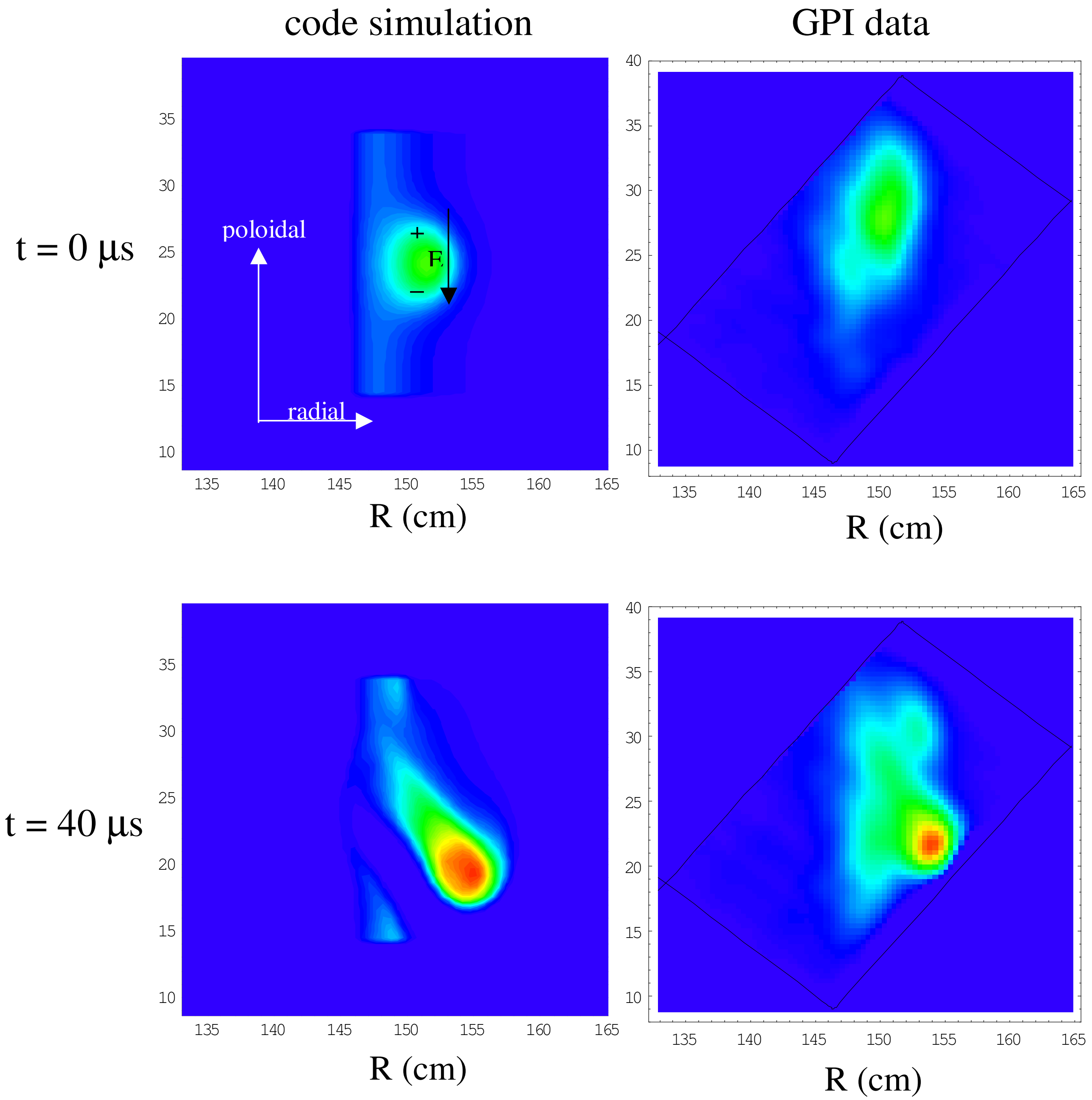
$$\mathbf{v} = \mathbf{b}\times\nabla\Phi$$

$$\Phi_B = \Phi_{B0}T(n)$$

Bohm sheath potential

- drop $d/dt\ \nabla^2\ \Phi$ for large blobs $(\rho_s/a)^4 << \alpha$ $\Rightarrow$ coherent objects not turbulence
- diffusion term D is small (just for numerical smoothness)
- take $\nu \sim \mathbf{v}\cdot\nabla \sim \Phi_{B0}/a_s^2$ where $a_s^2 \equiv \nu/\alpha$ is the viscous smoothing radius
- $\beta/\alpha \equiv L_{||}/R \equiv q_{eff}$ controls the blob's radial motion

Code / GPI data comparison



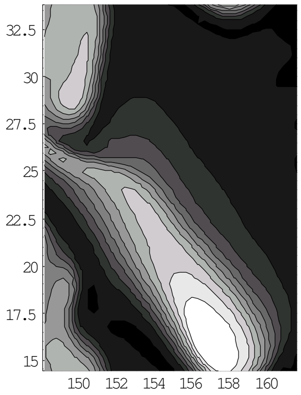
Comparison of simulated (left) and GPI (right) images at two times, t = 0 (top) and t = 40 μs (bottom) for (H mode shot NSTX #108311). Camera view is indicated by rectangle on GPI images. Midplane R is indicated.

Simulation Notes:

- background n_e and T_e profiles from Thompson data
- initial condition for blob
  - n_e and T_e peak amplitude is taken from reconstruction procedure
  - size is taken from GPI image
- simulated emission intensity is obtained from effective 2D neutral density profile (DEGAS-2, Stotler, et al., paper LP1.007) and atomic physics

Main features:

- Blob moves down (poloidally) because of E×B drift in Bohm sheath potential.
- Blob moves out (radially) because of curvature drift.
- Blob changes shape in time and leaves a wake (radial streamer) because of drag on background plasma. Leading edge also steepens (as seen in probe data).



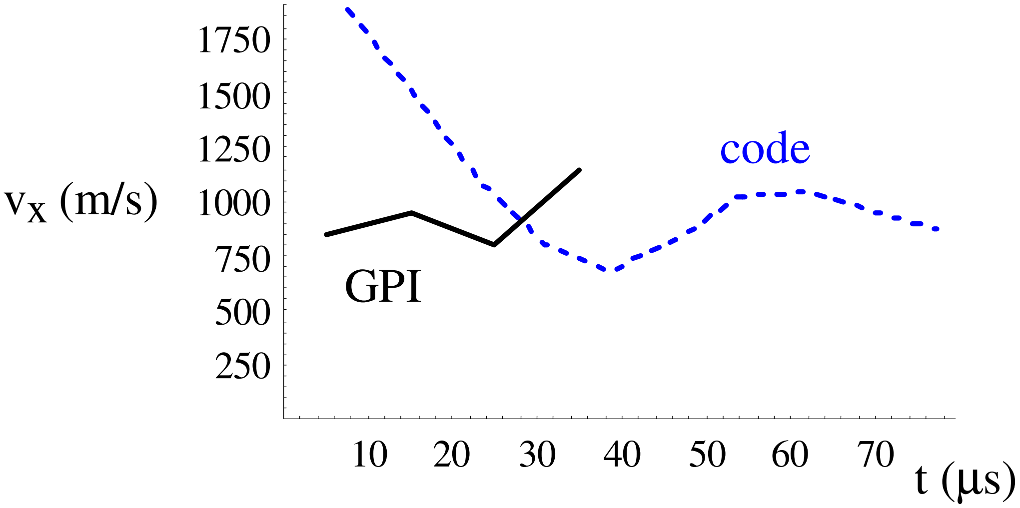
Blob density contours from simulation.

R (cm)

Also:

- simulated t = 40 μs image is brighter than GPI
  - may indicate some blob cooling is occurring
  - uncertainties in orientation of image wrt. n_0
- emission brightens between t = 0 and 40 μs because blob is propagating into region of increasing $n_0(x)$

radial velocity

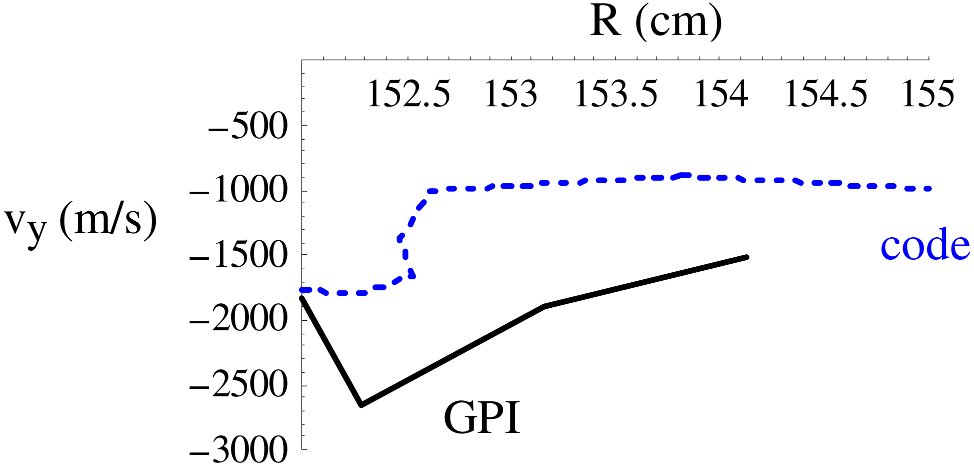


Evolution of radial velocity for simulated and observed blob (H mode shot NSTX #108311). q_{eff} = 13.5 fits the data well.

Simulation Notes:

- simulation is run longer than data to allow transient to relax
- spinning blob: $\Phi_{B0} = 4.5$, parallel connection to divertor plates is assumed
- simulation parameters are $q_{eff} = 13.5$ chosen to fit the data, $a_s = 10$.
- taking uncertainty of parameters into account, $q_{eff} > 8$ is needed to give reasonable agreement with observed v_x.
- need to compare $q_{eff} = L_{||}/R$ with geometrical value from EFIT

poloidal velocity

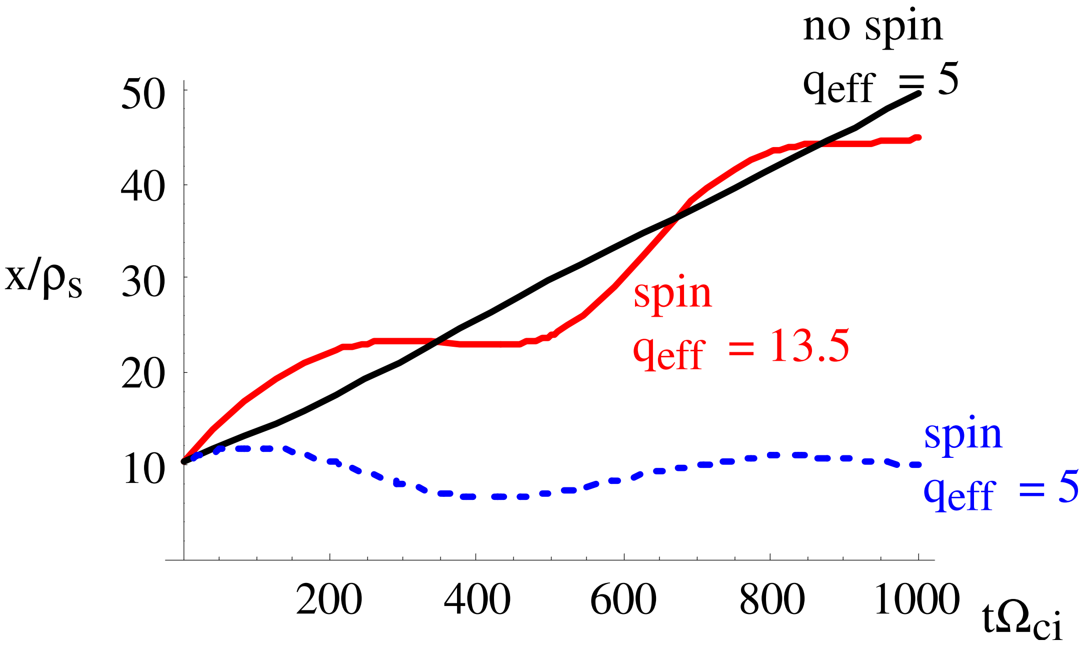


Poloidal velocity vs. blob position (mapped to the midplane) for simulated and observed blob (H mode shot NSTX #108311).

Notes:

- same simulation case as above
- Bohm sheath $\Phi \sim 4.5\ T_e$ would give monotone v_y
  - near separatrix Reynolds Stress reverses E_r ? (hint of this in data)
- simulated velocity is too small for all reasonable parameter choices ⇒ additional mechanism for edge E_r necessary
  - toroidal rotation?:
    - would need $v_\zeta \sim 6\ (B_\zeta/B_\theta)$ km/s
    - $E_r \sim 0.6$ kV/m

role of blob spin and q_{eff} in simulations



Evolution of radial position of blob in simulations that vary blob spin and q_{eff}. Similar radial velocities (that fit data) are achieved with smaller $q_{eff} = 5$ if the blob doesn't spin.

Notes:

- spin $\Rightarrow \Phi_{B0} = 4.5$
  - parallel connection to divertor plates
  - sheath potential $\Phi \sim T$
  - local max of $T \Rightarrow$ spin
- no spin $\Rightarrow \Phi_{B0} = 0$
  - no parallel connection to divertor plates
    - T varies along B, is small at plates
    - blob is localized by resistivity near X-points (analogous to RX mode seem in BOUT and BAL codes)
- spin slows blob down for same q_{eff}
- spinning blob can be trapped by shear layer

Conclusions

- Given the neutral density, the emission intensity I from the GPI diagnostic can be "inverted" to give n_e and T_e for interchange turbulence.
- A sample NSTX H-mode blob has a peak n_e and T_e that is characteristic of its birth surface: $n_e \sim 10^{13}/\mathrm{cm}^3$, $T_e \sim 20$ eV.
    - blob has a radial streamer character, and is more detached in emission I than in n_e because of n_0 profile
- A simple statistical model may be useful in interpreting data. $\sigma(S)$ is non-monotonic; skewness S increases as one goes into the SOL.
- Nonlinear 2D fluid simulations capture many features of the GPI data: poloidal and radial motion, shape distortion.
- NSTX H-mode #108311 has a significant E_r in the SOL other than that of the Bohm sheath. Toroidal rotation may be a plausible explanation.
- The radial blob velocity can be reproduced by the simulations in two scenarios with very different implications:
    - spinning blob with $q_{\mathrm{eff}} \sim 10 \Rightarrow$ parallel connection (and heat pulse propagation) to the divertor plates. Geometry alone may not allow this large a q_{eff}, $\Rightarrow$ more than ∇B (neutral wind, centrifugal)?
    - non-spinning blob with $q_{\mathrm{eff}} \sim 5.$ $\Rightarrow$ parallel disconnection from plates due to X-point or $\nabla_{\|}T$ effects (and hence short-circuiting of the divertor).
- Simulations elucidate blob dynamics:
    - Spin slows down blob v_x,
    - Spinning blob can be trapped by shear flow layer.