Confinement regimes in simple magnetized toroidal plasmas

I. Furno, A. Fasoli, J. Guterl, B. Labit, P.Ricci, C. Theiler

Centre de Recherches en Physique des Plasmas
Ecole Polytechnique Fédérale de Lausanne Switzerland

B. N. Rogers
Department of Physics and Astronomy, Dartmouth College
Hanover NH 03755

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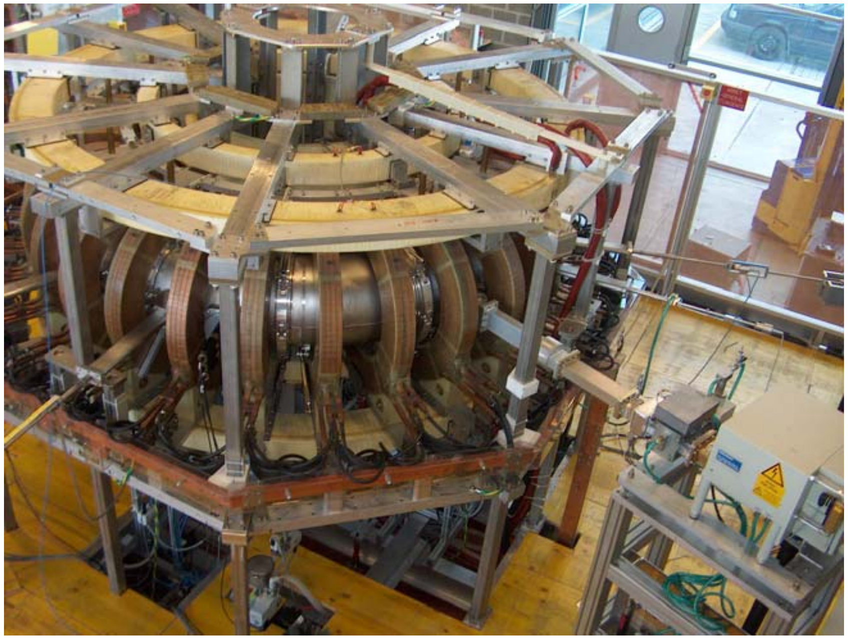
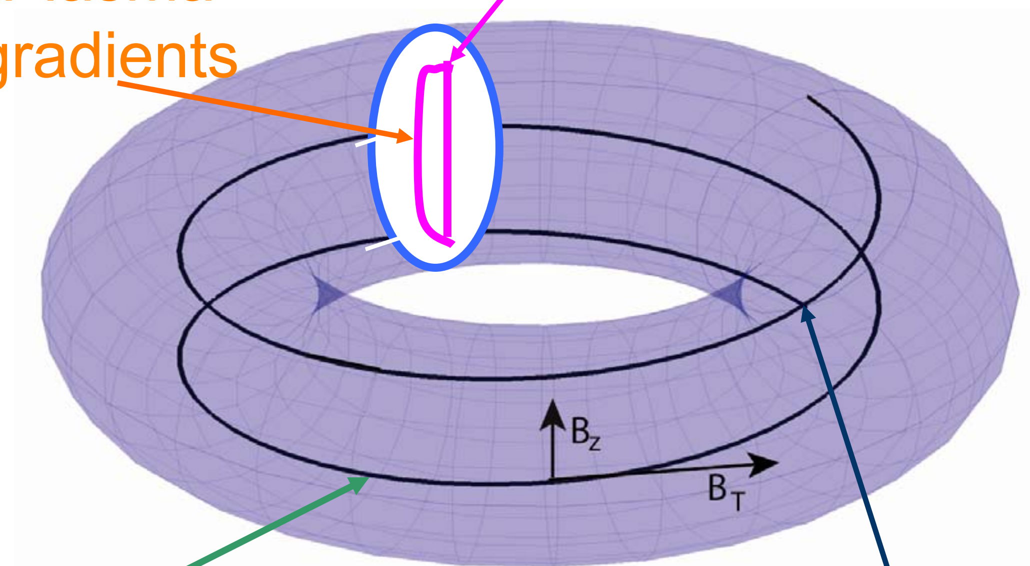
The TORPEX device



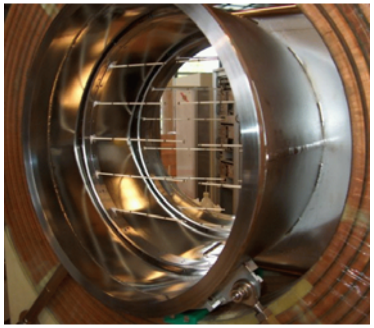
[A. Fasoli et al., Phys. Plasmas **13**, 055902 (2006)]

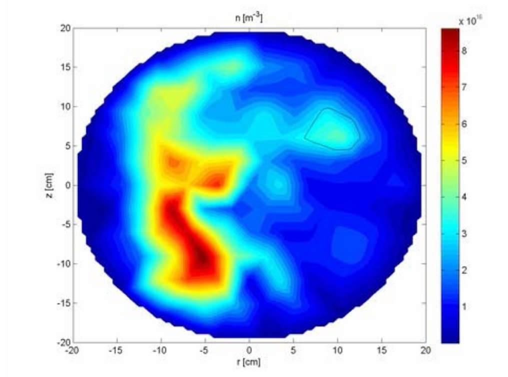


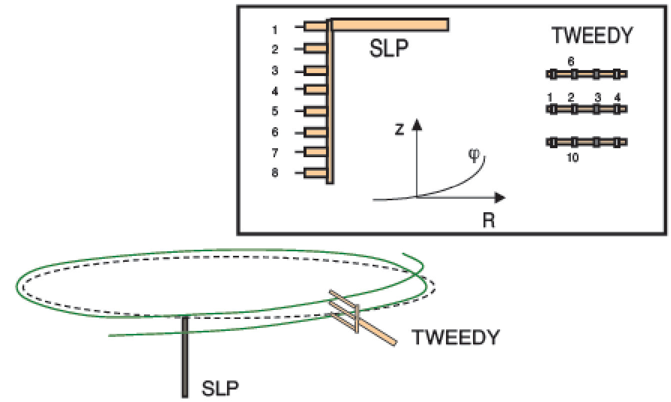
- Toroidal device: R=1 m, a=0.2 m
- Open field lines
- Plasma production: magnetron (LFS O-mode, 2.45 GHz, < 50 kW, ~1 s); Primary ionization at EC layer, main contribution from UH resonance

- **H_2, He, Ne,… plasmas**
- P_{rf} = 400 W
- B_t=76 mT on axis
- Flexibility in parameter scan

Extensive set of diagnostics







- HEXTIP: 86 electrostatic probes
  - $n \propto$ ion saturation current
  - Floating potential
- Complete coverage of the poloidal cross section
- Background/fluctuation profiles (250kHz acq. freq.).
- Structure analysis

- Movable Langmuir probes
- Time averaged 2D profiles of N_e, T_e, V_{pl}, V_{ExB}
- Complete characterization of waves:
  - Dispersion relation
  - ω, k_z, $k_{//}$

S. H. Mueller et al., Phys. Plasmas 13, 100701 (2006).

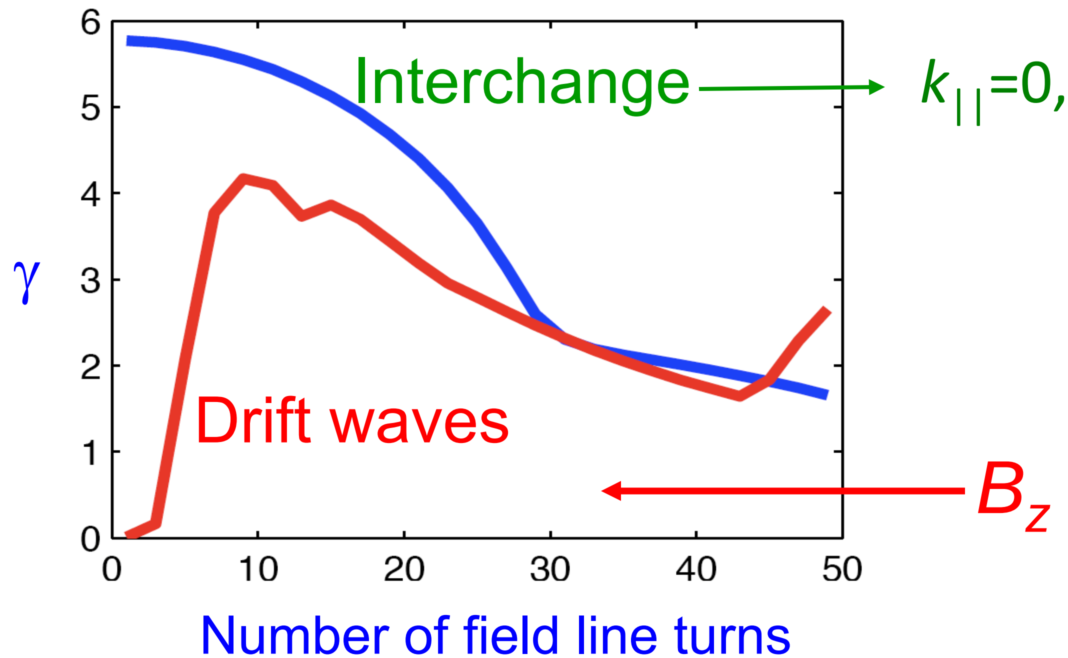
F. M. Poli, Phys. Plasmas 13, 102104 (2006)

Linear theory: drift and interchange modes are unstable

Plasma gradients
+
Magnetic curvature

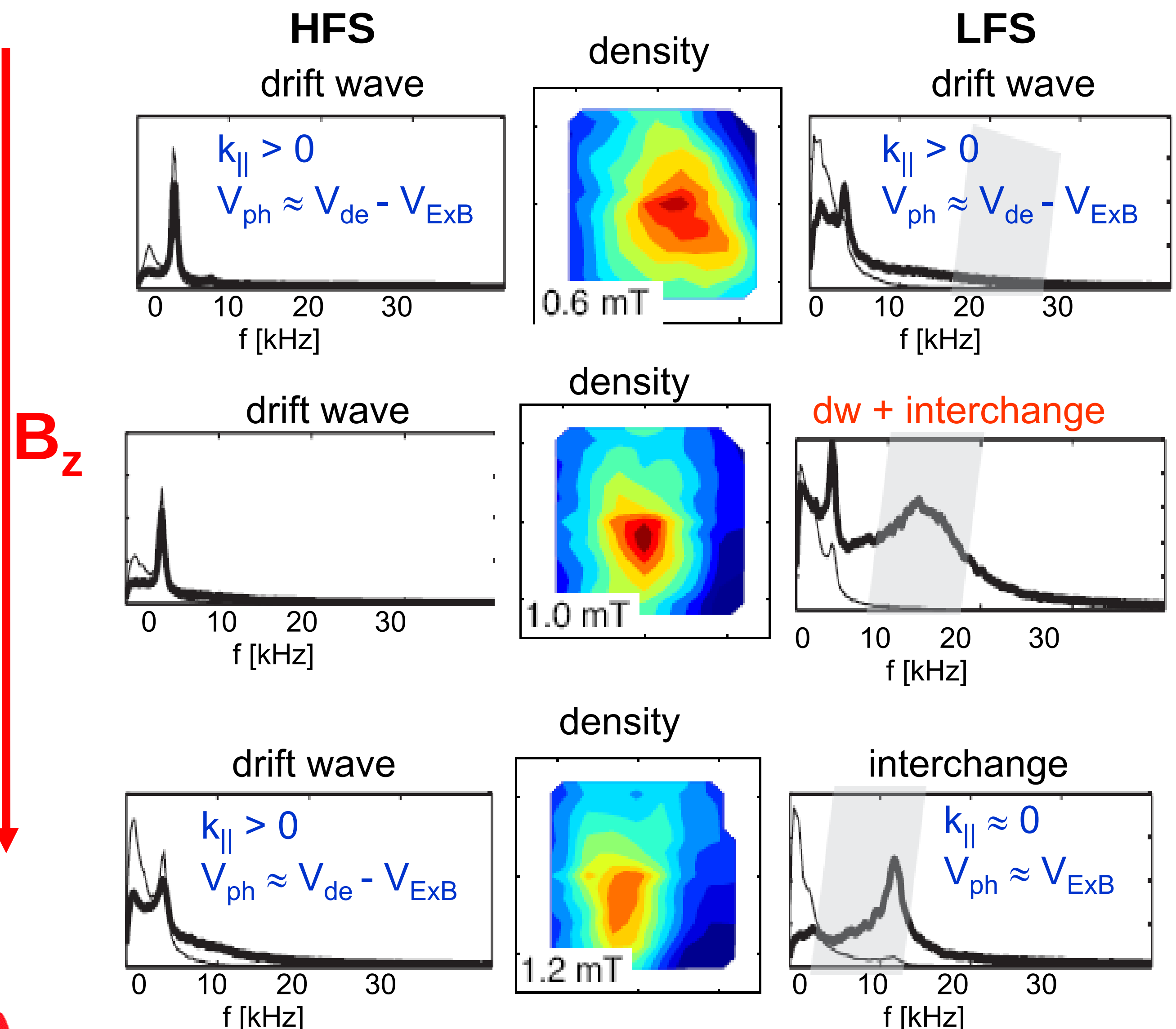
→

Drift waves
Interchange waves



$k_{||}=0, \quad \gamma \sim \frac{c_s}{\sqrt{RL_p}}$

Experiments: B_z controls the nature of the instabilities



- Both drift and interchange instabilities observed
- Only DW on the HFS
- Co-existence in the unfavorable curvature region

high $B_z \Rightarrow$ interchange dominated regime

$\Downarrow$

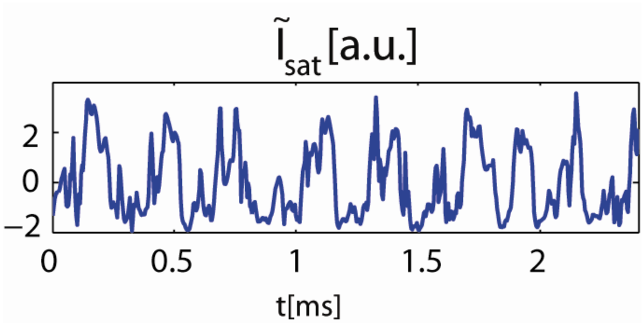
Focus of the work

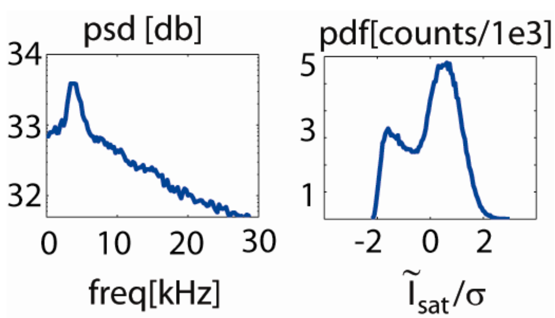
CRPP

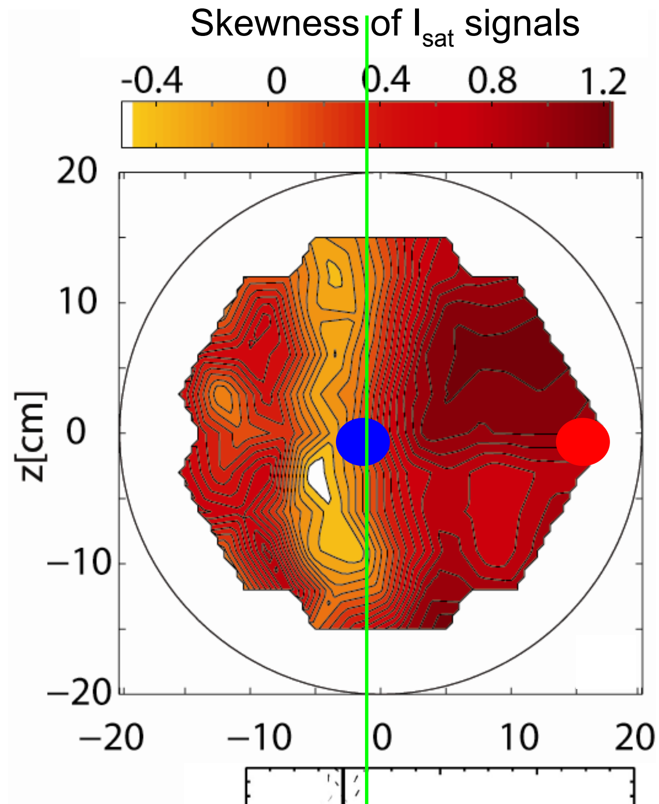
F.M. Poli, *et al.*, PoP (2006); PoP (2007); PoP (2008)

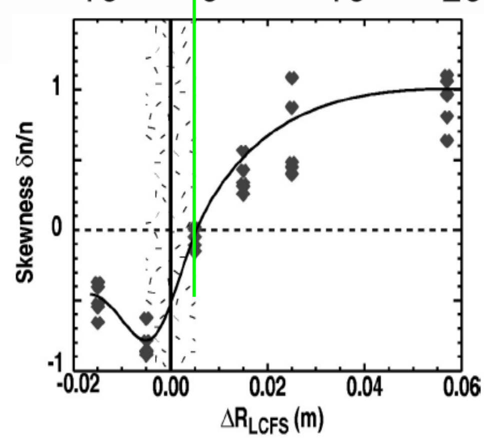
High $B_z \Rightarrow$ SOL – like configuration

Main plasma region



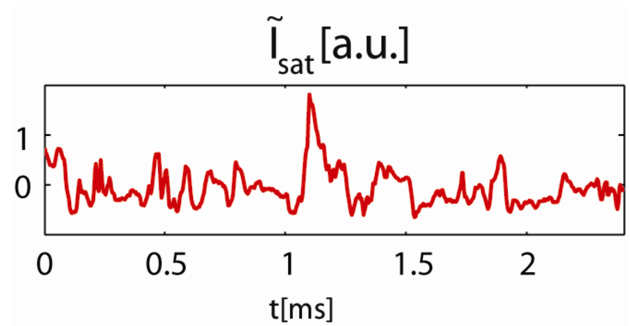


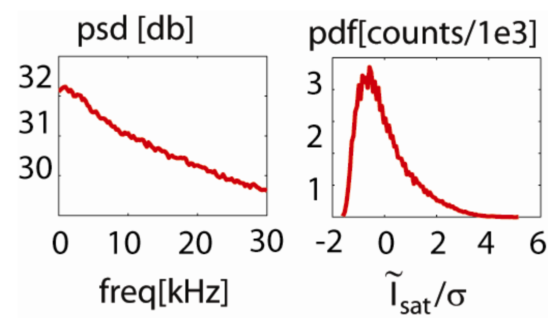




Courtesy of J. Boedo

Source-free region



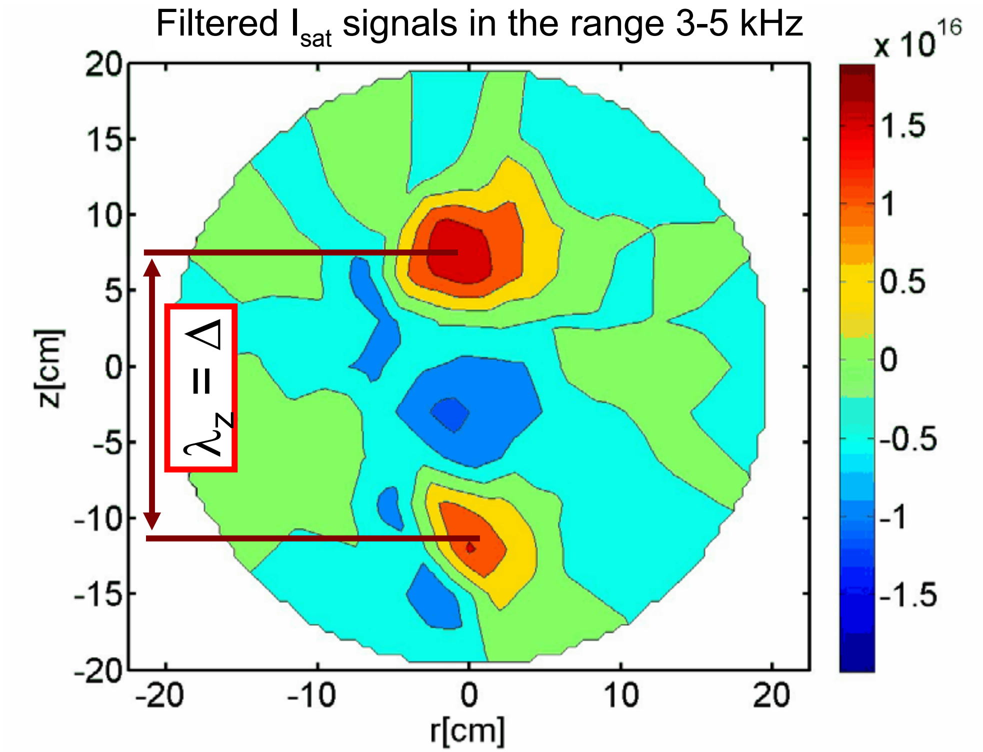


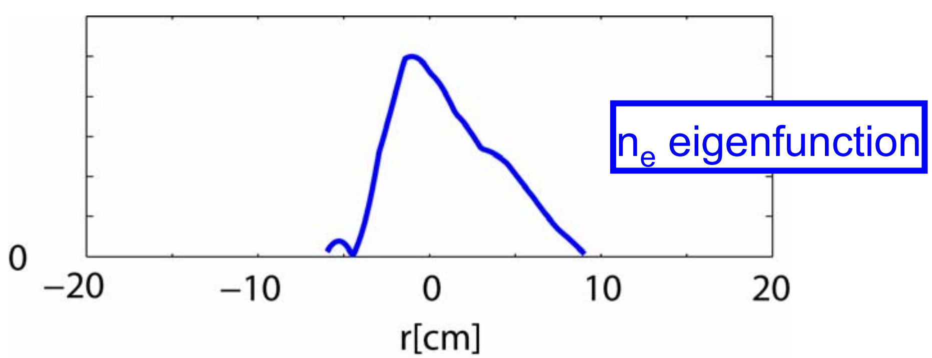
- Double-humped pdf
- Coherent interchange mode at f ~ 4kHz

- Intermittent events
- Broad-band spectra
- Positively-skewed pdf

S. H. Müller, et al., Phys. Plasmas **14**, 110704 (2007)

Main plasma: interchange wave





- Mode localized around max $|\nabla p_e / p_e|$
- Using a two-point correlation technique:
- $k_z \sim 30\ m^{-1} \Rightarrow \lambda_z$ = field line return distance
- $k_{//} < 0.046\ m^{-1} << k_z \Rightarrow$ interchange
  - $V_z \sim 1.2$km/s $\Rightarrow$ consistent with $<V_{\mathbf{E\times B}}>_t$
- Linearized three-field fluid model:
  - Exper. profiles of $<n_e, V_{pl}, T_e>_t$
  - Interchange mode unstable
  - Convected by **E** x **B** flow

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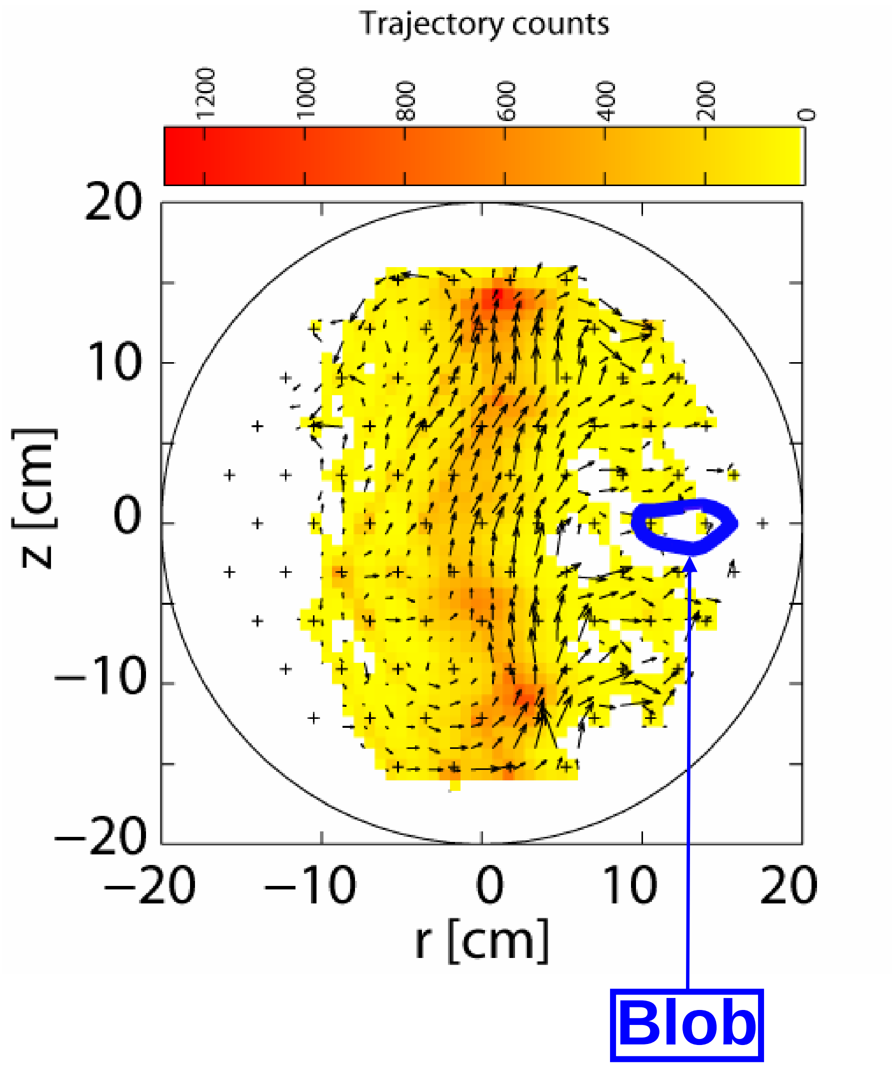
I. Furno, et al., Phys. Plasmas **15**, 055903 (2008)

Source-free region: blobs

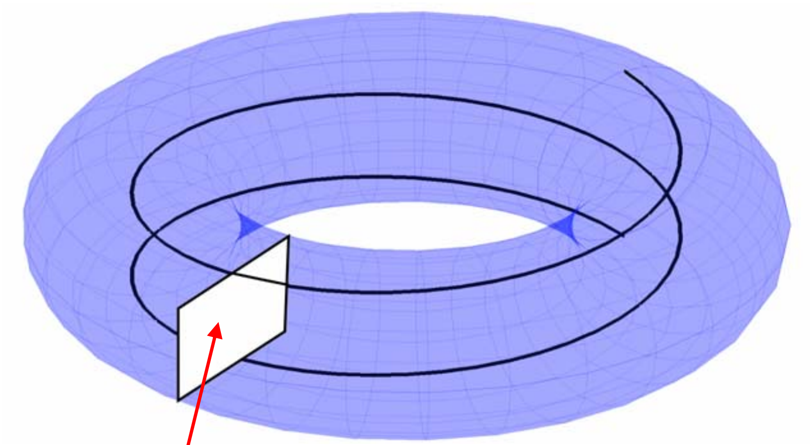


- Intermittent events are associated with blobs
- Blobs originate from the interchange wave in response to an increase of the interchange drive
- The wave is sheared off by the ExB flow
- Blobs propagate radially outwards (1-2km/s) in the source-free region

I. Furno, et al., Phys. Rev. Lett. **100**, 055004 (2008)

C. Theiler, et al., Phys. Plasmas **15**, 042303 (2008)

Theory development



2D domain

- 2-Fluid model, evolving N, ϕ, T_e.
- ∇B and curvature taken into account.
- 2D geometry with dissipation in the parallel direction.
- Diffusion coefficients from Braginskii equations.
- Source terms from the experiment.

Density

$$\frac{dN}{dt} = D_n \nabla^2 N + \frac{2}{R}\left(N \frac{\partial T_e}{\partial z} + T_e \frac{\partial n}{\partial z} - n \frac{\partial \phi}{\partial z} \right) - \sigma N \sqrt{T_e}\, e^{\Lambda - \phi/T_e} + S_n$$

Temperature

$$\frac{dT_e}{dt} = D_T \nabla^2 T_e + \frac{4}{3R}\left(\frac{7}{2} T_e \frac{\partial T_e}{\partial z} + \frac{T_e^2}{n} \frac{\partial n}{\partial z} - T_e \frac{\partial \phi}{\partial z} \right) - \sigma \sqrt{T_e^3}\, e^{\Lambda - \phi/T_e} + S_T$$

Potential

$$\frac{d\nabla^2 \phi}{dt} = D_\phi \nabla^4 \phi + \frac{2}{R}\left(\frac{T_e}{n} \frac{\partial n}{\partial z} + \frac{\partial T_e}{\partial z} \right) + \sigma \sqrt{T_e}\left(1 - e^{\Lambda - \phi/T_e} \right)$$

Advection | Diffusion | Interchange drive | Parallel losses | Sources

Simulation prediction: L-H transition

Simulations in the regime with negligible sheath effects:

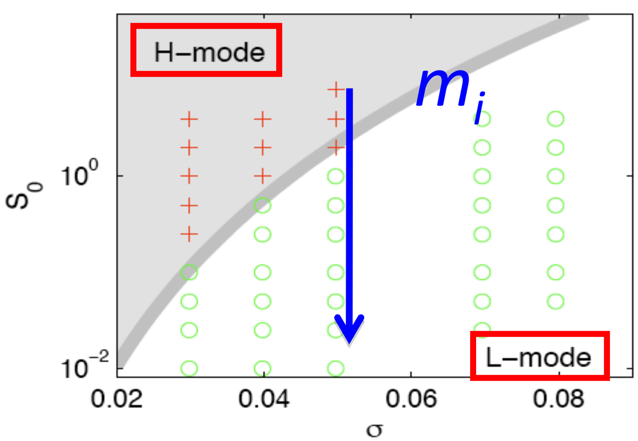
$$(k_\Delta \rho_s)^2 \geq \sigma \sqrt{\frac{L_p}{2R}}$$

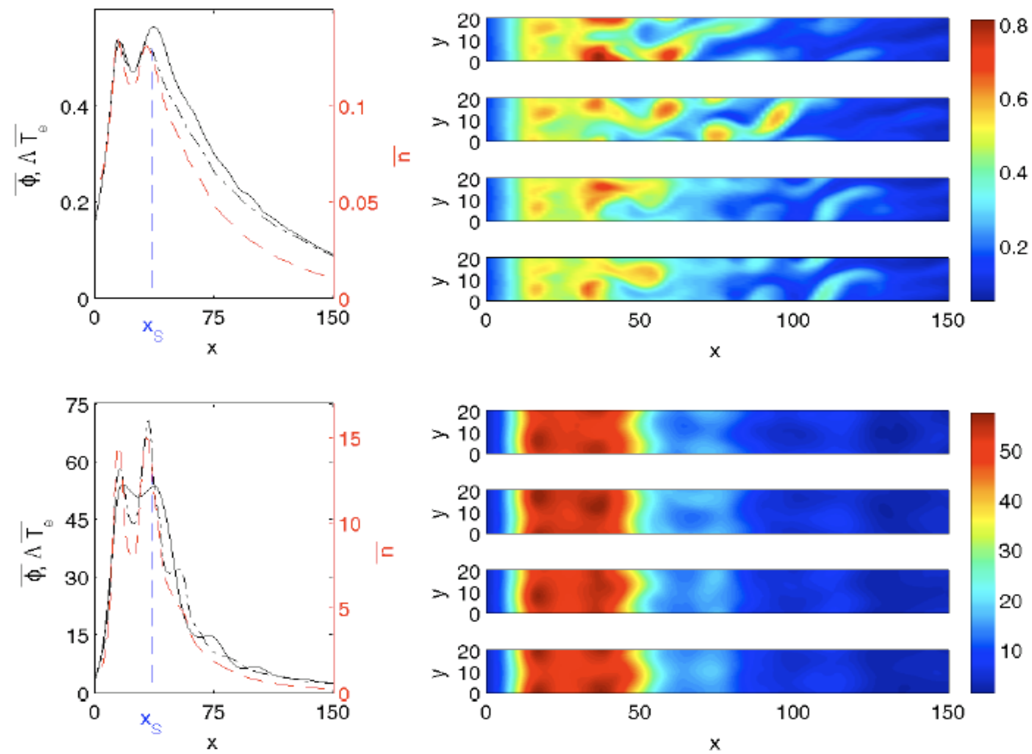
$$\sigma = \Delta / (2\pi\ L_v)$$

Two turbulent regimes

-L mode: blobs, no important shear flow

-H mode: no blobs, transport barriers due to strong shear flow





- **High S**
- **Low magnetic field**
- **High ion mass**

→ **H mode**

P. Ricci, et al., *High and low confinement modes in simple magnetized toroidal plasmas*, acc. Phys. Rev. Lett.

Theory predictions

L-mode

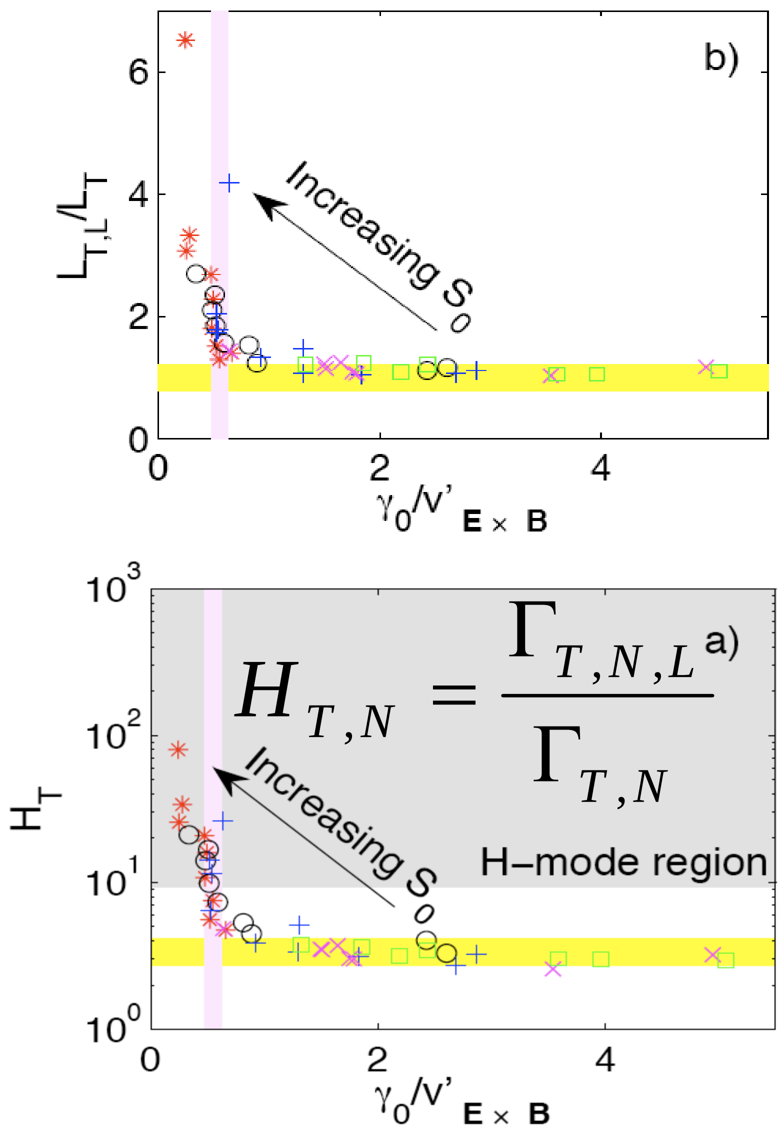
$$L_{T,N} \sim (L_V \sqrt{R})^{2/3}$$

$$\tilde{n} \sim \bar{n}\sqrt{k_y L_p} / L_n$$

$$\Gamma = \bar{n}\sqrt{2RL_p \bar{T}_e} /(L_n k_y)$$

H mode
$L_{T,N|L}/L_{T,N}>1$

Profile steepening
Reduction of transport



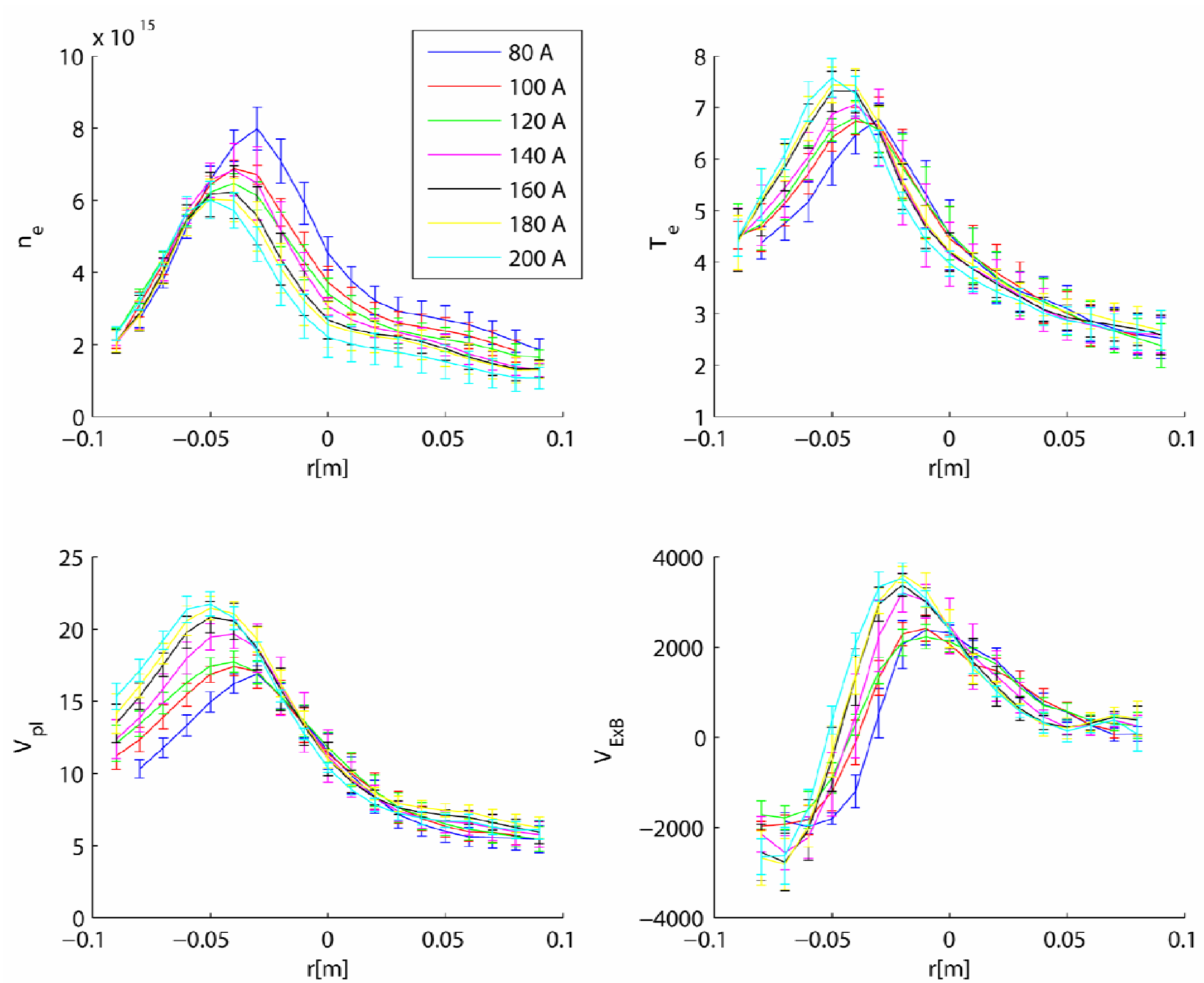
Interch. growth rate
$\gamma = (2/RL_p)^{1/2} c_s$

Shearing rate
v'_{ExB}

γ / v'_{ExB}
controls the transition

P. Ricci, et al., *High and low confinement modes in simple magnetized toroidal plasmas*, acc. Phys. Rev. Lett.

B_z scan : time-averaged profiles



- **H_2 plasmas**
- P_{rf} = 400 W
- B_t=76 mT on axis
- B_z = 1.7mT ⇒ 4.2mT
- Δ= 14 cm ⇒ 34 cm
- Vertically elongated (slab-like) profiles

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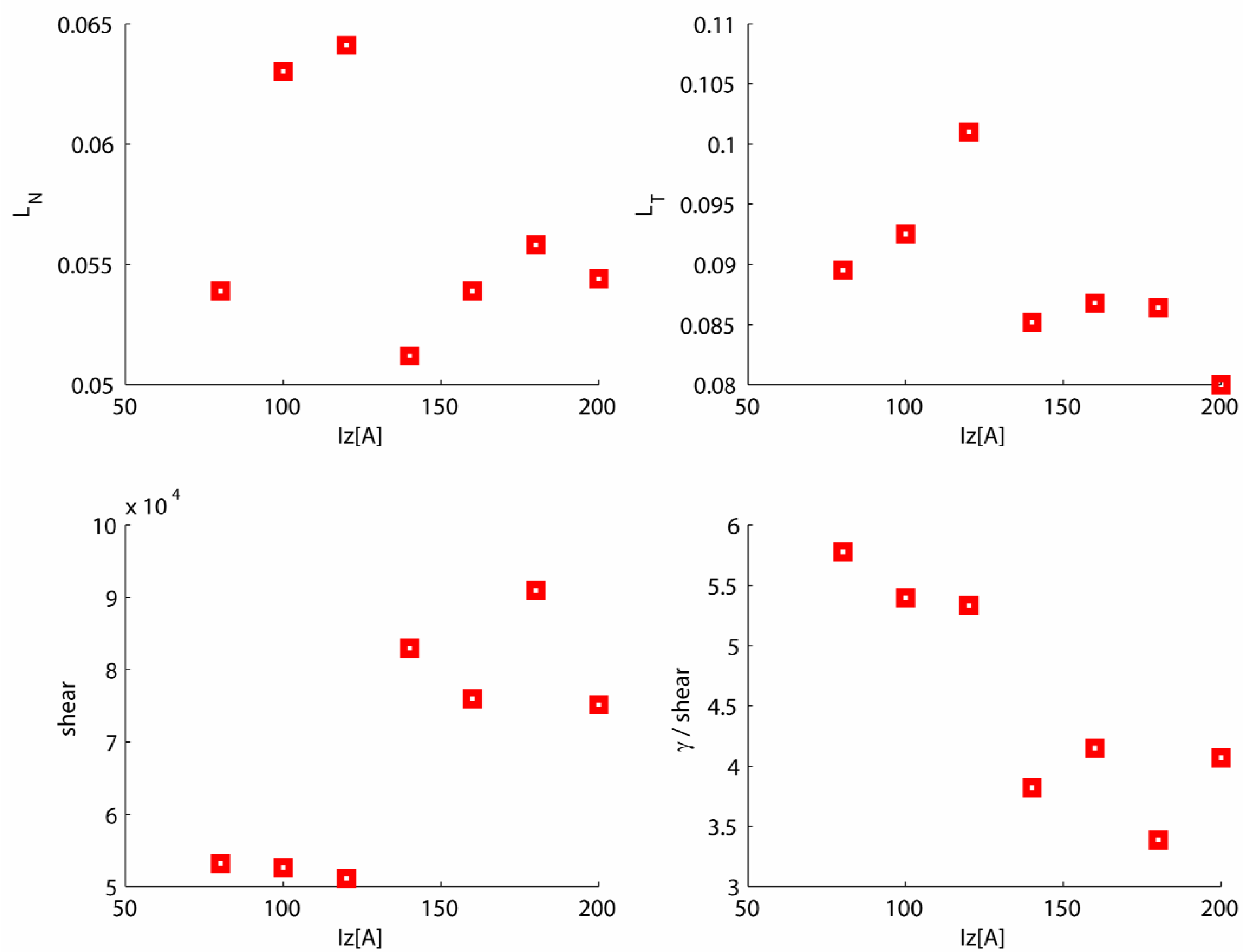
B_z scan: scale lengths



$\sigma = \Delta / (2\pi L_v)$

$$\frac{(k_\Delta \rho_s)^2}{\sigma \sqrt{L_p / 2R}} > 1$$

$\Downarrow$

No sheath effects

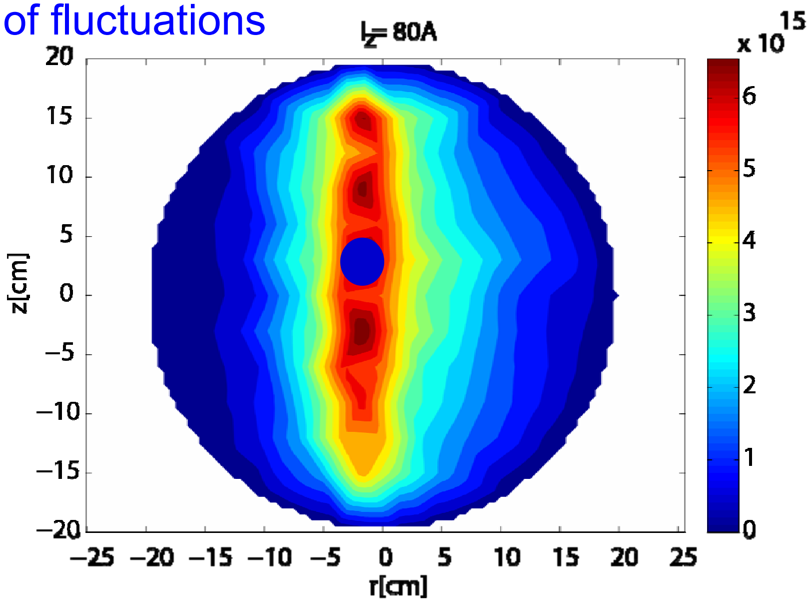
$$\frac{\gamma}{V'_{ExB}} > 1$$

$\Downarrow$

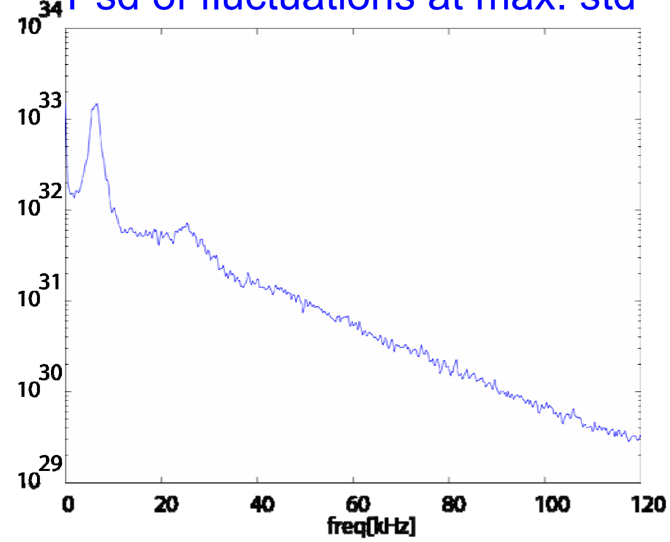
No shear flow stabilization

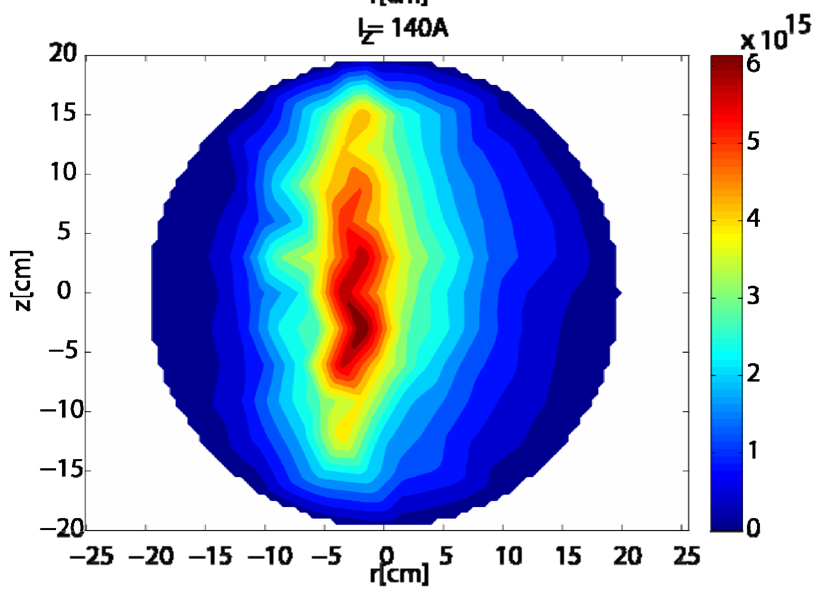
L-mode regime: multiple coherent modes

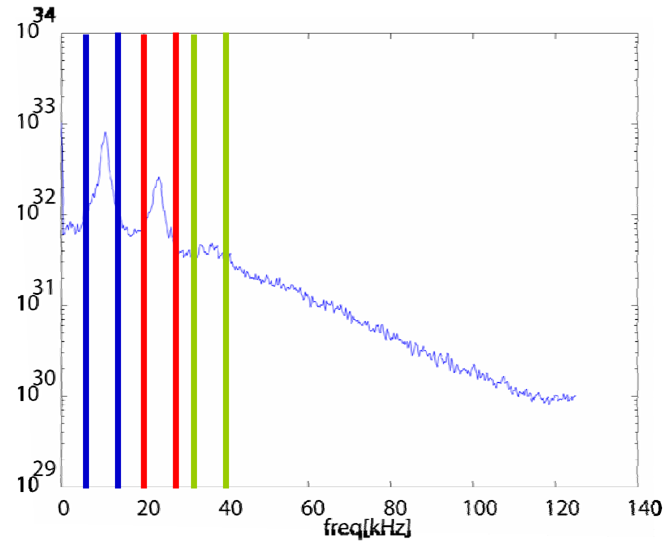
Std of fluctuations



Psd of fluctuations at max. std







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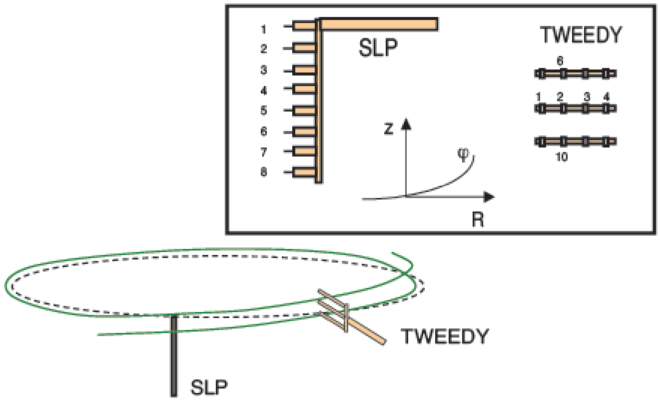
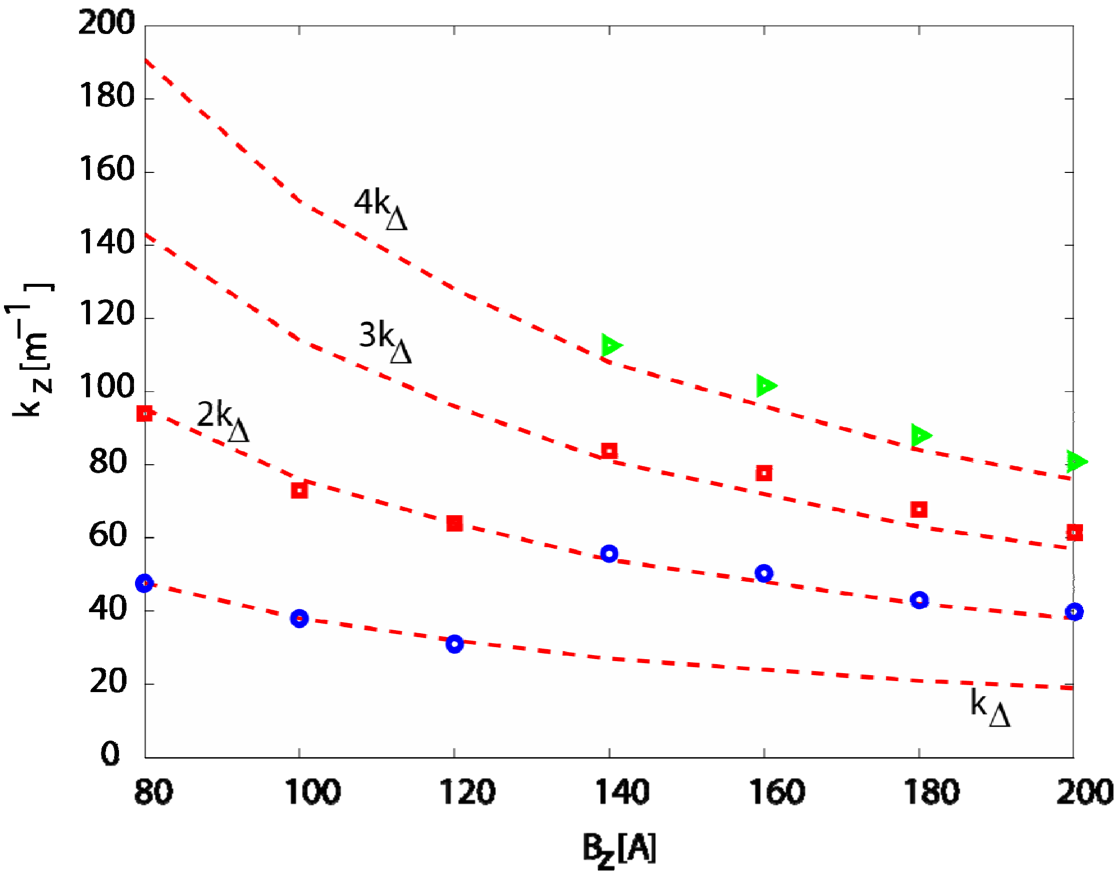
Fluctuations with $k_{//}=0 \Rightarrow$ interchange modes

LPs for disp. relation measurements



F.M. Poli, *et al.*, PoP (2006); PoP (2007); PoP (2008)



Interchange modes
localized around max $|\nabla p_e / p_e|$

$k_{//} < 0.046\ m^{-1} << k_z \Rightarrow$ **interchange**

k_z is multiple of k_Δ

$V_z \Rightarrow$ consistent with $<V_{ExB}>$

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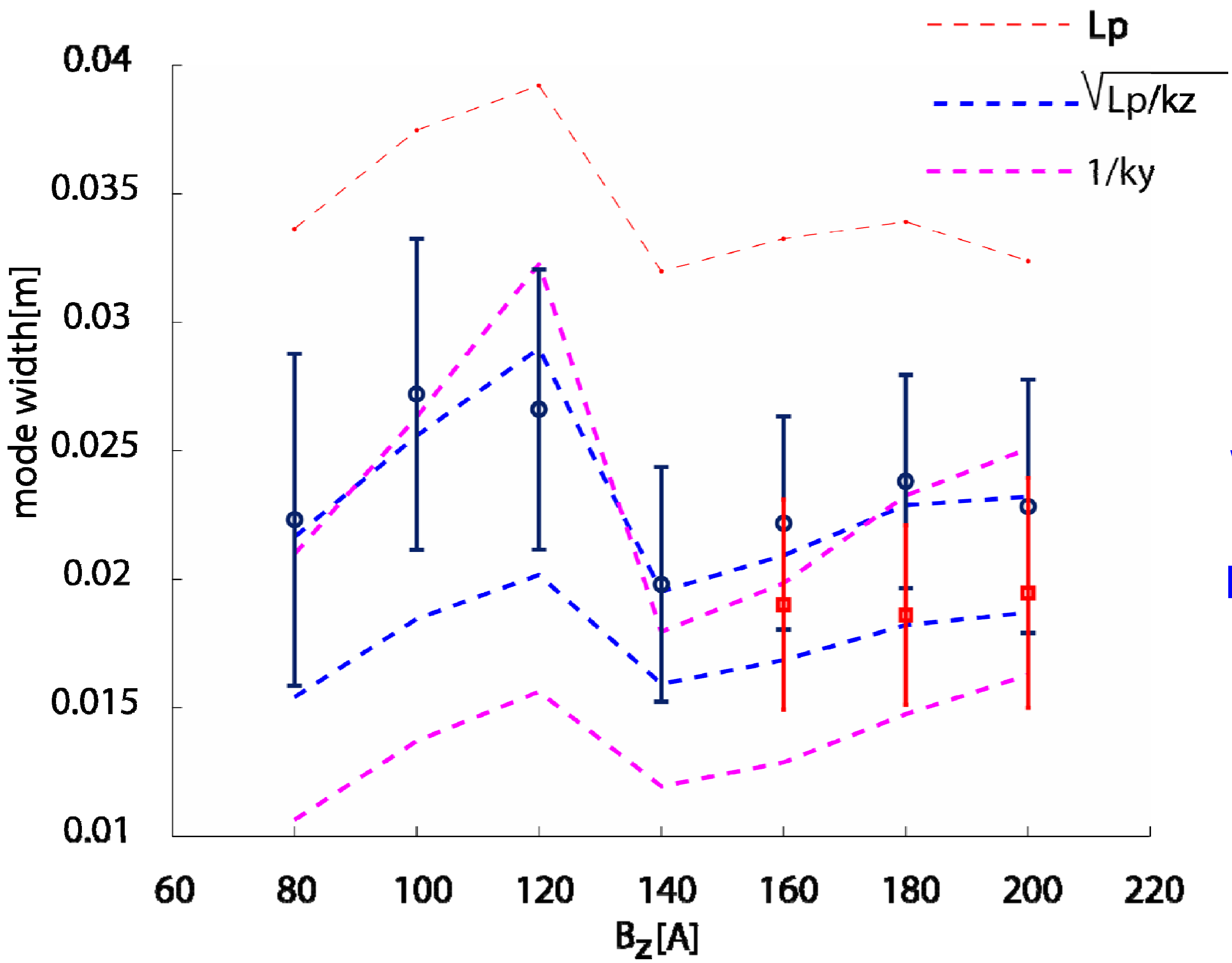
Radial width of interchange modes

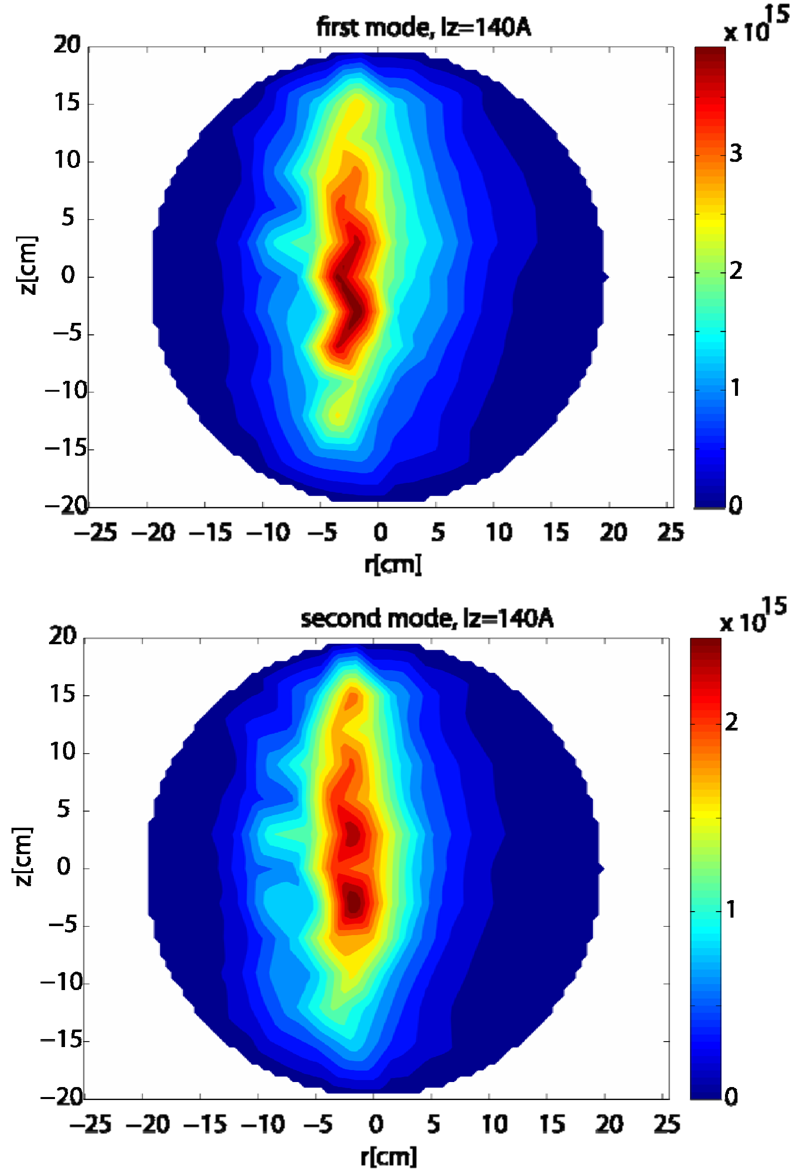


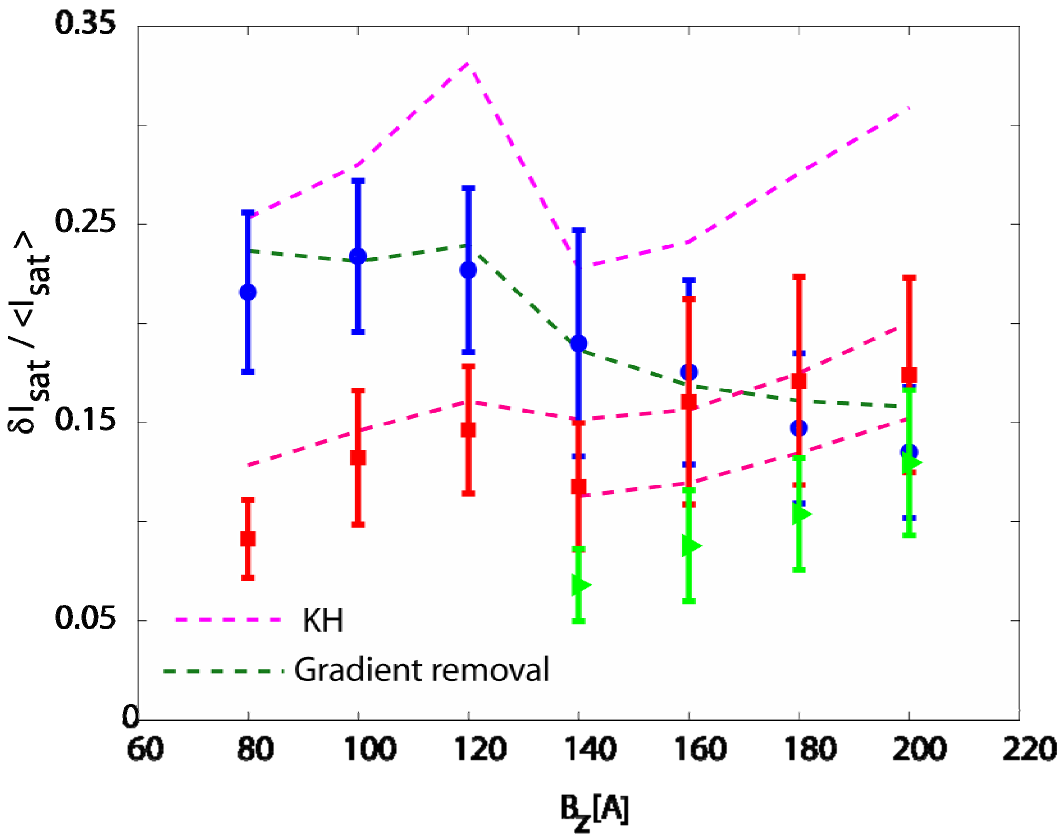
Mode width from conditionally sampled data

Width is smaller for high k_z mode

Different mode width scalings are tested

Amplitudes of interchange modes





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Possible saturation mechanisms

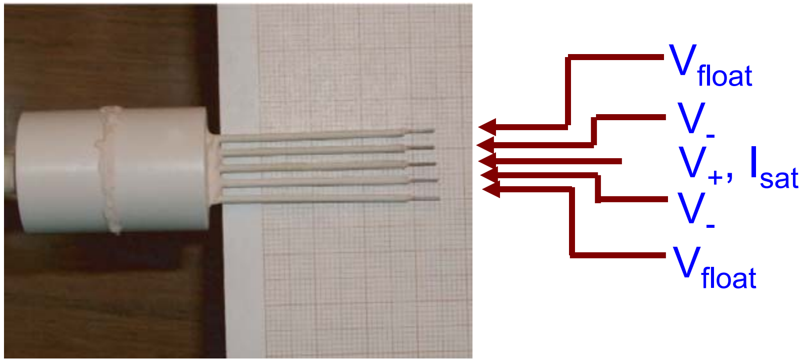
GRADIENT REMOVAL: turbulence saturation occurs when the drive is removed from the system: $\partial_r \check{n} \sim \partial_r \langle n \rangle$

- Typical radial extension of the interchange mode is $\sim (L_p/k_y)^{1/2}$, therefore $\partial_r \check{n} \sim \check{n}\,(k_y/L_p)^{1/2}$
- The sat. level is: $\check{n} \sim \langle n \rangle (L_p/k_y)^{1/2}/L_n$ [Ricci P., et al., Phys. Rev. Lett. **100**, 225002 (2008)]
- In the experiments, multiple modes are present: k_{y1}, k_{y2}, …
- The previous estimate can be written as: $\partial_r \langle n \rangle \sim [k_{x1}\,\check{n}_1 + k_{x2}\,\check{n}_2 + k_{x3}\,\check{n}_3 + \ldots]$
- Therefore: $\check{n}_1 \sim \langle n \rangle / L_n / [k_{x1} + k_{x2}\,a + k_{x3}\,b]$, where $a = \check{n}_2 / \check{n}_1$, $b = \check{n}_3 / \check{n}_1, \ldots$
- To compare with experimental data: $I_{sat1} \;/ \langle I_{sat} \rangle \sim [L_p/(k_{y1} + k_{y2}\,a + k_{y3}\,b]^{1/2}/(1/L_n + 1/2L_T)$

KH SATURATION: $\check{n} \sim \langle n \rangle /(L_n k_y)$

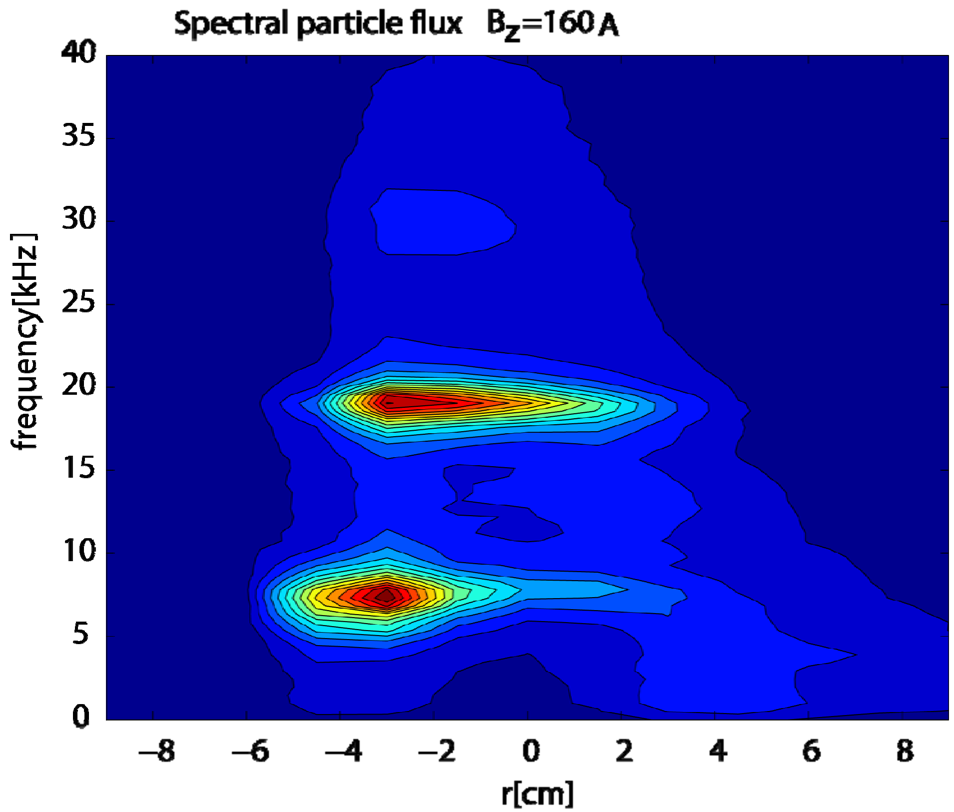
- To compare with experimental data: $I_{sat1} \;/ \langle I_{sat} \rangle \sim 1/(1/L_n + 1/2L_T)/k_y$

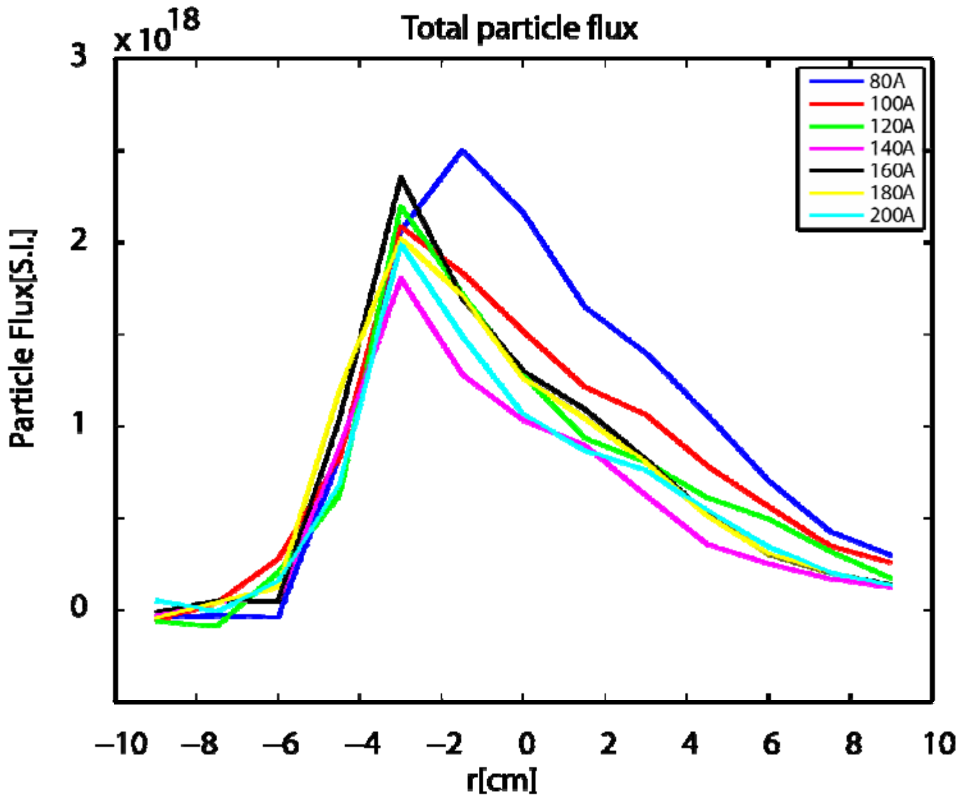
Particle flux measurements



Dedicated flux probe

Triple probe method for T_e correction





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Particle flux estimate is in agreement with data

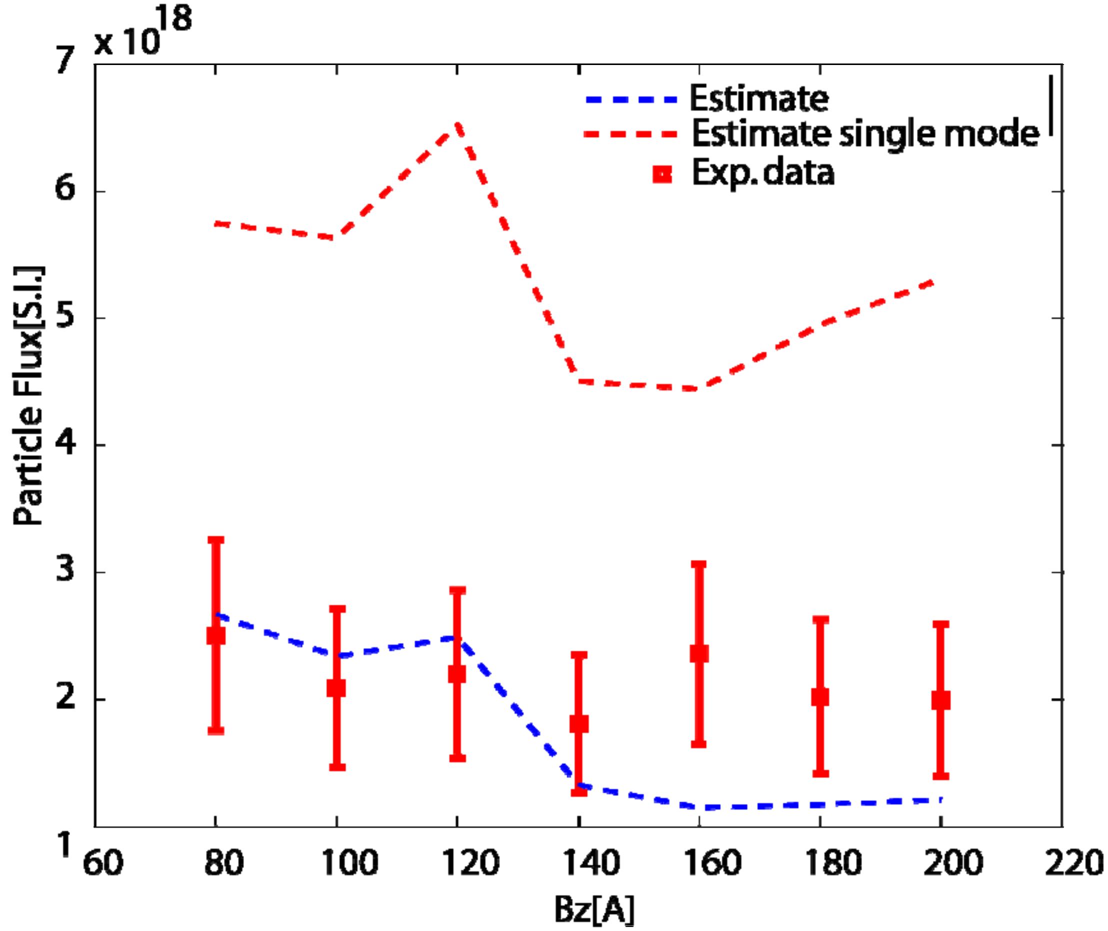
- Since shear flow is not important:

$\partial_y \tilde{U}_{pl} \sim \gamma_0 \check{n} / (R\, \partial_r \langle n \rangle)$

[Ricci P., et al., Phys. Rev. Lett. **100**, 225002 (2008)]

- Particle flux can be estimated as:

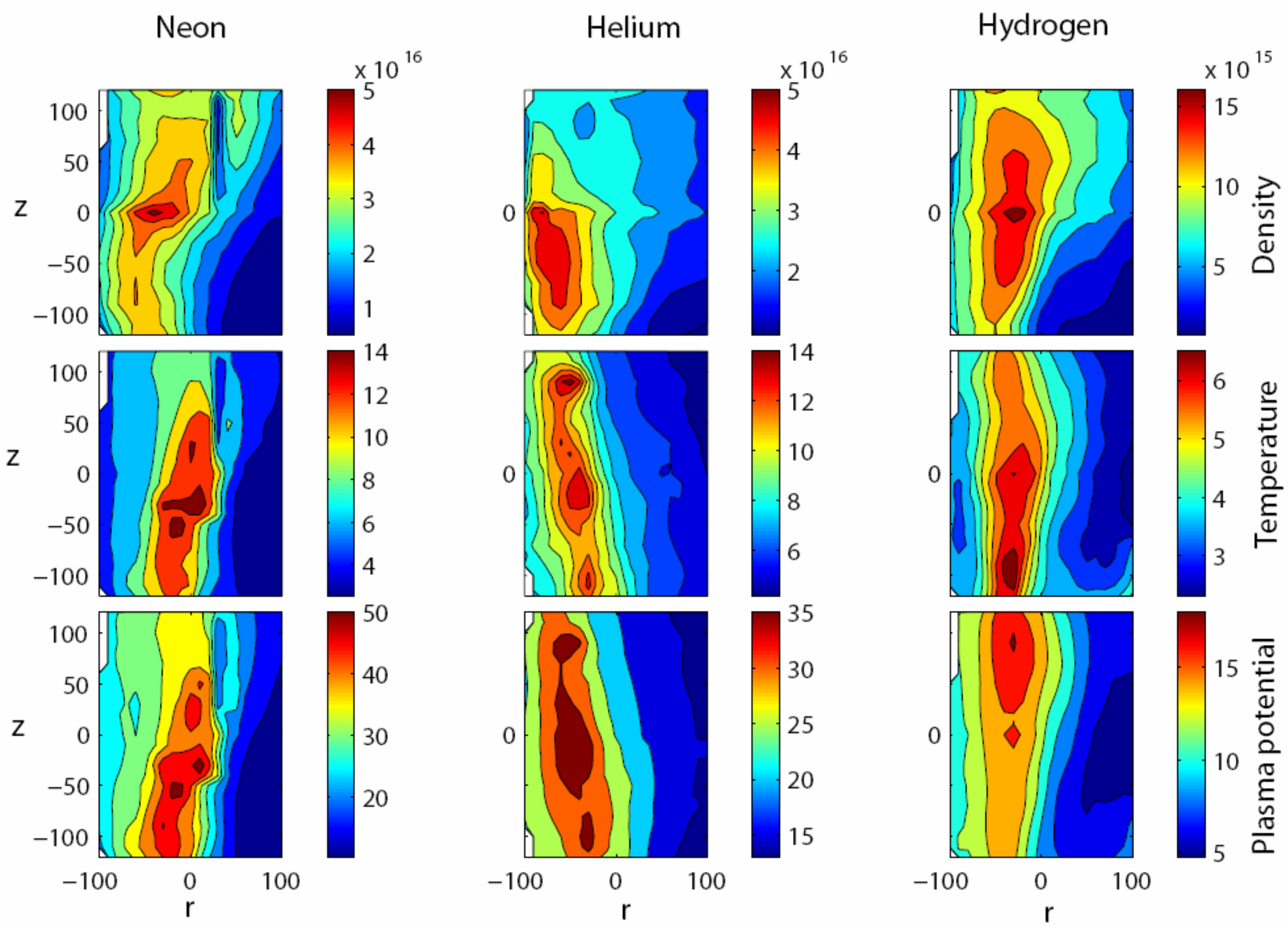
$\Gamma = \langle n \rangle\, (2R\, L_p \langle T_e \rangle)^{1/2} / (L_n k_y)$



- Taking into account multiple harmonics:

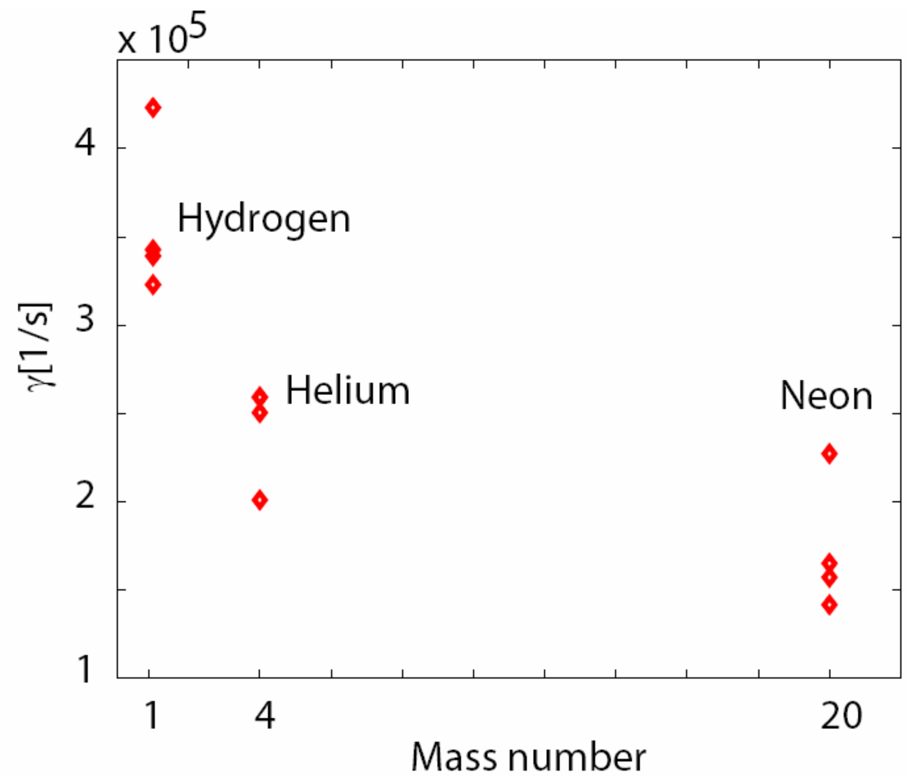
$\Gamma = \langle n \rangle\, (2R \langle T_e \rangle)^{1/2} L_p \;/\; L_n\; \Sigma_m (a_m)^2 / [\, (\Sigma_{m'}\, a_{m'}\; \sqrt{k_{ym'}})^2]$

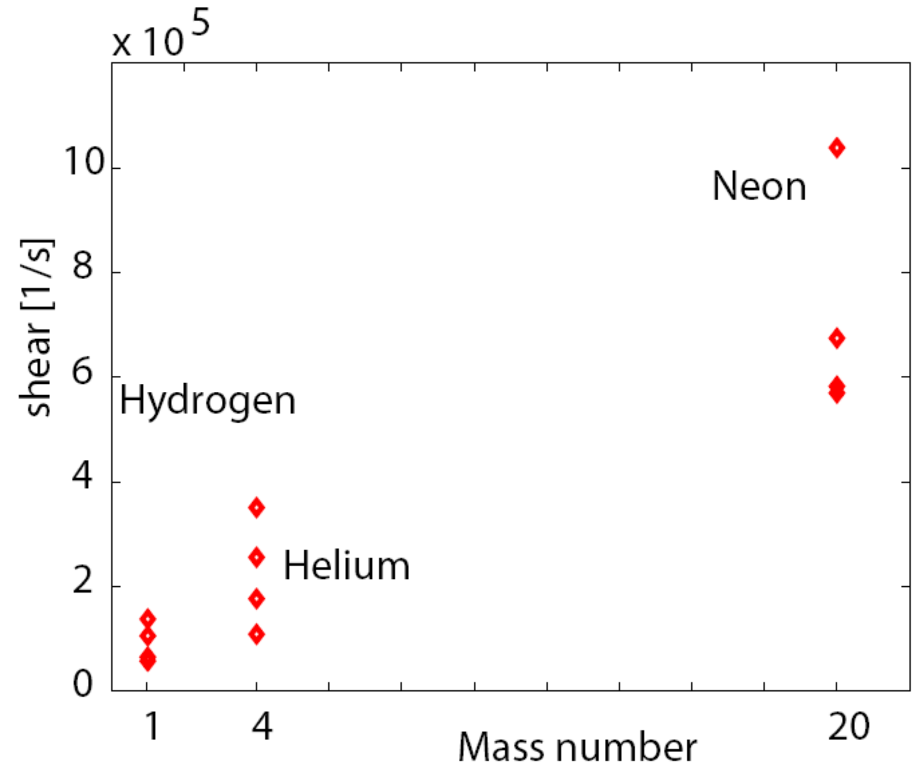
The quest for the H-mode: mass scan (H_2, He, Ne)



- Gases: H_2, He, Ne
- Varying pressure
- Varying B_z
- Only discharges with negligible sheath effects are retained
- Compute: $L_{T,N}$, V_{ExB}, shear,…

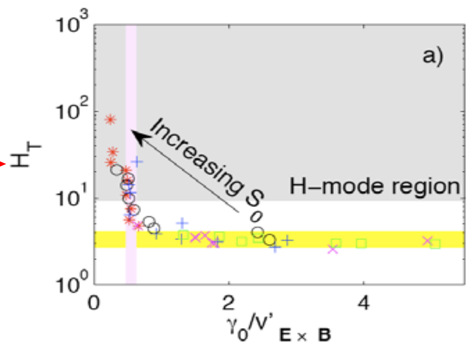
γ and v'_{ExB} scaling



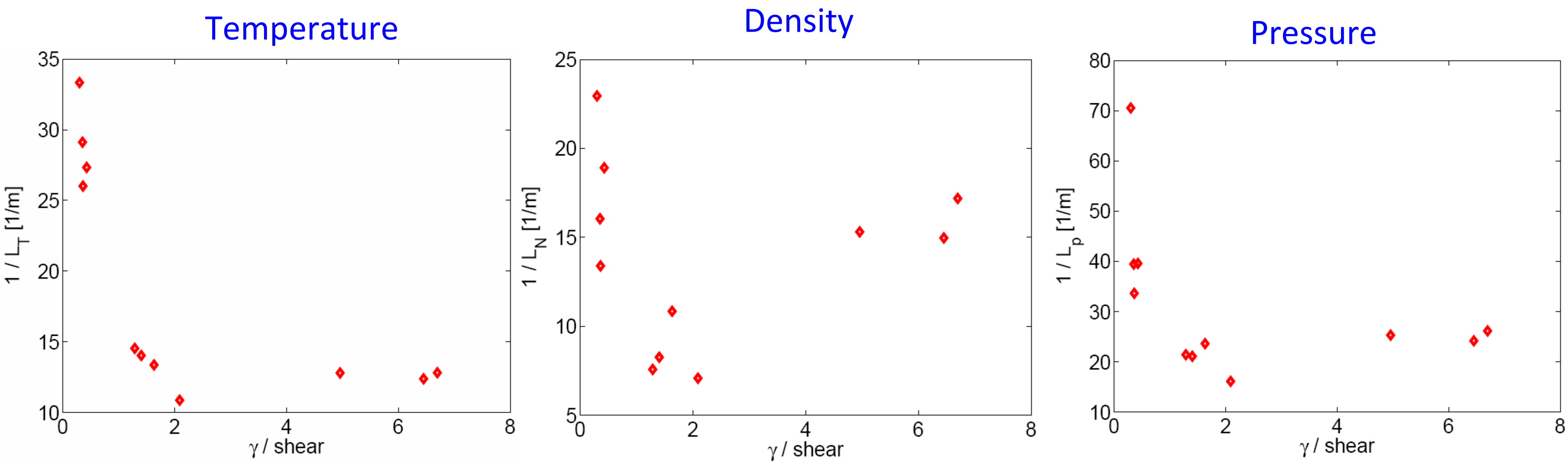


0.3 – 0.4 < γ / v'_{ExB} < 6 - 7

Access into H-mode



Scaling of L_p, L_N, and L_T



- ❑ The scaling of $1/L_T$ is in good agreement with theory
- ❑ Less clear the scaling of $1/L_N$
- ❑ Possible influence of the source position?

Experimental evaluation of the $H_{n,T}$ factor: $H_{n,T} = \dfrac{\Gamma_{n,T,L}}{\Gamma_{n,T}}$

Balance between perpendicular transport and parallel losses:

$$\frac{\partial \Gamma_n}{\partial x} = S_n - \sigma n c_s$$

Global balance (integration in the full domain):

$$S_n = \sigma n_{\max} c_{s,\max} \left[\frac{2 L_n L_T}{2 L_T + L_n} + \xi x_s \right]$$

Transport (integration up to $x > x_s$):

$$\Gamma_n = n_{\max} c_{s,\max} \frac{2 L_n L_T}{2 L_n + L_T} \exp\left(-x \frac{L_n + 2 L_T}{2 L_n L_T} \right)$$

From theory:

$$\Gamma_{n,L} = \frac{\sqrt{2 R L_{p,L}}\, c_{s,\max} n_{\max}}{L_{n,L} k_\Delta} \exp\left(-x \frac{L_{n,L} + 2 L_{T,L}}{2 L_{n,L} L_{T,L}} \right)$$

$$H_n = \frac{L_v \sqrt{2 R L_{p,L}}}{L_{n,L}} \left(\frac{1}{L_n} + \frac{1}{2 L_T} \right)$$

$$H_T = \frac{9 L_v \sqrt{2 R L_{p,L}}}{4 L_{T,L} L_T}$$

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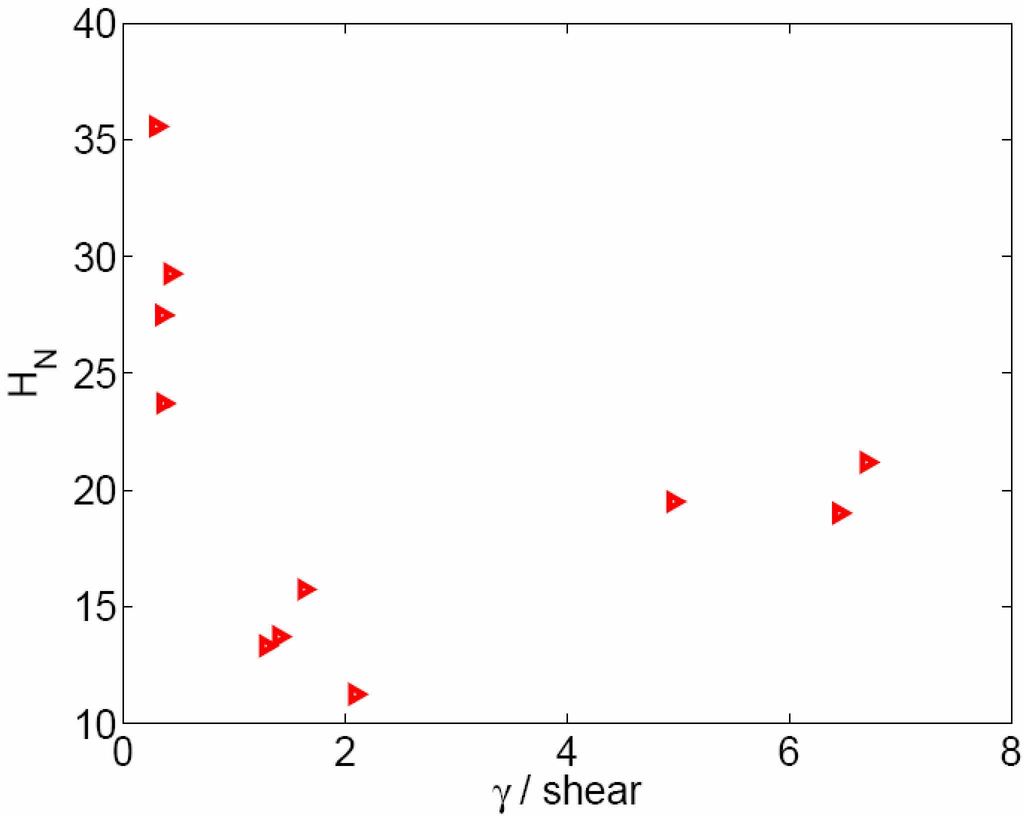
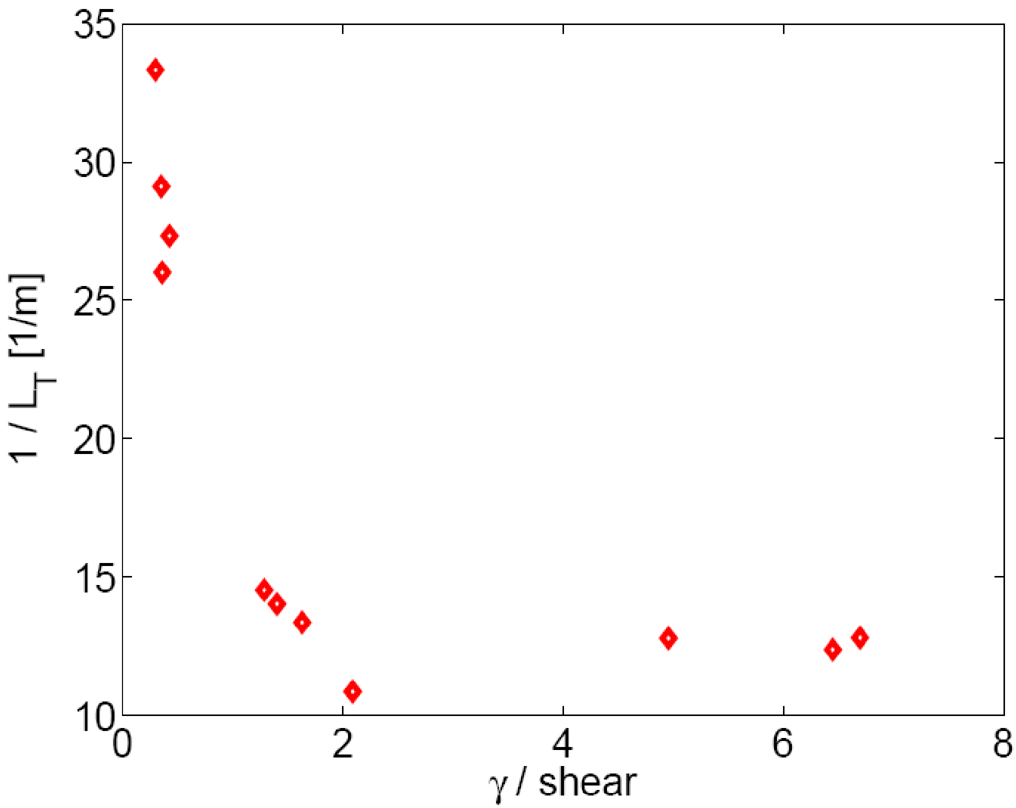
Experimental scaling of the $H_{N,T}$ factor





Confinement improvement at low γ / v'_{ExB} in agreement with theory

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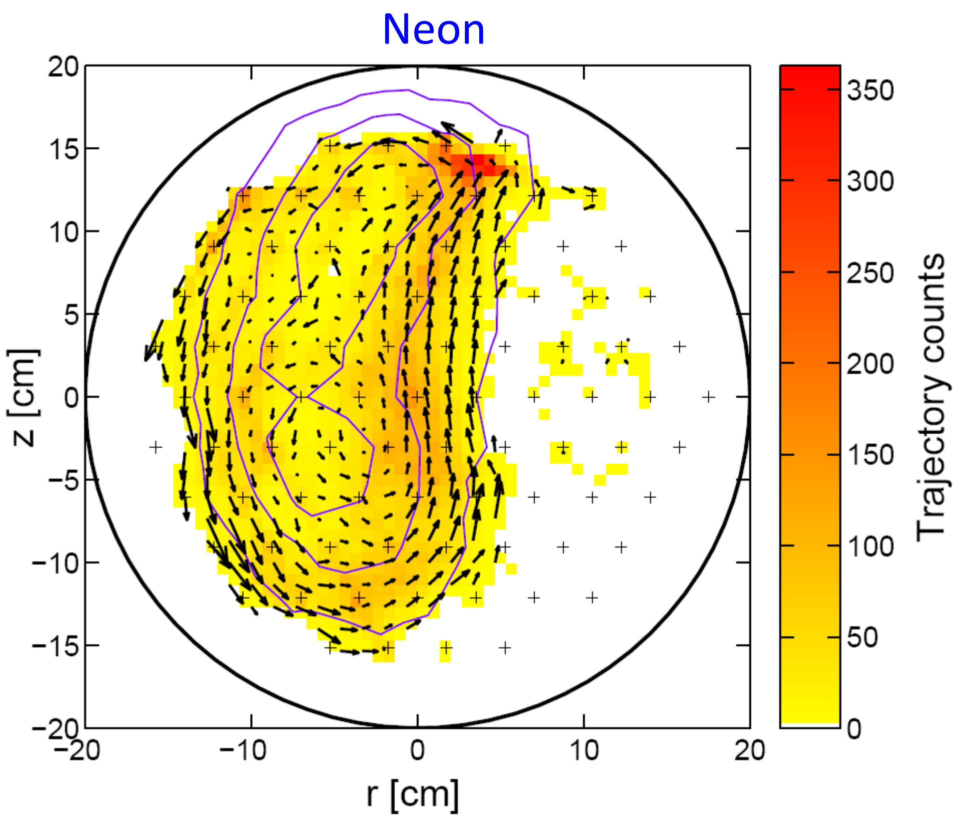
Are there blobs at low γ / v'_{ExB}?



- Pattern-recognition based analysis

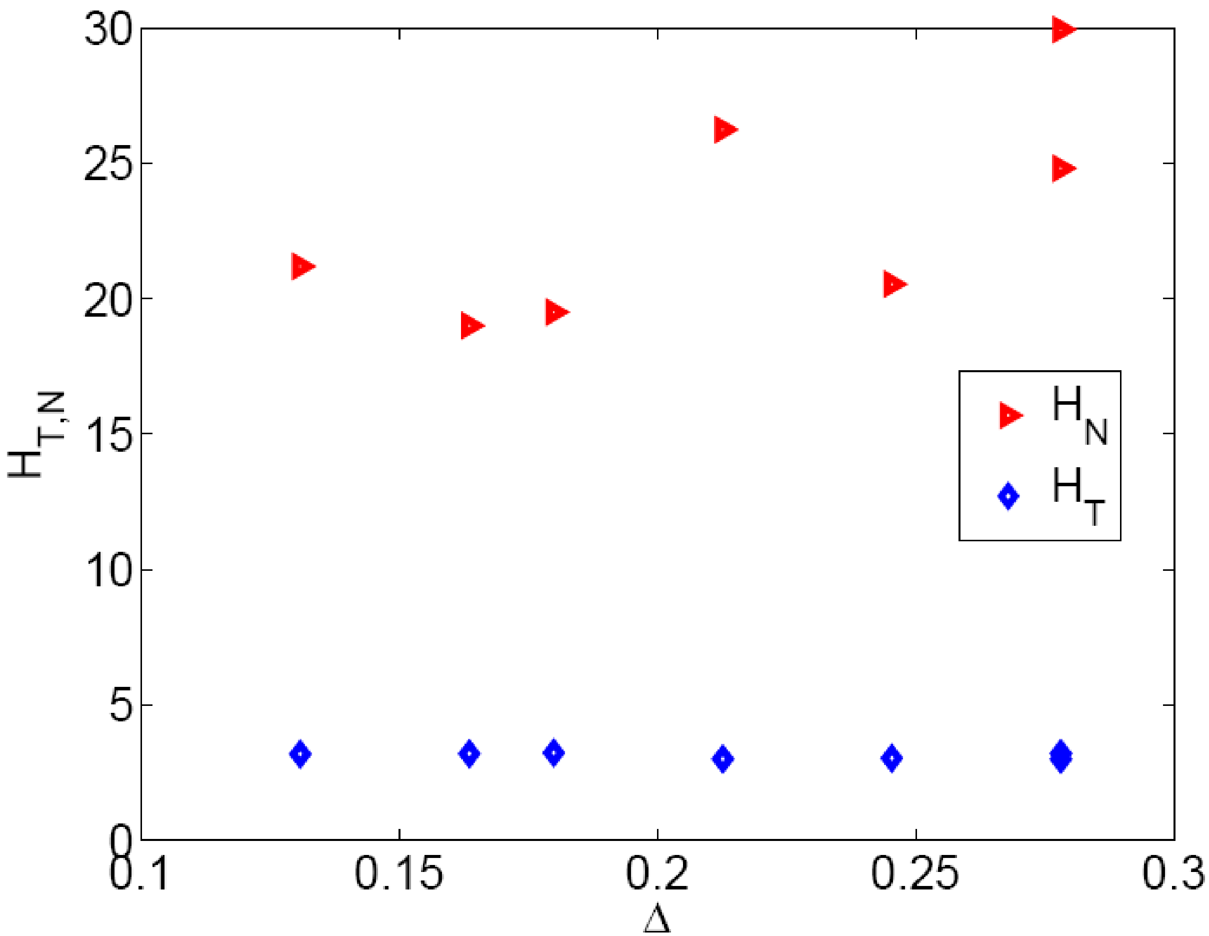
  S. H. Müller et al., PoP **13**, 100701 (2006)

- Tracking positive ($I_{sat} > I_{thres}$) and negative ($I_{sat} < I_{thres}$) structures $\Rightarrow$ speed, size, trajectory,…

- No clear sign of blobs $\Rightarrow$ reduction in perpendicular transport?

S. H. Mueller *et al.*, Phys. Plasmas **13**, 100701 (2006).

$H_{N,T}$ factor in the case of dynamics with sheath effects



Data suggest that the particle confinement is improving at large Δ

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