Blob birth and transport in NSTX: GPI data analysis and theory

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Background & Motivation

- programmatic: ITER
  - **pedestal/edge parameters** critical for performance, Q ⇒ understand edge T&T
  - **power handling**: PFC damage by impact from blobs, ELMs, short-circuit divertor?
  - **wall content** (tritium inventory)
  - **SOL environment** for RF antennnas
- science: edge and blobs physics
  - **convective** (vs. diffusive) transport
  - **strong nonlinearity** (~ 1 fluctuations, no space scale separation)
  - emergence of **coherent** structures, **intermittency** from turbulence

- competition: parallel transport (well-known) vs. ⊥ convective blob transport
  - need **radial blob velocity v_x** } this talk
  - need **blob parameters** (n, T) } this talk
  - need **rate of blob generation** (for $\langle\Gamma\rangle$)

Preview

- use gas-puff-imaging (GPI) diagnostic to extract blob parameters:
  - birth zone
  - scale size
  - radial velocity v_x
  - density and temperature (DEGAS-2 model using He 5876 emission)
- birth zone and blob parameters are related to the local maximum of the edge $\nabla \mathit{ln}\ \langle p \rangle \Rightarrow$ blob generation by underlying edge instability.
- categorize NSTX blobs by theory regime
- observed v_x bounded by theoretically predicted min and max

Outline

- **theory background**
- **data analysis**
- **future work; conclusions**

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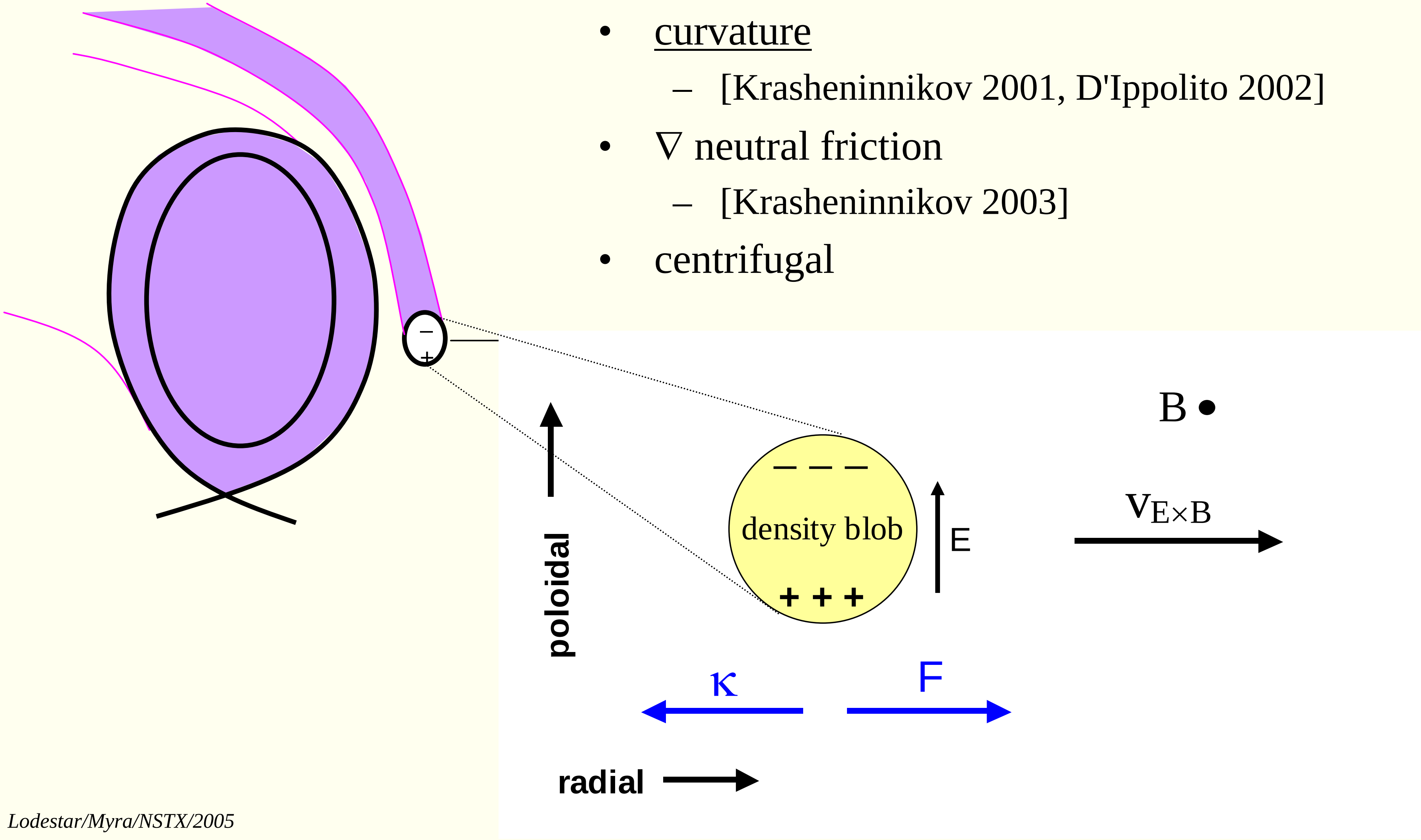
What is a blob?

- blob = flux tube containing (much) more plasma than its surroundings
  - localized ~ 1 density enhancement
  - coherent object formed from edge turbulence
  - filamentary along B, cm-scale across B
- moving blobs are naturally associated with:
  - convective $\perp$ B (non-diffusive) transport
  - intermittency
- evidence for blobs comes from
  - probe data
  - Gas Puff Imaging (GPI) data
  - numerical simulation
- blob physics is relevant to
  - edge turbulence, ELMs, pellets

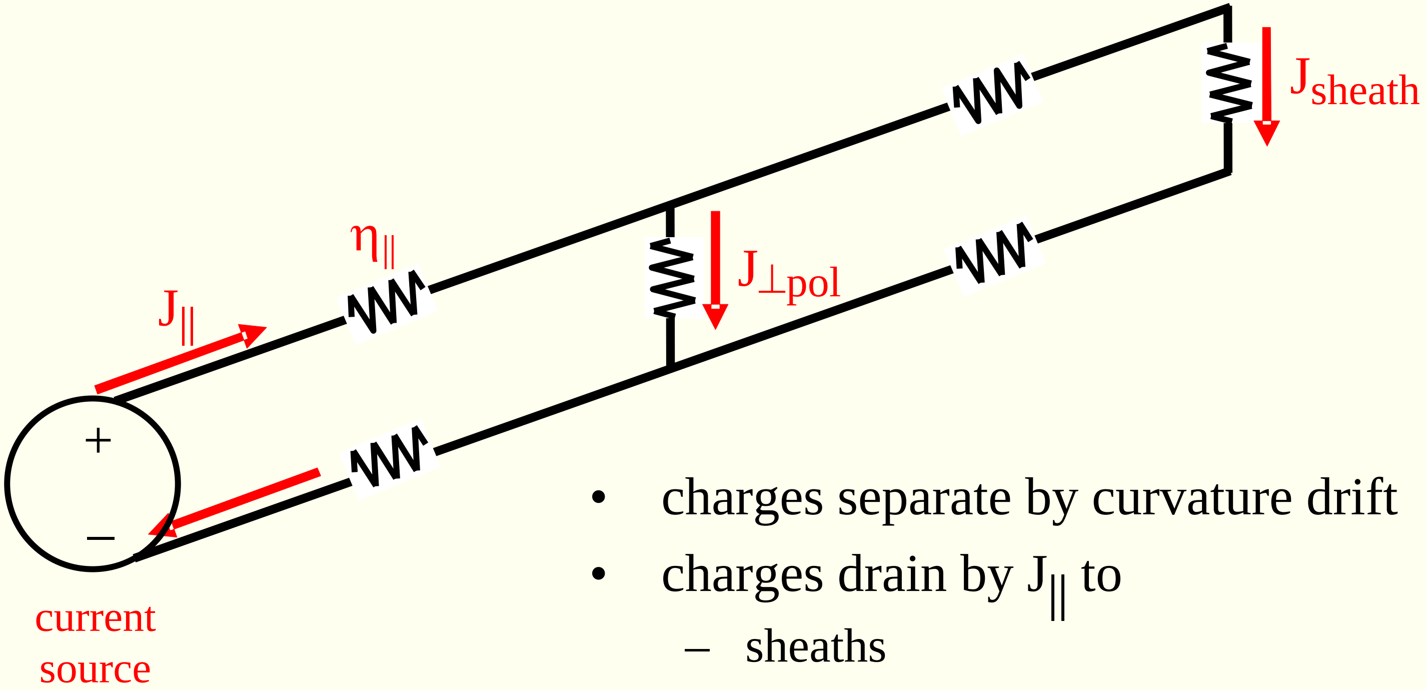
Blob filaments break off from edge plasma, charge polarize and convect outwards

- <u>curvature</u>
  - [Krasheninnikov 2001, D'Ippolito 2002]
- ∇ neutral friction
  - [Krasheninnikov 2003]
- centrifugal



Lodestar/Myra/NSTX/2005

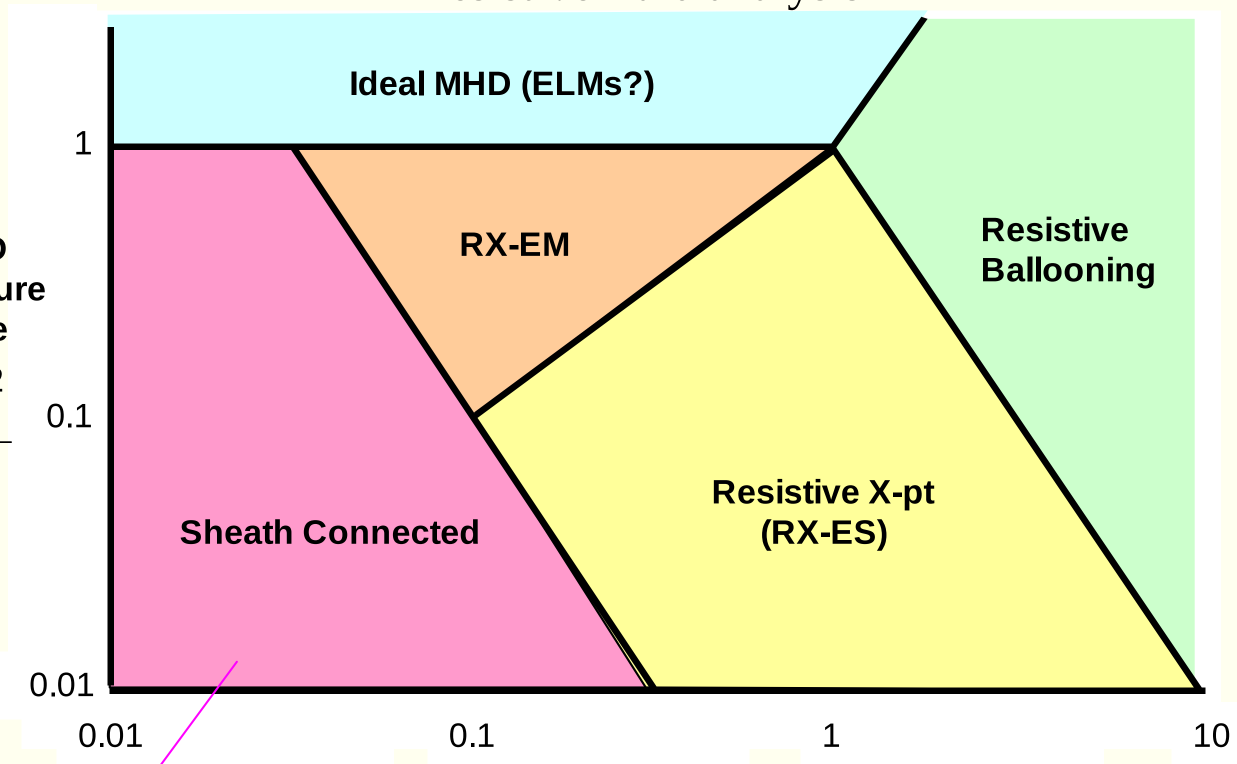
Currents drain charges



- charges separate by curvature drift
- charges drain by $J_{||}$ to
  - sheaths
  - X-point (thin fans reduce ⊥ resistance)
  - outgoing Alfvén waves
- charges mix by spin
- effective circuit resistance ⇒ potential Φ, speed v_x

Current path determines blob regime

resistive fluid analysis



$\frac{\beta_p}{a_b}\frac{L_\parallel^2}{R}$

$\gamma \rightarrow \frac{v_x}{a_b}$

$\frac{\eta_\parallel L_\parallel}{a_b^2}\frac{c^2}{4\pi v_a}$

$$v_x \sim 2.9\times 10^{10}\,\frac{qT_e^{3/2}}{a_b^2 B^2}$$

each regime has a characteristic magnitude and scaling of blob radial velocity

$v_x(n_e, T_e, a_b; B, q, R)$

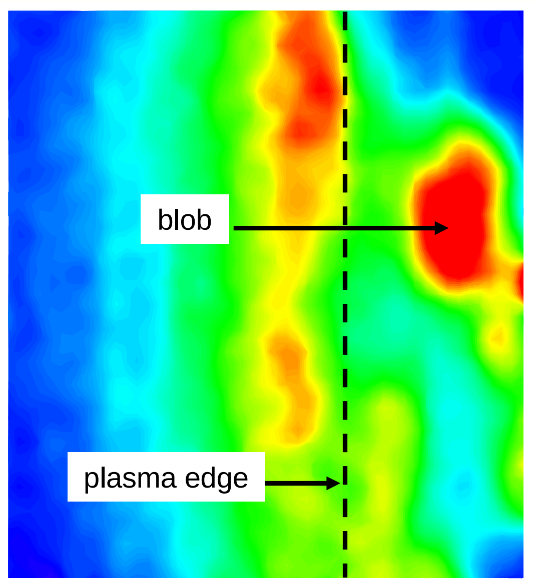
Important parameters affecting blob speed

- scale size a_b
- T_e
- collisionality $\eta_{||}(n_e, T_e)$
- field line geometry $\Rightarrow$ position wrt. separatrix
  - $L_{||}$, (weighted connection length) or $q_{eff} = L_{||}/R$
  - X-pt shear $\Rightarrow \varepsilon_x \sim 1/$(X-pt "fanning")
- amplitude of blob above background plasma, $\delta n/n_{bkgd}$

- theory background
- **data analysis**
- future work; conclusions

Background – GPI experiment

- Gas Puff Imaging (GPI)
  - Zweben 2004; Maqueda 2003; Terry 2003
  - 2D movies of blob motion
- test theory of blob v_x
- difficult to do with probe data alone
  - 1D time-slice through blob
  - unknown impact parameter (no y info)
- NSTX GPI diagnostic well matched to blob dynamics
  - spatially and temporally
- GPI measures light intensity, not n_e, T_e
- new nonlinear camera calibration recently available
  - present results assume camera signal $\propto$ light intensity
  - some details may change (before APS)



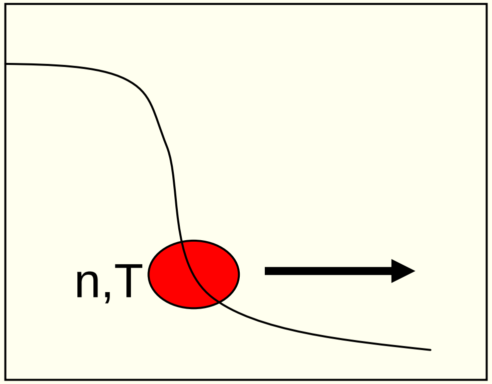
sample GPI frame

shot 112825
L mode 4.5 kG, 800 kA
0.8 MW NBI
He puff (HeI filter)

GPI atomic physics, and modeling

- HeI 5876 line intensity is **$I = n_0 F(n_e, T_e)$**
  n_0 = neutral He density
  $F(n_e, T_e)$ = atomic physics

- 2 basic ideas
  - nonlinear interchange modes **passively convect n_e, T_e** together
    $\Rightarrow$ **$T_e = T_e(n_e)$** from equilibrium
  - n_0 is not measured so: "**calibrate**" I **to** median ("**equilibrium**") n_e, T_e using Thompson Scattering, probe data [Boedo] and DEGAS-2 modeling [Stotler]

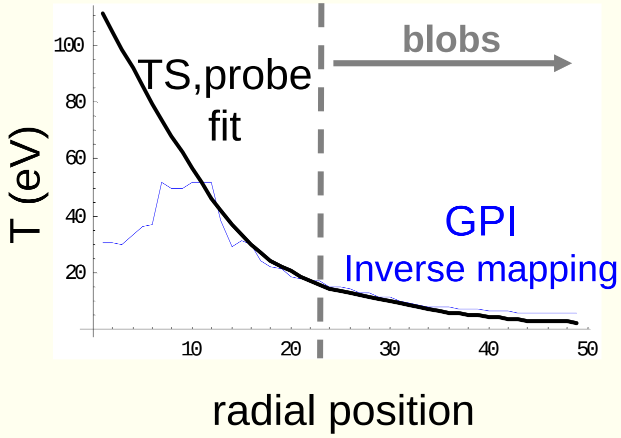


- apply inverse mapping of $I \rightarrow n_e, T_e$ derived from equilibrium profiles to turbulent (bloby) camera frames
  - n_0 unaffected by blobs (assume)

Determination of the n_0 profile

$$n_0 = \frac{I_{camera}}{F(n_e, T_e)}$$

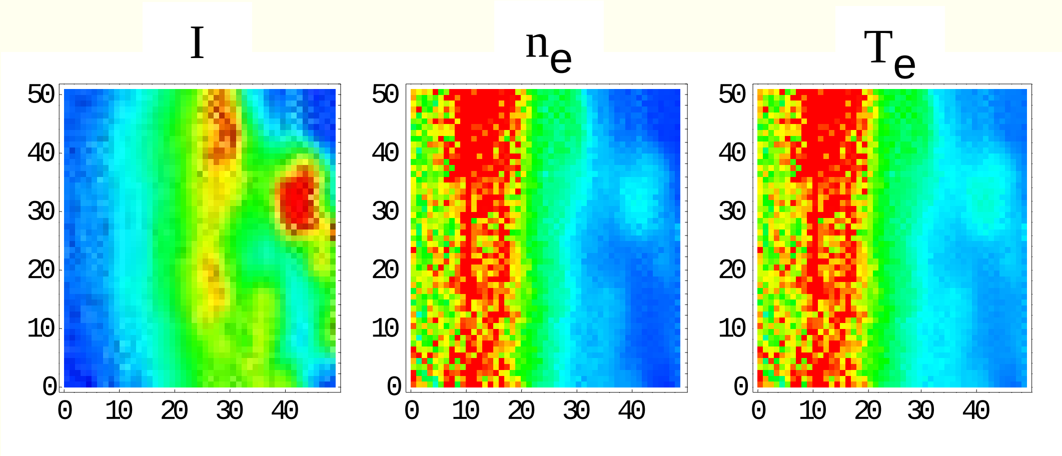
n_0 = neutral He density
$F(n_e, T_e)$ = atomic physics

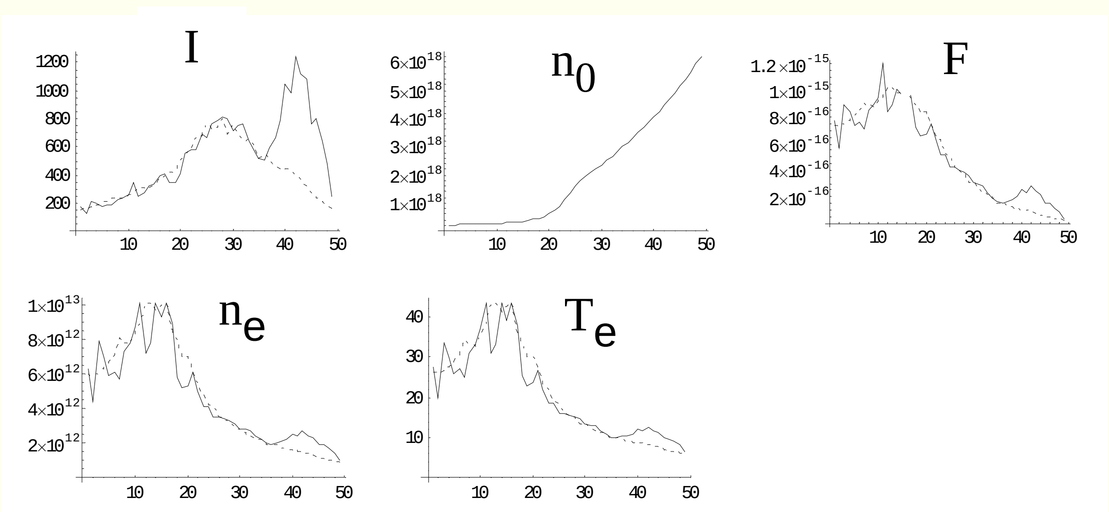


- empirical procedure for deducing effective n_0 works well where I and F are large (inside separatrix for equilibrium)

- use D. Stotler's DEGAS-2 code for n_0 in far SOL and match
  - 3D Monte-Carlo simulation that tracks penetration, ionization, radiation etc. of He states
  - extract chord corresponding to 2D camera view
    - yields effective n_0 profile

Sample “inversion” I → n_e, T_e

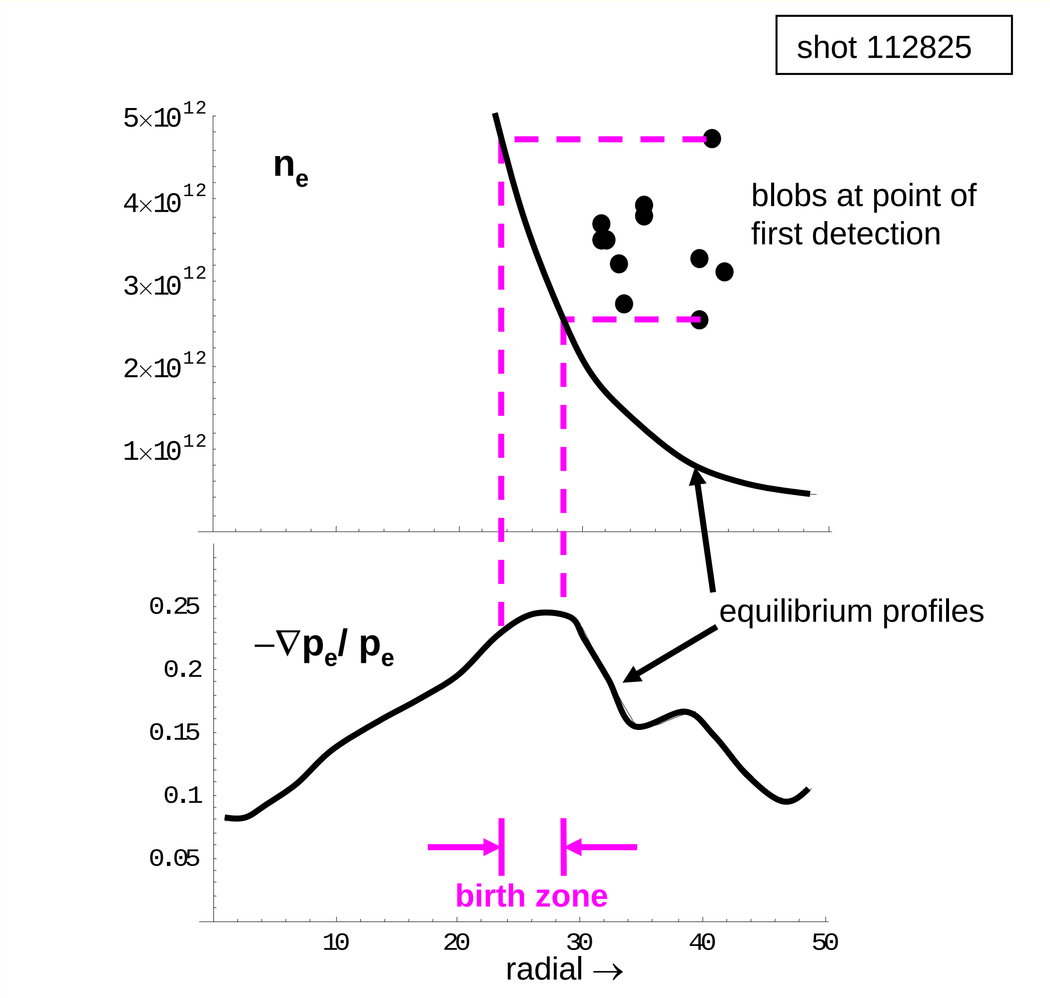




radial cuts through a blob

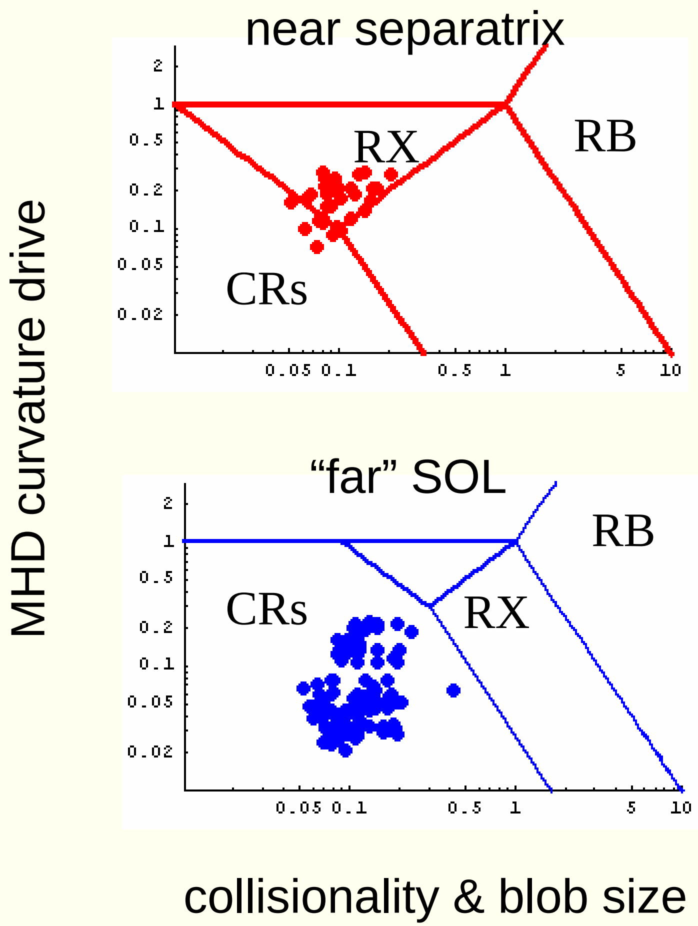
- GPI is a very sensitive blob diagnostic
- allows crude estimate of n_e and T_e of individual blobs
- can project back to determine birth region for each blob

Blob birth zone confirms edge instability drive



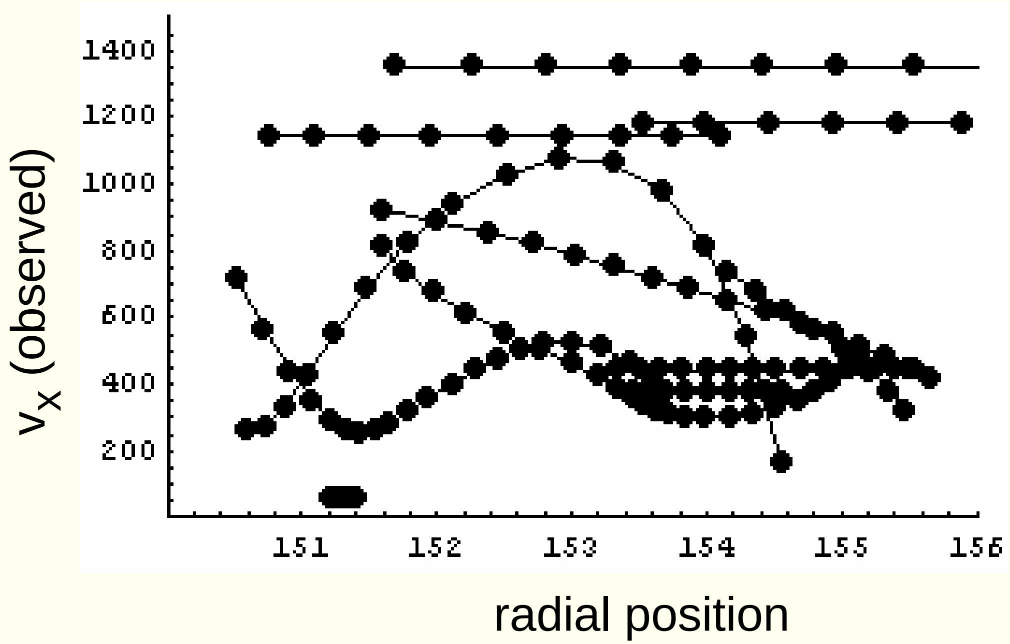
- blobs are born with a density (and temperature) characteristic of where the underlying linear instability peaks
- not e.g.
  - condensation of turbulent structure from deeper in core
  - core SOC avalanche

Regime diagram for "typical" NSTX L-mode blobs



- shot 112825
- blob database using n_e,T_e from "inversion" procedure
- mostly sheath-connected (CRs) regime, near RX boundary
- current loop resistance dominated by sheath resistance with some ⊥ ion polarization currents at X-point
- blobs are well away from resistive ballooning regime (RB)

Observed radial velocity v_x of blob tracks show large scatter



- observed velocities seem “random”
- *what order, if any, is present in this dataset?*
- needs a theoretical framework

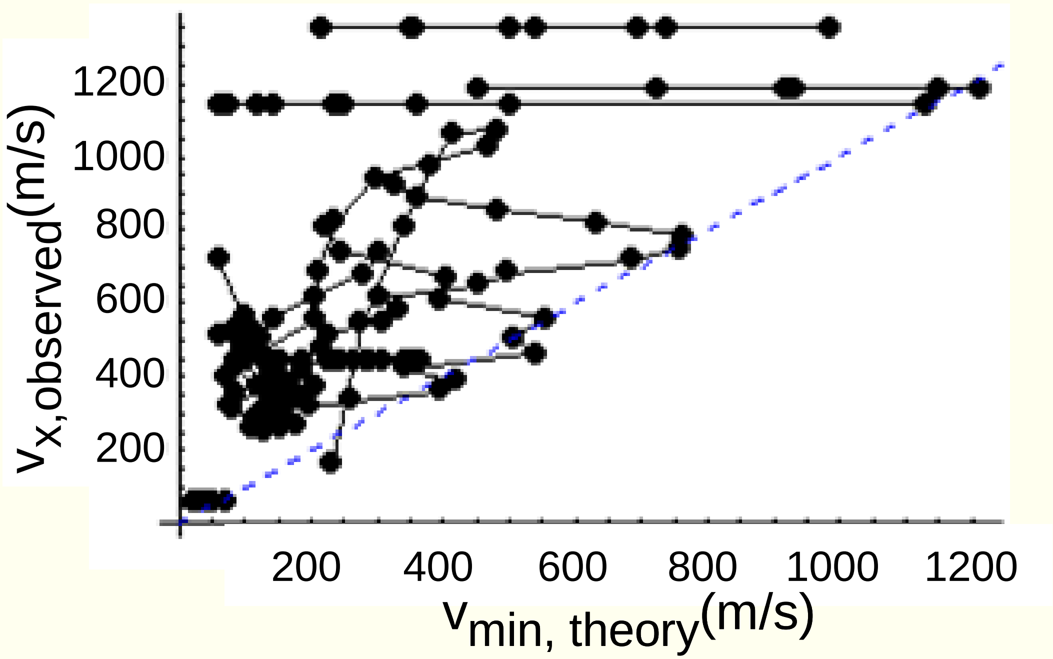
Observed blob velocity is bounded by theoretical minimum

- sheath-connected blobs have minimum v_x of all the regimes

$$v_x \sim 2.9 \times 10^{10} \frac{qT_e^{3/2}}{a_b^2 B^2} f$$

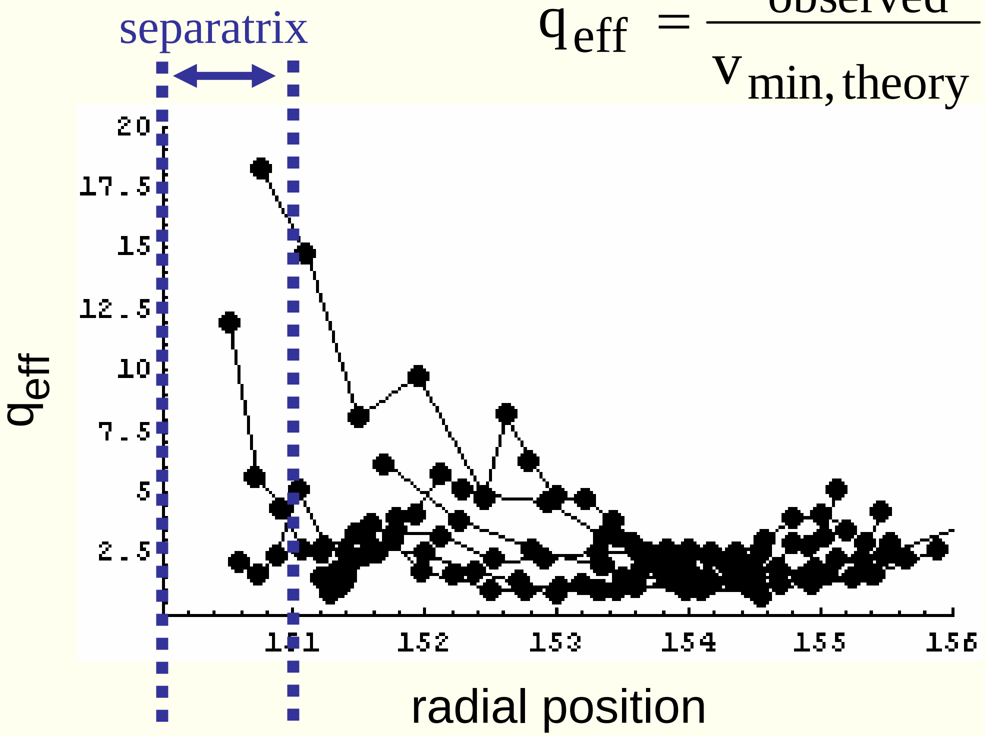
$f \sim \delta p/p \sim$ blob amp above background

- for spatial min set $q = L_{||}/R = 1 \Rightarrow v_{min}$



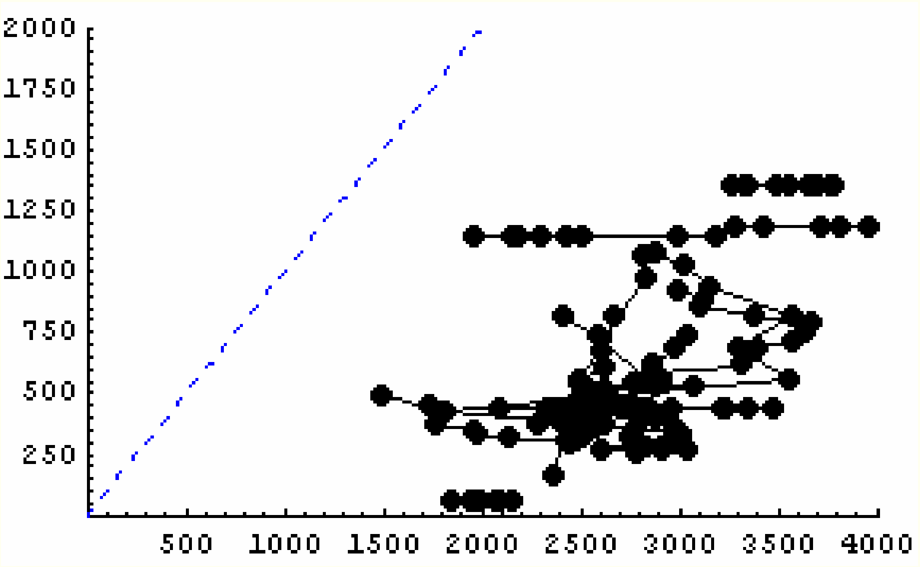
Radial dependence of q_{eff}

$$q_{eff} = \frac{v_{observed}}{v_{min,\, theory}}$$



- trend consistent with q profile expected from geometry
- significant variations of blob velocity remain and are not explained by present model
  - analysis errors?
  - parallel blob structure?
  - blob spin?

Observed blob velocity is bounded by theoretical maximum



$v_{x,\text{ observed}}$ (m/s)

$v_{\text{max, theory}}$ (m/s)

- blob scaling in the resistive ballooning regime gives maximum v_x
- expect and confirm that observed $v_x \ll v_{max}$
- simple theoretical estimates bound the observed blob velocity $v_{min} < v < v_{max}$

$$v_{\text{max,theory}} \sim 6.9 \times 10^5 \frac{a_b^{1/2} T_e^{1/2}}{R^{1/2}} f$$

- theory background
- data analysis
- **future work; conclusions**

Ongoing & future work

- effects of new nonlinear camera calibration (APS)
- simplified, more automated analysis that doesn’t require tedious DEGAS-2 modeling
- application to more shots, and blob regimes
- numerical simulation with 2D turbulence code (D. Russell’s SOLT code)
  - detailed blob dynamics
  - blob generation rate

Summary

- edge turbulence produces coherent propagating structures - blobs
- blobs are born with a density and temperature characteristic of where the underlying linear instability peaks
- dynamics of blobs is consistent with simple theoretical models
  - radial blob velocity arises from blob curvature-induced charge polarization and $E\times B$ convection
  - identified the dependence on key blob parameters
  - theoretical estimates bound the observed blob velocity
- blob velocity is also influenced by effects not in the model used here:
  - parallel blob structure?
  - internal net vorticity (blob spin)?

Challenge questions

- **Can we understand the dynamics of an individual blob with known properties?**
  - given n_e, T_e, a_b compare observed v_x and evolution with theory and simulation

well in hand

- **What properties are blobs created with and why?**
  - rate & statistics of blob generation, scale size a_b, n_e, T_e
  - linear γ, k $\rightarrow$ a_b, parallel mode/blob structure vs. circuit path
  - v_y shear, nonlinear coupling effects on blob generation
  - electromagnetic blobs and ELMs

exciting work for the future