What is a blob?

Blob dynamics and the tokamak scrape-off layer width

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What is a blob?

- Coherent plasma structures observed in edge of confined plasmas, including tokamaks, stellarators, reverse field pinches, etc...
- Density and temperature monopole propelled cross-field by $E \times B$ drifts generated by electric field dipole
- Aligned to the magnetic field, with small parallel wavenumber, responsible for a large fraction of the cross-field transport

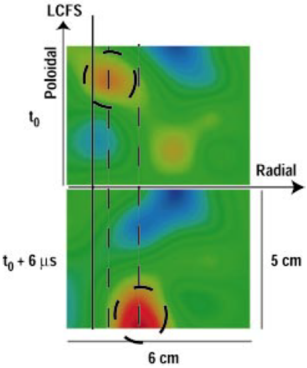
Most of this talk is devoted to discuss experimental observations, theory, and simulations of filamentary transport as well as their effect on the tokamak SOL width

Why are blobs important? Why do we care?

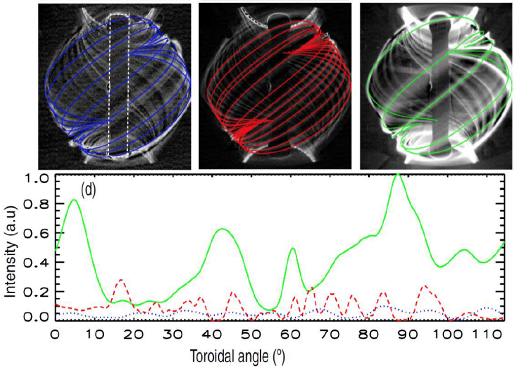
Inter-ELM SS heat-fluxes depend on filamentary transport

- **Must limit steady-state heat-flux** $\sim P/A$ **to avoid excessive erosion**
- **For ITER** $P \approx 100MW \times (1 - f_{rad}) \sin\theta \approx 1MW$**,** $A \approx 2\pi R \lambda_q$ **results in** $P/A \approx 5MW/m^2$ **with slanted target, partial detachment,** $\lambda_q \approx$ **5mm**
- **Multi-machine scaling** (Eich, PRL (2013)) **gives** $\lambda_q \propto B_\varphi^{-0.8} q_{95}^{1.1} P^{0.1} R^0$**, extremely challenging problem for DEMO variants**
- **Large fraction of cross-field heat-flux (**$\sim 50\%$**) determined by blobs**
- **Analogies between blobs and turbulence allows inference about** λ_q

Why are blobs important? Why do we care?
Peak heat load from Edge Localized Modes (ELMs)



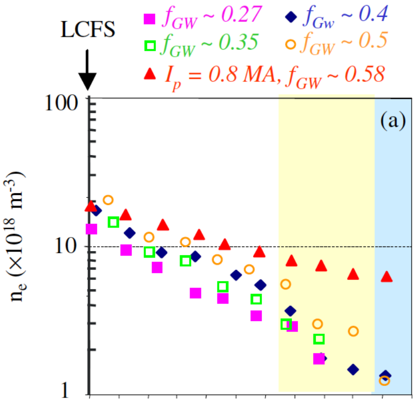
(Boedo, PoP (10), 1670 (2003))



(Ben Ayed, PPCF 51, 035016 (2009))

- **ELM heat deposition results from propagation of field-aligned plasma filaments similar to blobs**

Why are blobs important? Why do we care?
Possible relation between blob transport and density limit



- Close to density limit, density/energy carried by blob increases, plasma profiles flatten and develop "shoulder" (Rudakov et al., NF 45, 1589 (2005))

Outline

Objective: Understand the physics of **blob filaments** and their role in tokamak edge transport

- Describe experimental observations of structure, propagation
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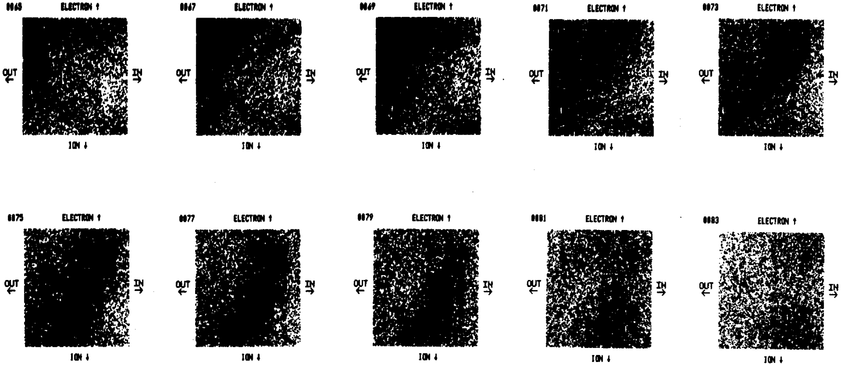
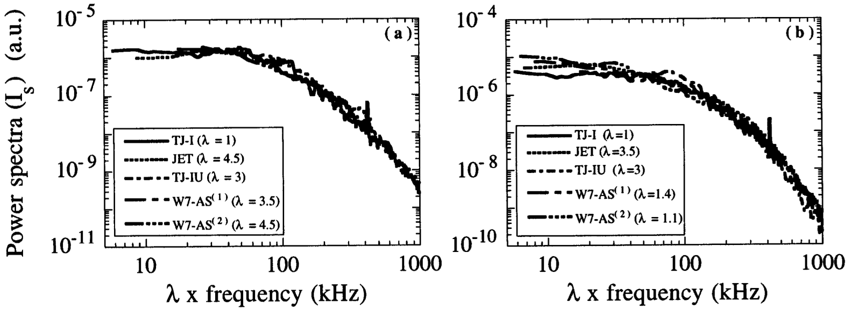
Early observation of tokamak edge turbulence shows coherent density structures



- Measurements show "spatial patterns of density fluctuations $\tilde{n}$ appear to consist of localized blobs" (Zweben, Phys.Fluids (1984))
- Even earlier observations from analog age (Zweben, PPCF 49, S1 (2007))

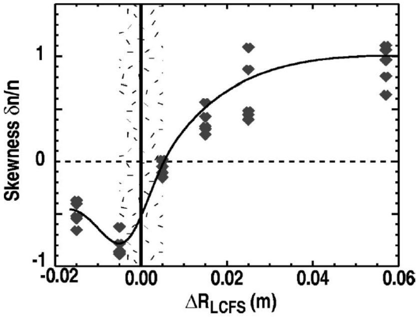
Frequency spectra of I_{sat}, V_{fl} show same qualitative behavior across several tokamaks/stellarators



- Indication that edge turbulence self-similar, long-time correlations, plasma size/parameter independent (Carreras, PRL 80, 4438 (1998);Pedrosa, PRL 82, 3261 (1999))

Increasing skewness in DIII-D far-SOL indicative of important role of filamentary transport setting λ_q

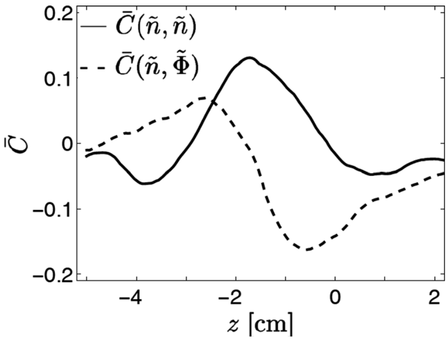
- BES measurements in DIII-D show increasing deviation from Gaussian fluctuation PDF
- Region near separatrix has negative skewness, e.g. "holes", indicative that blobs are created just outside LCFS
- Same effect observed in OH,L,H-mode plasmas, with blobs contributing $\sim 50\%$ of radial particle transport



(Boedo et al., PoP 10, 1670 (2003))

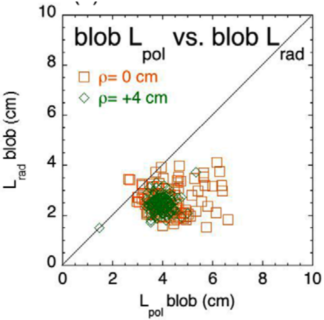
Individual blobs characterized by a density monopole with associated potential dipole

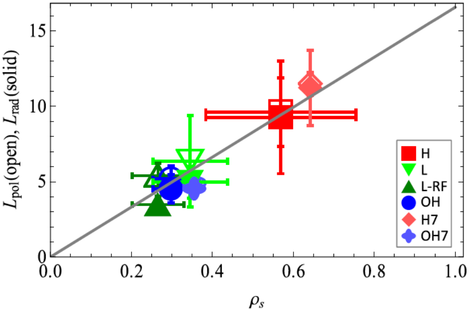
- Correlation between Langmuir probe and GPI diagnostic as function of vertical probe position in C-Mod
- Density correlation function essentially Gaussian in space with FWHM $\sim$ 1cm
- Electric potential phase shifted from density, slope indicates electric field across structure (charge separation)



(Grulke, PoP 16, 012306 (2006))

Blobs have roundish structure with $L_{rad} \sim L_{pol}$ roughly proportional to ρ_s in OH,L,H-mode





- Aggregate analysis L_{rad}, L_{pol} of 10k's of blobs in NSTX OH,L,H-mode discharges measured using GPI (Zweben, NF 55, 093035 (2015) ; Myra, PoP 23, 112502 (2016))
- Myra finds best fit for $k_\perp \rho_s \approx 0.17$ – result largely agrees with anecdotal evidence in non-linear simulations of edge turbulence

C-Mod GPI measurements reveal high correlation between filaments at midplane and X-point regions

- **Average magnitude parallel wavenumber $\langle k_{\parallel} \rangle \approx 3\text{–}4 \times 10^{-2}\text{cm}^{-1}$**
- **Inferred parallel propagation speed consistent with $v_{th,e}$ or v_A**

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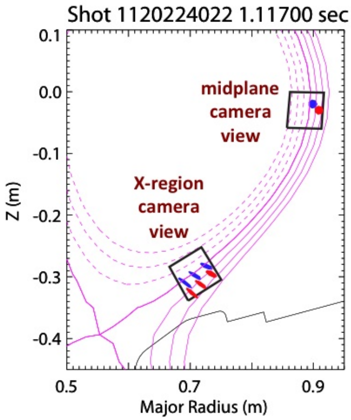

(Grulke et al., NF 54, 043012 (2014))

Summary of observations

- Long history of observations of coherent structures in edge turbulence, from analog age to state-of-the-art 2D imaging with BES/GPI
- Blobs posed as origin of non-Gaussian PDFs for edge fluctuations accounting for large fraction of SOL particle and heat transport
- Density monopole with associated potential dipole $\Rightarrow$ propagation primarily due to E $\times$ B drift driven by charge separation
- GPI reveals ”round blobs”, filamentary structure $L_{rad} \sim L_{pol}$, field-line-following structure with very small $k_{\|}$, $L_{\|} \sim 1$m

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Density and charge conservation provide analytical framework to understand blob propagation

Simplest model describing blob propagation stems from fluid equations

(Krasheninnikov, PLA 283, 368 (2001))

$$\frac{\partial n}{\partial t} \approx -\mathbf{v_E} \cdot \nabla n \qquad (1)$$

$$\nabla \cdot \frac{d}{dt}\left(\frac{nm_i}{eB^2}\nabla_\perp \phi\right) = \nabla \cdot j_\parallel + \nabla \cdot j_* \qquad (2)$$

- **Electric field resulting from polarization propels blob**
- **Magnetic field curvature $\nabla \cdot j_*$ drives charge separation**
  - Analogous to gravity force in Raleigh-Taylor instability
- **Flow of parallel currents counteracts the blob motion**
  - Many closure schemes and physical effects (Krasheninnikov, JPP 74, 679 (2008))

Analytical estimates for blob propagation speed obtained from analogy with linear instability

- Referred to as the blob correspondence principle (Myra, PoP 12, 092511 (2005))

$\gamma \Rightarrow v_x/\delta_b$	Linear growth rate $\sim$ radial velocity v_x / size δ_b
$k_\perp \Rightarrow \delta_b^{-1}$	Wavenumber is inverse of the blob size
$L_n \Rightarrow \delta_b$	Effective gravity provided by blob structure
$k_\parallel \Rightarrow L_\parallel^{-1}$	Filament occupies entire field line

- Conceptually simple method to obtain blob velocity
- Estimates in good agreement with experiments and simulations

Analytical estimates for blob propagation speed obtained from analogy with linear instability

Using charge conservation together with the blob correspondence expressions, and estimating $\phi \sim v_x \delta_b B$ we obtain

$$\gamma \frac{v_x}{\delta_b} = \frac{2}{n_0} \frac{n_b}{\delta_b} - \frac{j_{||}}{n_0 L_{||}} \tag{3}$$

In the simplest limit, $\gamma \sim \sqrt{2} c_s / \sqrt{R \delta_b}$ and $j_{||} \approx e n_0 c_s (e\phi / T_e)$ is an approximation to the sheath current, leading to the estimate

$$v_\perp = v_0 \frac{\sqrt{2\delta_b/\delta_0}}{1 + \sqrt{2}\,(\delta_b/\delta_0)^{5/2}} \frac{n_b}{n_0 + n_b} \tag{4}$$

where $v_0 = (2L_{||}\rho_s^2/R^3)^{1/5} c_s$ and $\delta_0 = (2L_{||}\rho_s^2/R^3)^{1/5} \rho_s$ are reference values

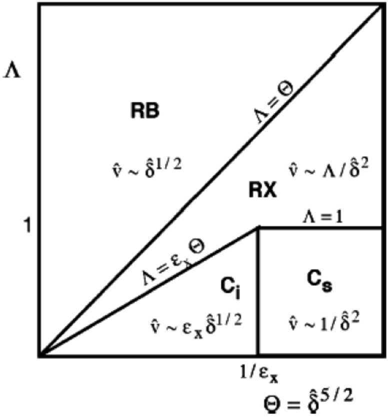
In more realistic models, blob propagation also depends on collisionality, magnetic configuration

Curvature drive can be balanced by

- Connected ideal-interchange (C_i):
  X-point enhanced inertia
- Sheath-connected (C_s):
  Parallel currents to sheath
- Resistive X-point *RX*:
  Parallel currents in divertor region
- Resistive Ballooning *RB*:
  Inertia in midplane region

$\Lambda \Rightarrow$ collisionality

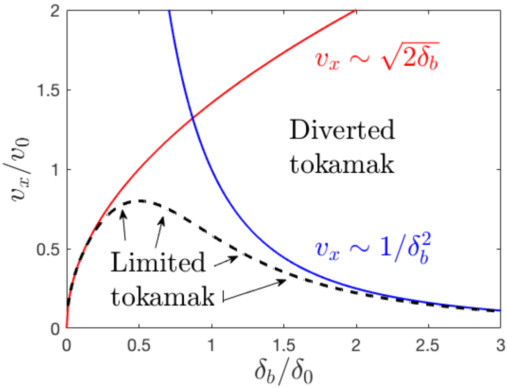
$\epsilon_X \Rightarrow$ local field line length $\sim 1/L_{||}$



(Myra, PoP 13, 112502 (2006))

Simple analytical relations for velocity scaling give bounds for v_x as function of the blob size δ_b

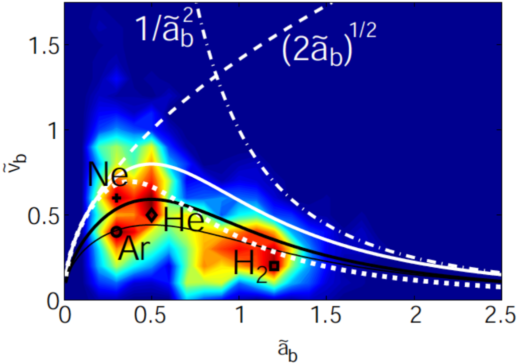
For a diverted tokamak, the C_s and RB regimes give $\delta_0^2/\delta_b^2 < v_x/v_0 < \sqrt{\delta_b/\delta_0}$



Limited tokamaks follow scaling combining C_s/RB regimes

Blob velocity distribution in TORPEX stems from combined C_s and RB scaling

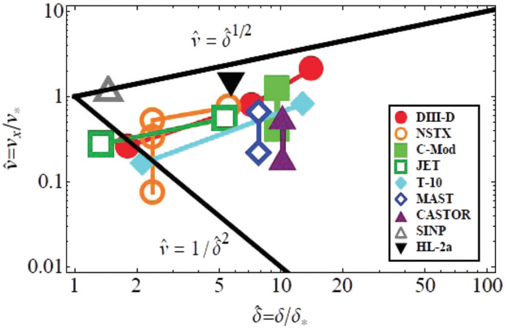
- **Small blobs: polarization currents give** $v_x \sim \sqrt{\delta_b}$
- **Large blobs: sheath currents give** $v_x \sim 1/\delta_b^2$



(Theiler et al., PRL 103, 065001 (2009))

Inter-machine comparison shows reasonable agreement with v_x bounds for diverted tokamaks

- **Lower bound: plasma inertia bounds** $v_x < \sqrt{\delta_b}$
- **Upper bound: sheath currents bounds** $v_x > 1/\delta_b^2$



(D'Ippolito et al., PoP 18, 060501 (2011))

Summary of propagation theory

- ”Blob correspondence principle” gives consistent framework for evaluating blob velocity scaling using linearized fluid equations
- Velocity scaling depends on $\|$ dynamics (e.g. field-line-bending term), including effect of X-point, collisionality, sheath physics
- Analytical models in good agreement with experimental observations

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Development of simulations, comparison with experiment crucial to understand SOL transport

- Many detailed comparisons between SOL measurements and theory, allowing clear interpretation and mostly verifying analytical estimates
- First 2D fluid simulations from late 90's/early 00's (ESEL/TOKAM2D/SOLT) allow quantitative comparisons of filament structure and propagation
- First 3D (gyro)fluid simulations in mid 00's (GEMR/NLET/TYR, flux tube), followed by global/flux-driven simulations (BOUT++/GBS/TOKAM3D)
- Massively parallel gyrokinetic simulations of edge turbulence in mid 2010s including neoclassical transport (XGC/GKEYLL)

SOL plasma dynamics described by fluid equations

- Turbulent modes field-aligned, separate $\perp$ and $\parallel$ dynamics
- Motion described by fluid drifts

$$\mathbf{v}_i \approx \mathbf{v}_{\parallel i} + \mathbf{v}_{\mathbf{E}\times\mathbf{B}} + \mathbf{v}_{*i} + \mathbf{v}_{\mathrm{pol},i}$$
$$\mathbf{v}_e \approx \mathbf{v}_{\parallel e} + \mathbf{v}_{\mathbf{E}\times\mathbf{B}} + \mathbf{v}_{*e}$$

- Conservation laws for density, vorticity, ion/electron $\parallel$ mom., i/e temperature

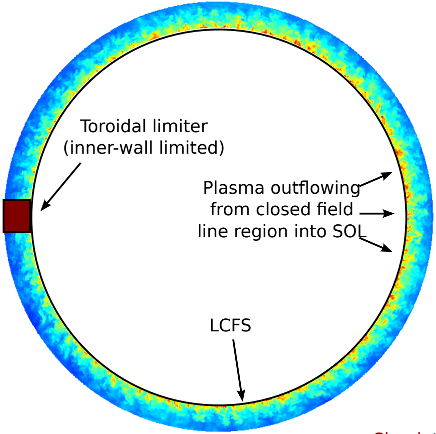
$$\frac{\partial n}{\partial t} = -\frac{\rho_\star^{-1}}{B}\{\phi, n\} + \frac{2}{B}\left[n\hat{C}(T_e) + T_e\hat{C}(n) - n\hat{C}(\phi)\right] - \nabla\cdot(n\mathbf{v}_{\parallel e}) + S$$
$$\frac{\partial \Omega}{\partial t} = -\frac{\rho_\star^{-1}}{B}\nabla\cdot(\{\phi,\omega\}) - \nabla\cdot[v_{\parallel i}\nabla_\parallel\omega] + \frac{B^2}{n}\nabla_\parallel j_\parallel + 2B\hat{C}(p) + \frac{B}{3n}C(G_i)$$
$$\frac{\partial U_{\parallel e}}{\partial t} = -\frac{\rho_\star^{-1}}{B}\{\phi, v_{\parallel e}\} - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left[\nu j_\parallel/n + \nabla_\parallel\phi - \frac{\nabla_\parallel p_e}{n} - 0.71\nabla_\parallel T_e - \frac{2}{3n}\nabla_\parallel G_e\right]$$
$$\frac{\partial v_{\parallel i}}{\partial t} = \ldots, \qquad \frac{\partial T_e}{\partial t} = \ldots, \qquad \frac{\partial T_i}{\partial t} = \ldots$$

+ BCs consistent with kinetic theory applied at magnetic pre-sheath entrance

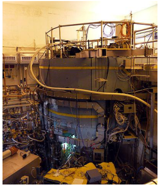
(Loizu, PoP (2012))

Start with inner wall limited geom. (ITER start-up)

It contains the main ingredients of more complicated configurations



Simulation of Alcator C-Mod
inner-wall limited discharge

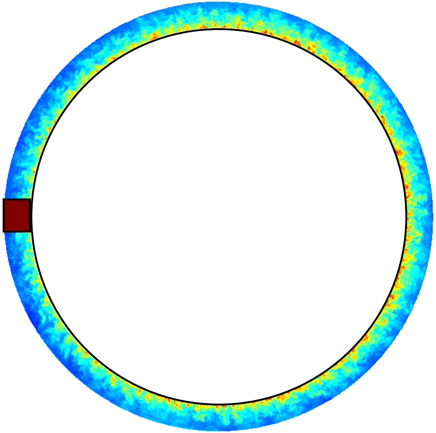


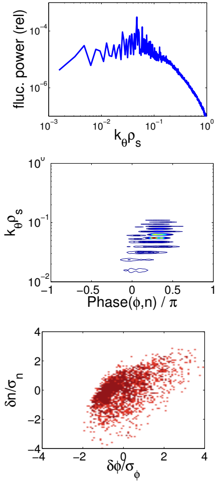
$B = 4\mathrm{T}$
$R = 0.67\mathrm{m}$
$a = 0.2\mathrm{m}$
$T_{e,LCFS} \sim 25\mathrm{eV}$
$n_{e,LCFS} \sim 10^{19}\mathrm{m}^{-3}$

Simulation cost: 0.5 million CPU hours

Pressure gradient driven turbulence...

Typical poloidal eddy size 1cm, $k_\theta \approx 0.1\rho_s^{-1} \sim 10\text{cm}^{-1}$

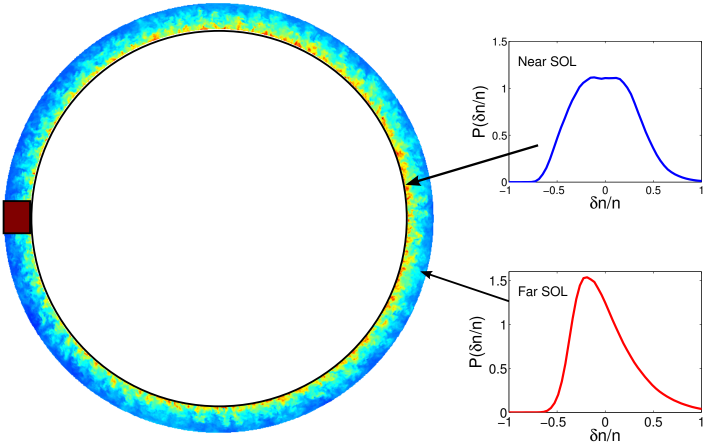




GENERAL ATOMICS

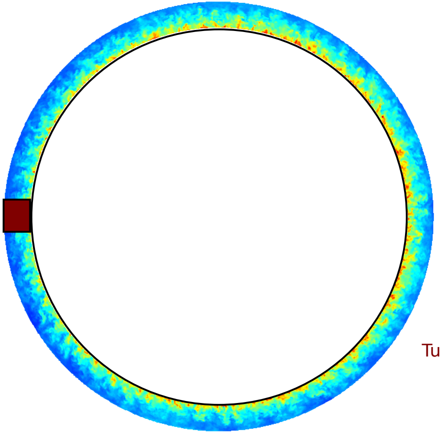
Gaussian PDFs in near SOL, intermittency in far SOL...

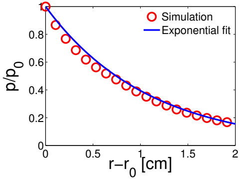
Transition between diffusive/convective transport



Power balance → exponentially decaying profiles...

Allows us to understand transport processes



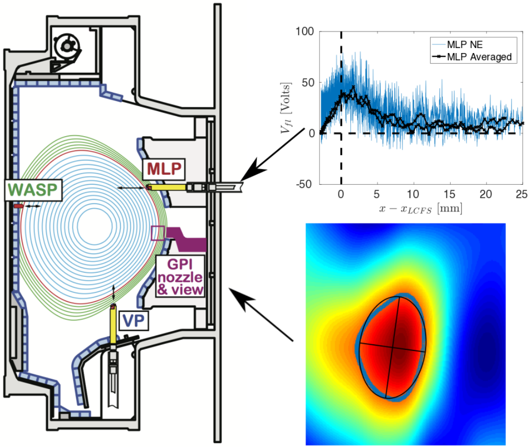


$$\nabla \cdot \Gamma_\perp + \nabla_\| \cdot \Gamma_\| = 0$$

Turbulence

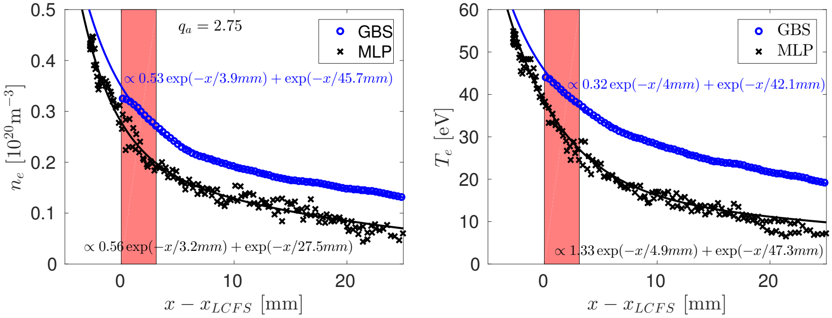
Sonic flows towards PFCs

High-res diagnostics allow detailed comparison of plasma and fluctuation profiles with simulations



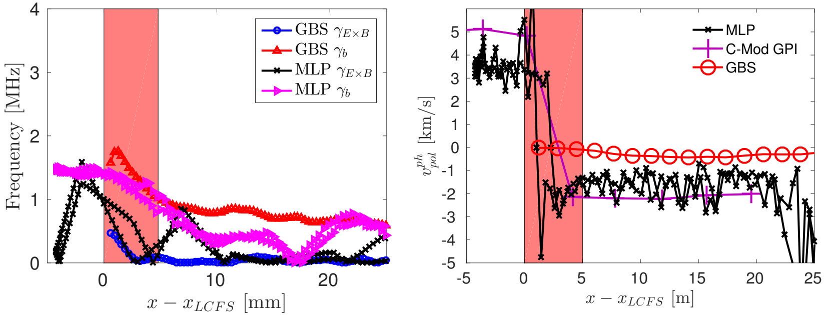
- **Array of 3 MLP allowing simultaneous profile measurement of V_{fl}, n_e, T_e**
- **Array of 10x9 GPI views for turbulence characterization**
- **MLP vs GPI vs simulation comparison**

High-res diagnostics allow detailed comparison of plasma and fluctuation profiles with simulations



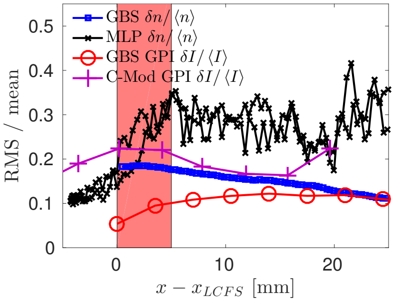
- **Time averaged profiles in simulations reproduce steep profile gradient, "narrow feature" no adjustable parameters** (Halpern, PoP (2017, under review))
- **Found very similar profile gradients, although feature strength reduced**

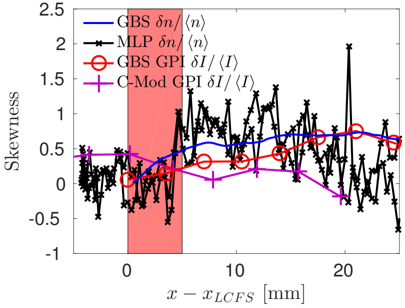
Profile steepening correlated to E × B shear layer



- High-resolution potential profiles allow evaluation of $\gamma_{\mathbf{E}\times\mathbf{B}}$, exceeds ideal ballooning growthrate $\gamma_b \sim c_s/\sqrt{RL_p}$
- Filament phase velocity shifts at LCFS due to E_r changing sign

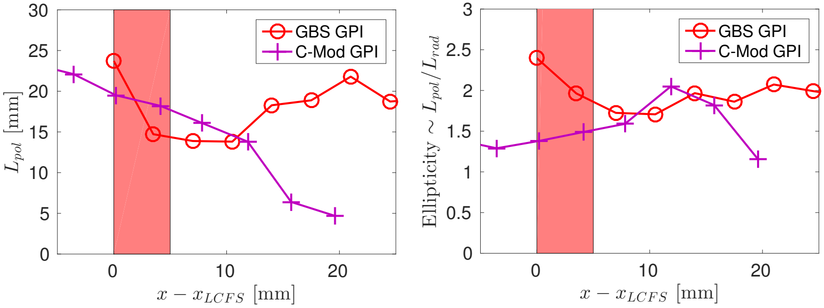
MLP and GPI measurements show large fluctuations around LCFS where plasma profiles are steep





- Thus lending credibility to theory that filaments driving transport even in near-SOL where profiles are steep (Halpern, NF (2017))
- Skewness lowest near LCFS, increases with radius

Simulations able to reproduce GPI measured filament correlation length, ellipticity



- **Noticeably, ellipticity roughly constant, not consistent with mesoscale argument $k_r \sim \sqrt{k_y/Lp}$ for mixing length**

Summary of simulation/experiment comparison

- State-of-the-art simulations can reproduce many features observed in filamentary transport quantitatively
- Filamentary structure sometimes matched essentially within experimental error bars
- Fluid simulations of plasma dynamics show two-scale decay length similar to what is observed in experiment

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Simulations containing open/closed magnetic field lines are used to study narrow-heat flux feature

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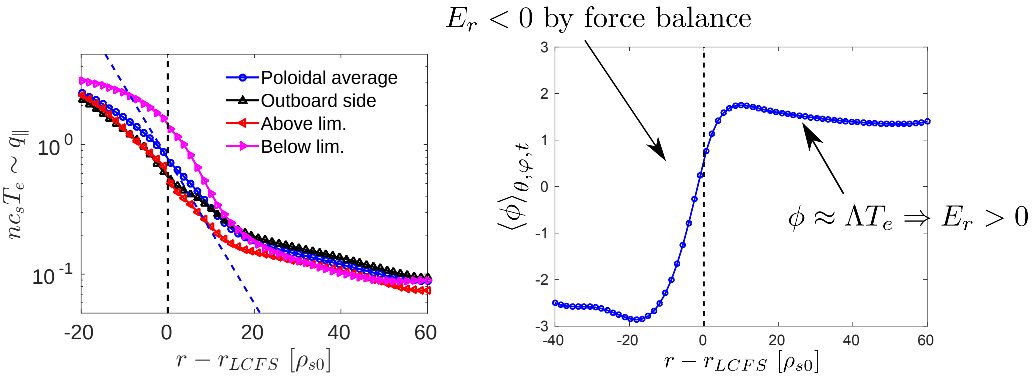
Density

Ion parallel velocity

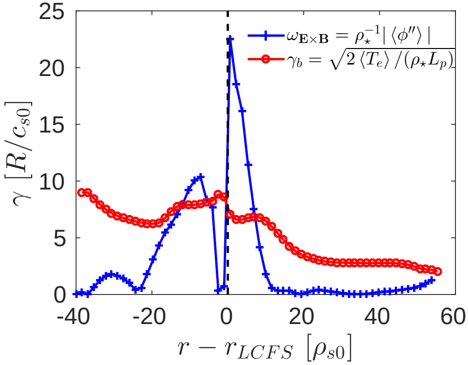
- **Sim. parameters:** $q = 4$, $\nu = 0.01$, $\rho_\star^{-1} = 500$ **(**$\sim$ **1/4 C-Mod @ 4T)**
- **Physical model:** $\rightarrow \tau = 0$**, Boussinesq, electrostatic, no neutrals**
- **Profiles from power balance, sheared flows, blob formation, etc...**

Simulations of generic IWL plasmas show two-scale profile with narrow heat-flux feature



- Strong E_r shear due to near-SOL ϕ and T_e profiles decoupling
- Largely consistent with C-Mod / TCV probe measurements

Magnitude of flow shear defines 3 distinct regions



- **Edge region: drift-resistive-inertial BMs "no man's land"**

  (Drake/Holland/Naulin/Rogers/Scott/Zeiler)

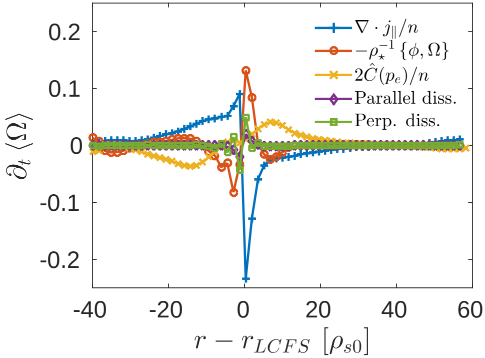
- **Near SOL: interaction between turbulence and sheath currents**

  (Halpern, NF (2017))

- **Far SOL: RB-like behavior, saturation likely due to profile modification**

  (Halpern, NF/PoP/PPCF (2013-16)), Myra/D'Ippolito/Russell

Vorticity (charge) balance again gives simplified model to interpret filament velocity



- **Analogous to blob velocity scalings**
  - Divergent cross-field currents compensated through $\int < \nabla \cdot j_{\|} >_{t,\varphi} d\theta$
- **Diamagnetic currents important in far SOL $\Rightarrow$ consistent with blob transport**
- **Balance between $\nabla \cdot j_{pol}$ and $\nabla \cdot j_{\|}$ important within the narrow feature**

Main result: connection length $L_{\parallel} \propto q$ regulates effective $v_{E\times B,r}$ across near-SOL

- Starting from simplified vorticity balance equation

$$\frac{1}{B^2}\frac{\partial}{\partial r}\left(\tilde{\Omega}\frac{\partial\tilde{\phi}}{\partial\theta}\right) \approx \rho_\star \frac{c_s}{\rho_s^2}\frac{(\Lambda T_e - \phi)}{L_{\parallel} B}$$

we find that the saturation level is independent of local γ_{lin}:

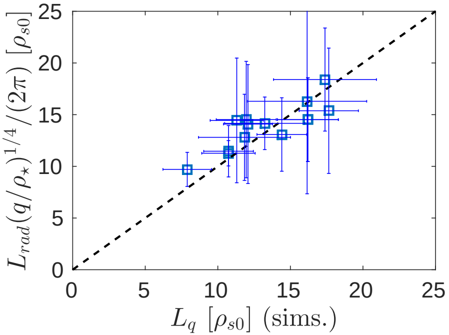
$$\left(\tilde{V}_{\mathbf{E}\times\mathbf{B},r}\right)^2 = \left(\frac{k_\theta\tilde{\phi}}{B}\right)^2 \approx \rho_\star \frac{c_s}{\rho_s^2}\frac{k_\theta}{k_r k_\perp^2}\frac{(\Lambda T_e - \phi)}{L_{\parallel} B}.$$

- Simulation scan reveals $\Lambda T_e - \phi \approx 2$, assume to be $\sim$ constant

Main result: Narrow feature gradient length λ_q constrained by correlation length L_{rad}

- **Perpendicular turbulent flux** $\Gamma_\perp \approx \tilde{p}\tilde{v}_{\mathbf{E}\times\mathbf{B}}$ **assuming** $\tilde{p} \sim p_0/(k_r L_p)$
- **Balance** $\nabla_\perp \cdot \Gamma_\perp$ **against sheath loss term** $\nabla_\| \cdot \Gamma_\| \sim p_0 c_s / L_\| \approx p_0 c_s/(qR)$

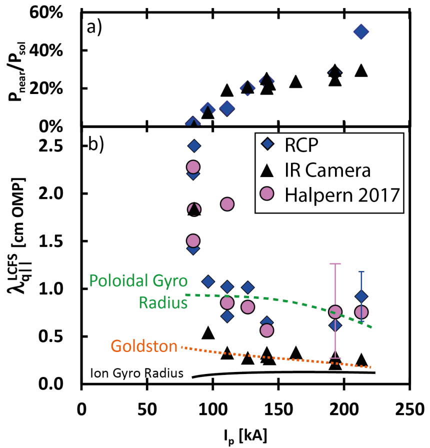
$$\frac{\lambda_q}{\rho_s} = L_q = \frac{L_{rad}}{2\pi}\left(\frac{q_a}{\rho_\star}\right)^{1/4}$$



- **Simulation parameters:**
  $q_a = 3$–16, $\hat{s} = 1.5$, $m_i/m_e = 200$–800, $\rho_\star^{-1} = 250$–1000, $\nu_{Sp} = 10^{-2}$–1
- **Most of** λ_q **variation stems from** $q_a \sim I_p^{-1}$**, compatible with Eich/Goldston scalings**

Comparison between theory estimates and TCV LP data shows good agreement for I_p scan discharges

- **Model matches variation of measured λ_q even when narrow feature is weak**
- **Variation of $\lambda_q \sim I_p^{-1}$ captured, likely due to BM turbulence with $L_{rad} \sim q_a \sim I_p^{-1}$**
- **BM turbulence explains ρ_{pol} scaling sometimes attributed to NC effects**



GENERAL ATOMICS

Summary and Conclusions

- **Experimental observations at the edge of essentially all fusion devices remark importance of filamentary transport**
- **Fluid equations give framework to study filament dynamics**
  - ✓ Charge conservation equation used to deduce blob motion
  - ✓ Analogy with linear perturbations allow simple evaluation of blob motion
  - ✓ Blob size, velocity, dependence on geometry, collisionality agree reasonably well with simulations / experimental data
- **Flux-driven turbulence simulations provide basic physics picture of narrow heat-flux feature formation**
  - ✓ Transition between edge and SOL drives strongly sheared E_r
  - ✓ $\nabla \cdot j = 0$ shows link between sheath currents and sheared $\perp$ currents
  - ✓ Heat flux decay width $\lambda_q \sim L_{rad}$ in agreement with IWL experiments

For further reference...

- S.I. Krasheninnikov et al., J. Plasma. Phys 74, 679 (2008):
  Review of theoretical aspects of blobs, including impact of X-point geometry, collisionality, plasma β
- D.A. D'Ippolito et al., Phys. Plasmas 18, 060501 (2011):
  Extensive review of experimental observations, summary of theory and simulation of filamentary transport (300+ references)
- S.J. Zweben et al., Plasma Phys. Control. Fusion 58, 044007 (2016):
  Characterization of blob structure and propagation dynamics in NSTX using gas-puff imaging of edge turbulence

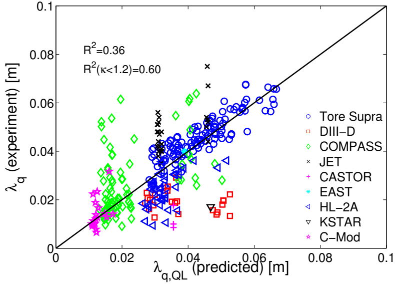
Extra slides

Far-SOL width interpreted with Q-L theory

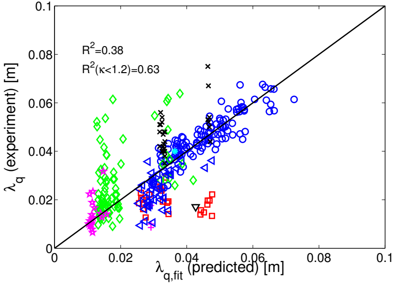
Variation of λ_q w.r.t. plasma parameters in ITPA "main SOL" database captured by Q-L theory (Halpern et. al. PPCF (2016), Horacek et al. PPCF (2016))

$$\lambda_{q,\mathrm{QL}} = 1.93 \times 10^{-4} n_0^{0.07} T_{e0}^{0.06} R^{0.68} q^{0.84} B_\phi^{-0.38} \quad [m]$$

$$\lambda_{q,\mathrm{fit}} = 2.83 \times 10^{-3} n_0^{0.02} T_{e0}^{0.10} R^{0.73} q^{0.76} B_\phi^{-0.29} \quad [m]$$

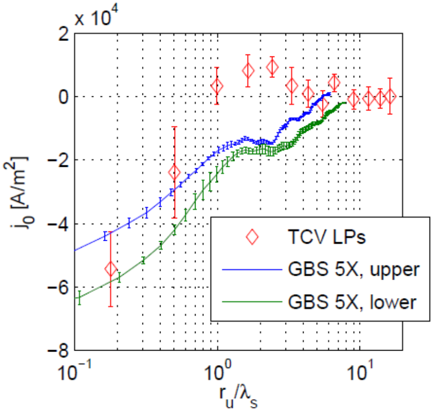


QUASI-LINEAR MODEL



BEST FIT

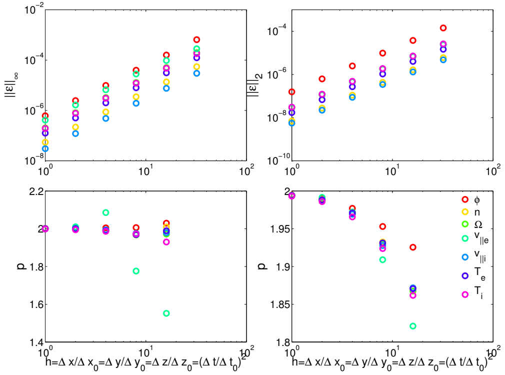
Currents at TCV limiter with wall mounted LPs (Nespoli, EPS (2015))



Since $j_{lim} \sim \phi - \Lambda T_e$, this is indicative of sheared flows within the narrow feature

GBS verified using manufactured solutions method

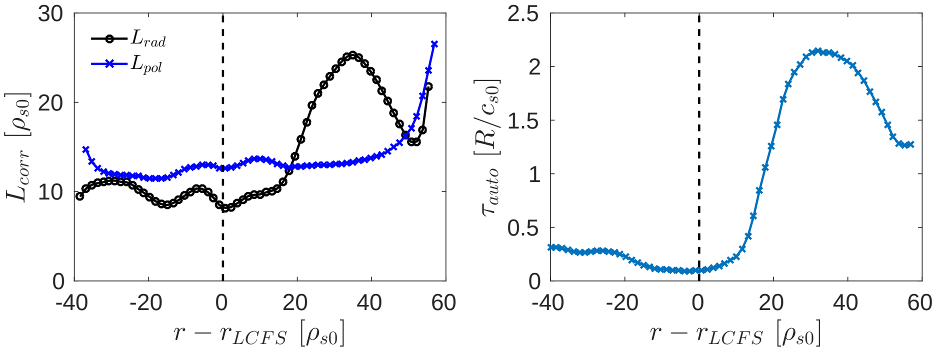
- **General and rigorous verification process carried out for GBS** (Riva, PoP (2014))



- **GBS converges to manufactured analytical solution with** $||\varepsilon|| \propto \Delta x^{-2}$

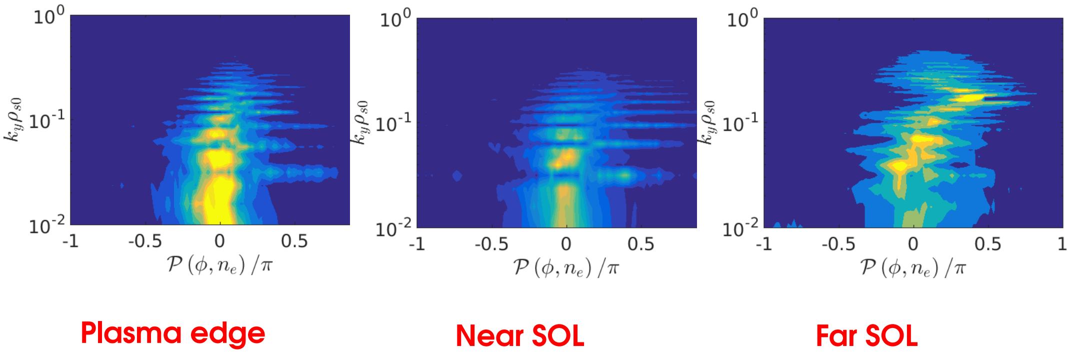
Evidence of flow shear effects in correlation length, autocorrelation time

- **Decrease in radial correlation length (modest), autocorrelation time (significant) around LCFS...**



(Computed from 2-point correlations using FWHM)

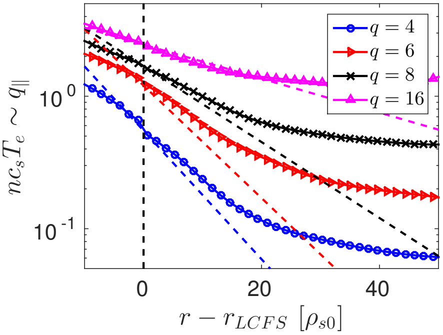
Phase between $\delta\phi$,δn_e shows transition from drift to interchange

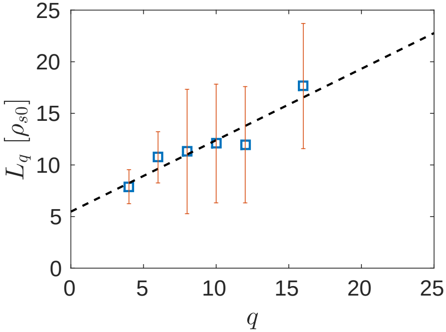


- Edge and near-SOL appear to be adiabatic (drift-like), mixed w/interchange
- Relative phase changes to interchange-like just outside narrow feature

Near SOL width ∼ proportional to safety factor

- **Narrow heat-flux feature weakens with increasing connection length**

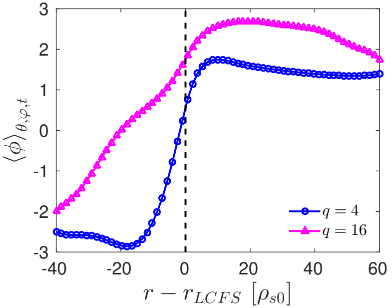


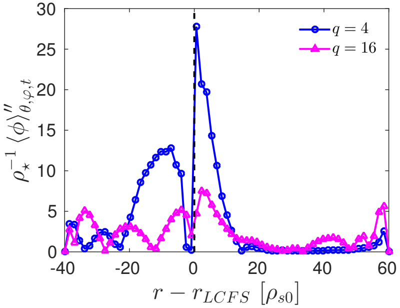


(For simplicity, $< nc_sT_e >_{\theta,\varphi,t}$ averaged radial profiles)

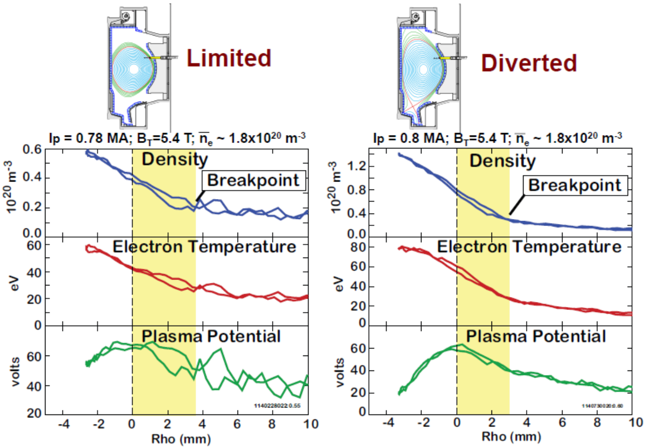
E × B shear rate weakens at high q

- **Electrostatic potential has much gentler slope around LCFS**
- **For $q = 16$ case, weaker $\omega_{E\times B}$ combined with higher linear drive at low wavenumber due to parallel dynamics**





Limited vs. diverted SOL "more similar than different"

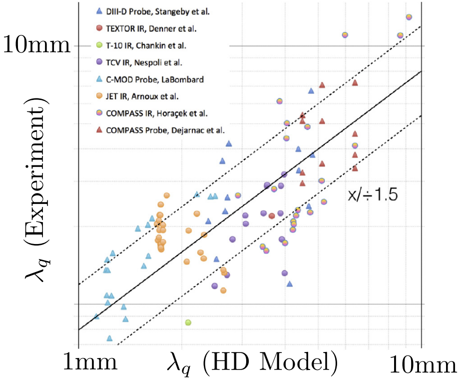


(LaBombard, APS (2014))

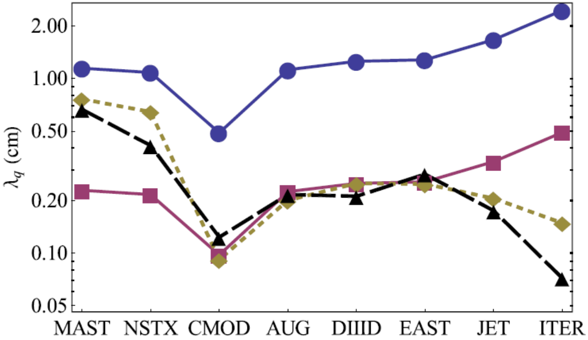
C-Mod $\lambda_q \sim I_p^{-1}$ in limited (narrow feature) or diverted configuration

Drift-Heuristic model fits IWL near-SOL data (Goldston, JNM (2015))

- **Predicts** $\lambda_q \approx (a/R)\rho_p$
- **Balance between sonic (Pfirsch-Schluter) parallel flows, particle drifts carrying plasma across LCFS...**
- **Developed for inter-ELM heat-flux decay length** (Eich, PRL (2011))



Turbulence-based scalings (for H-mode) yield results similar to Eich scaling / Goldston model (Myra, PoP (2015))



- Black long-dash line: Eich's fit / Gold dashed line: Goldston's HD (simplified)
- Blue line: Interchange instability, Barrier, Wave-breaking, Distributed

For ballooning turbulence, $L_q \sim q \sim 1/B_\theta$

- Assume ballooning type turbulence, estimate $\pi L_{rad}^{-1} = k_r \approx k_\theta \approx k_b$

- For resistive ballooning modes ($\nu > 0.01$), $k_b \propto q^{-1}\nu^{-1/2}\gamma_b^{-1/2}$ implies

$$L_q \propto q\rho_\star^{-2/5}\nu^{-2/5}$$

- For inertial ballooning modes ($\nu < 0.01$), $k_b \propto q^{-1}\gamma_b\sqrt{m_i/m_e}$ implies

$$L_q \propto q^{5/6}\rho_\star^{-1/2}$$

(HD scaling (simplified): $L_q \approx q$)