The simulation effort for the basic plasma experiment TORPEX

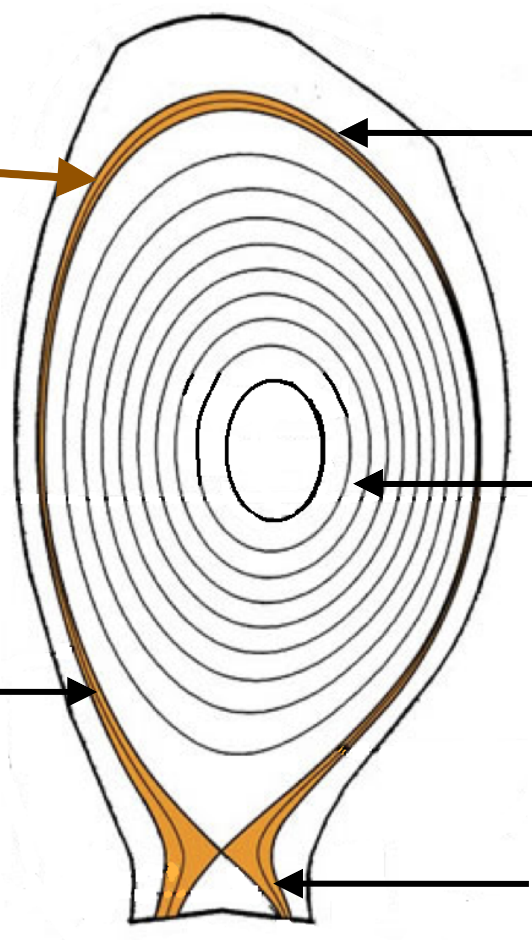
Paolo Ricci, B. Rogers[1],

and the TORPEX team

Centre de Recherches en Physique des Plasmas
École Polytechnique Fédérale de Lausanne, Switzerland
1) Dartmouth College, Hanover NH

Why TORPEX?
How its dynamics can be approached?
What are the turbulent regimes?
How do simulations and experiments compare?
What are we really learning from TORPEX simulations?

Plasma turbulence in the edge



Scrape-off Layer

Complex magnetic geometry

Coupling with core region

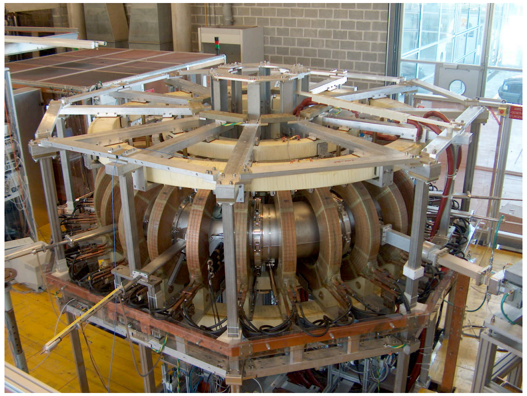
Difficult diagnostics access

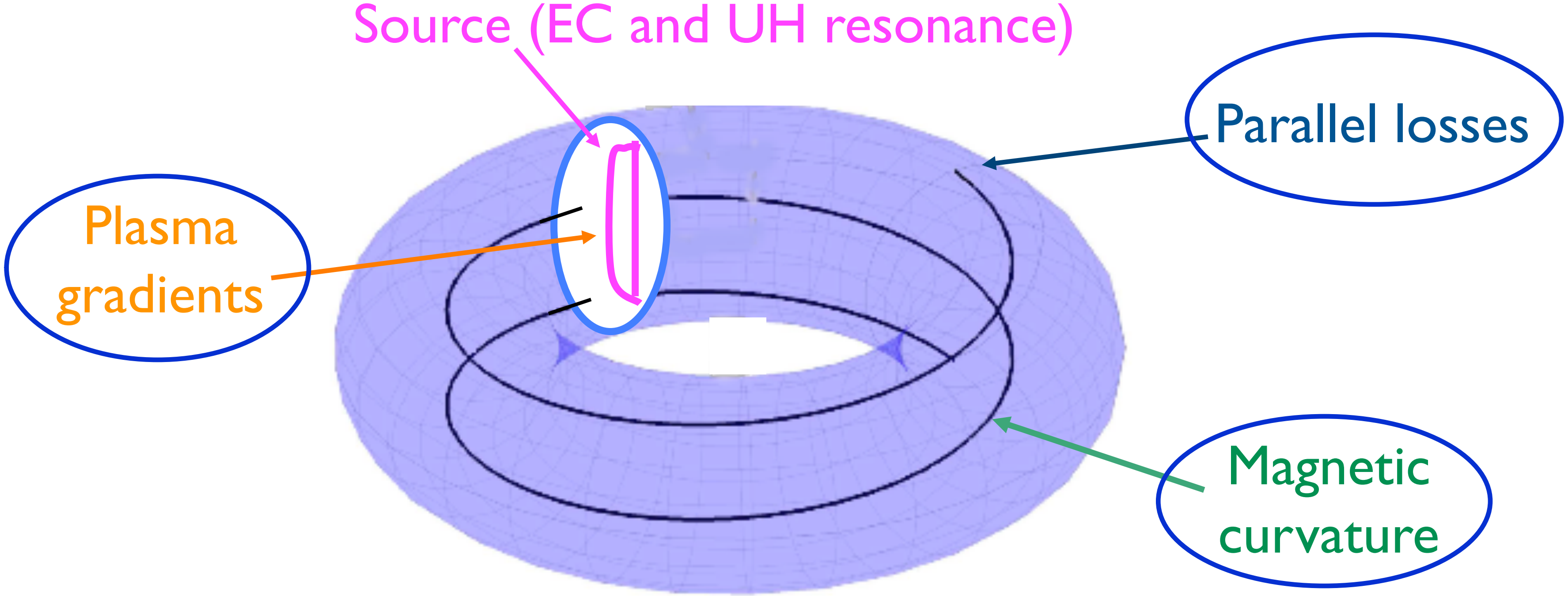
Sheath physics & atomic physics

➡ Need for basic plasma physics experiments

The TORPEX experiment, paradigm of edge turbulence

crpp.epfl.ch/torpex/

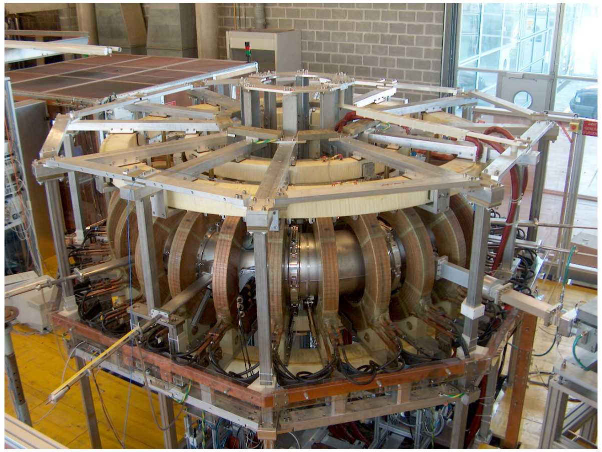


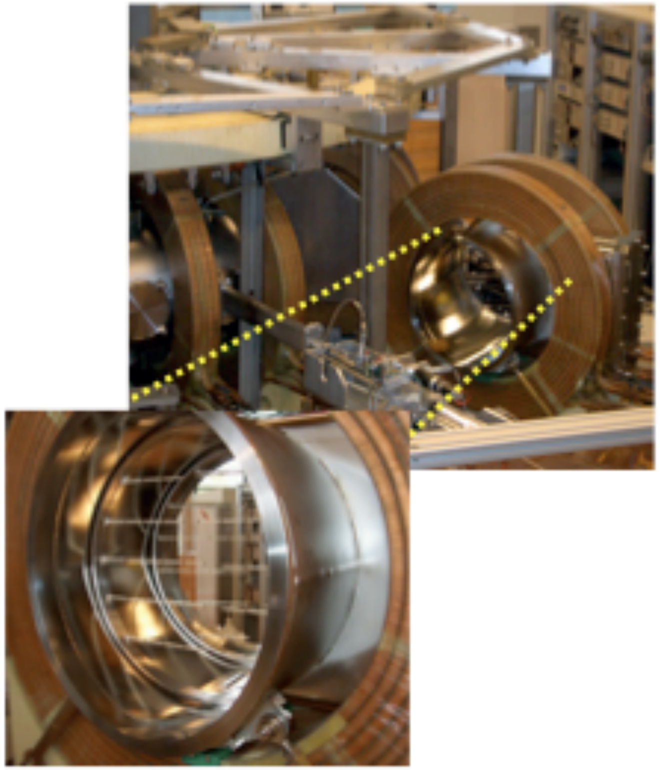


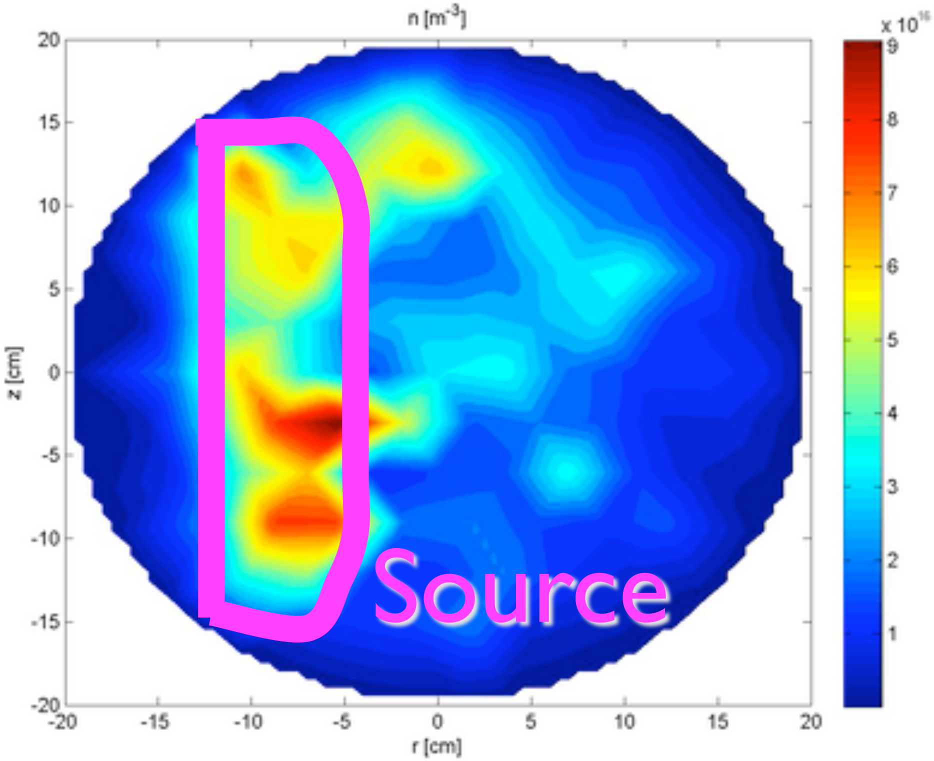
Fundamental elements of SOL turbulence

Fasoli *et al.*, PoP 2006

High resolution diagnostics with full coverage



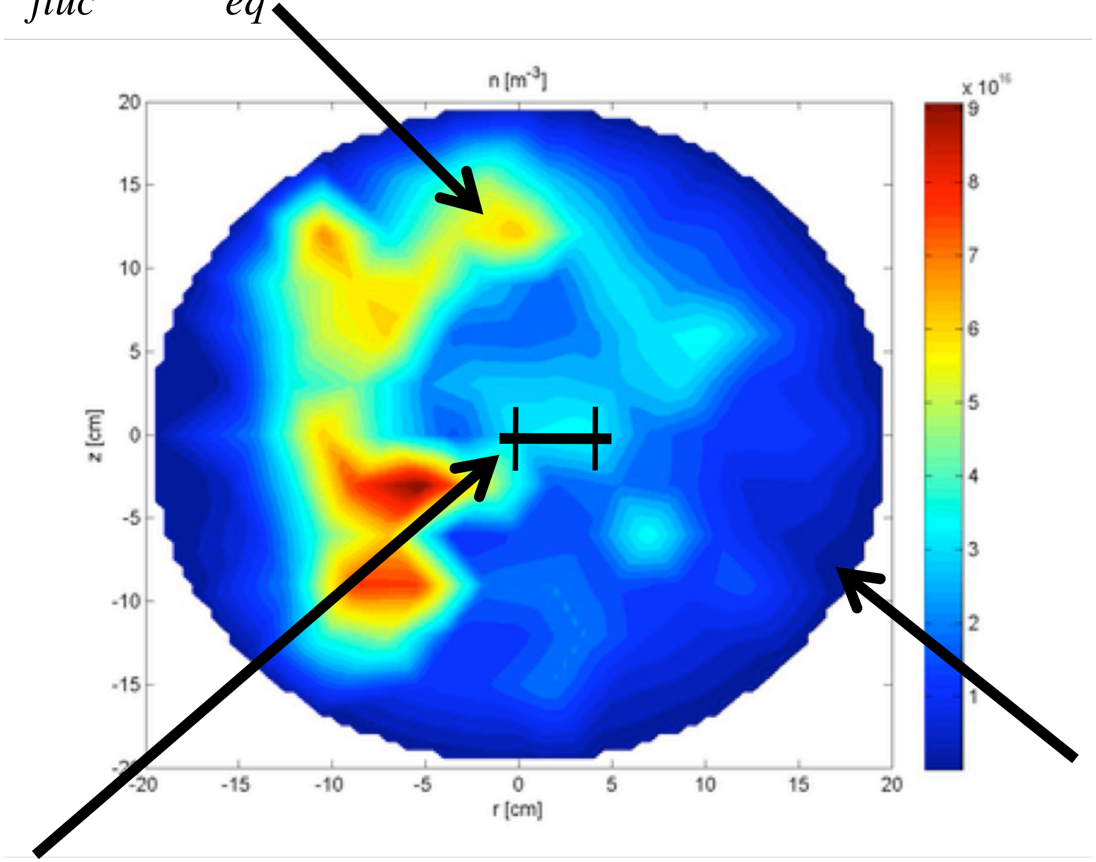




Measurements of all relevant plasma and field parameters

Properties of TORPEX turbulence

$n_{fluc} \sim n_{eq}$



$T_i << T_e$

$\beta << 1$

$\omega << \Omega_{ci}$

$L_{\parallel} >> L_{\perp}$

Collisional

$L_{eq} \sim L_{fluc}$

$L >> \rho_i$

Fluid model

Collisional Plasma → **Braginskii model** → $\rho_i \ll L,\ \beta \ll 1,\ \omega \ll \Omega_{ci}$ → **Electrostatic Drift-reduced Bragiskii equations**

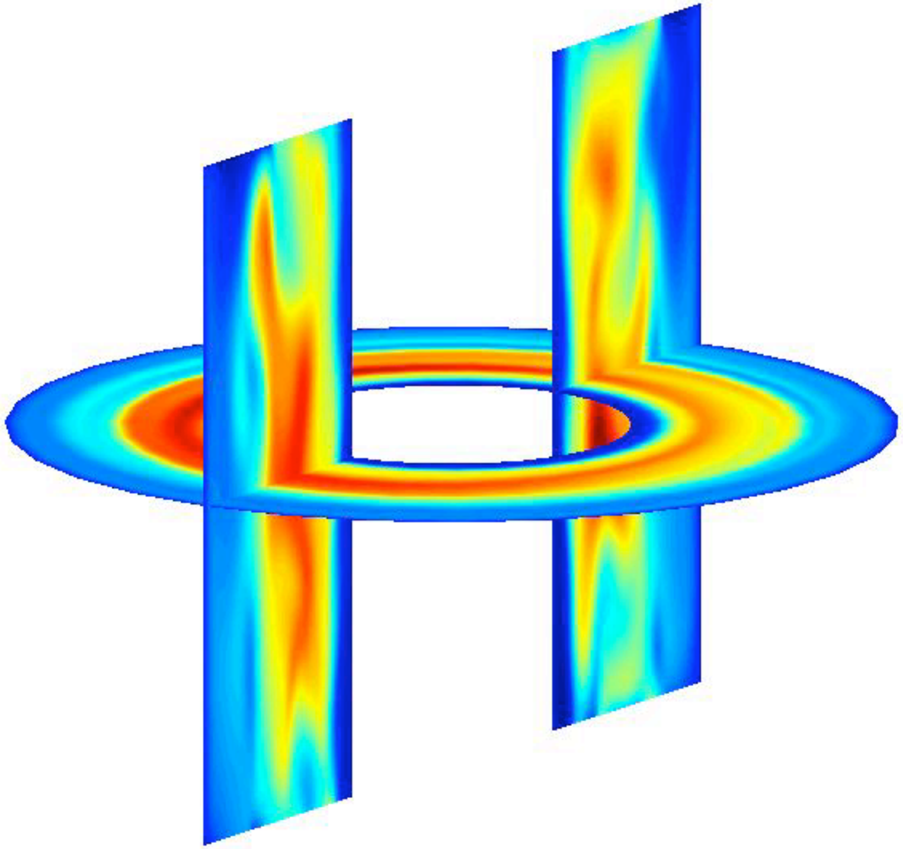
$$\overbrace{\frac{\partial n}{\partial t}+[\phi,n]}^{\text{Convection}} = \overbrace{D_n \nabla^2 n}^{\text{Diffusion}} + \overbrace{\frac{2}{R}\left(n\frac{\partial T_e}{\partial y}+T_e\frac{\partial n}{\partial y}-n\frac{\partial \phi}{\partial y}\right)}^{\text{Magnetic curvature}} - \overbrace{\nabla_{\parallel}(nV_{\parallel e})}^{\text{Parallel dynamics}} + \overbrace{S}^{\text{Source}}$$

T_e, Ω (vorticity) → similar equations

$V_{\parallel e}$, $V_{\parallel i}$ → parallel momentum balance

$$\nabla_{\perp}^2 \phi = \Omega$$

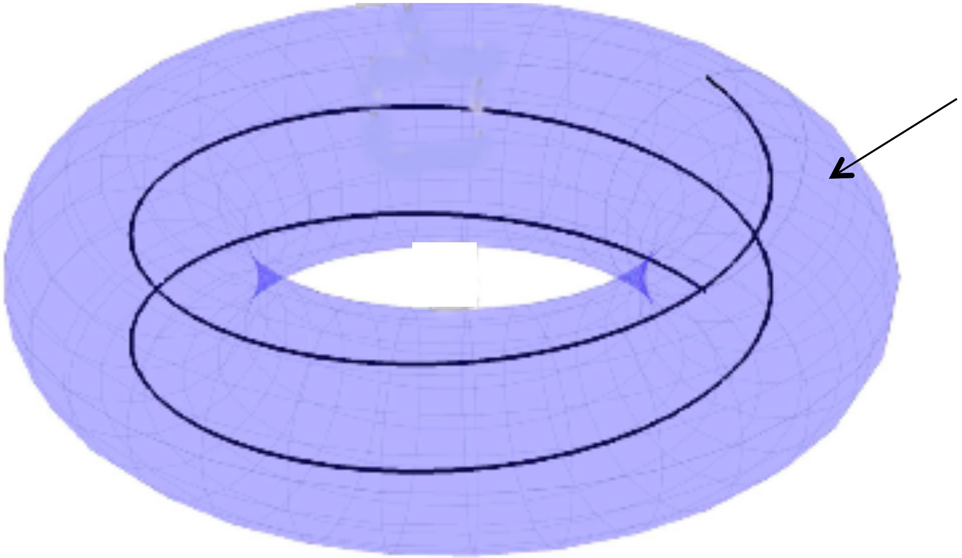
Global simulations



Evolve both equilibrium and fluctuations

The character of TORPEX turbulence

Depends on N, the number of B turns



Example: N=2

Low N: $k_{\|} = 0$ ➡ Ideal interchange dominated

High N: $k_{\|} \neq 0$ ➡ Resistive interchange dominated

Another instability regime – driftwaves – to be discussed later
(likely inaccessible to the experiments)

Ideal interchange mode

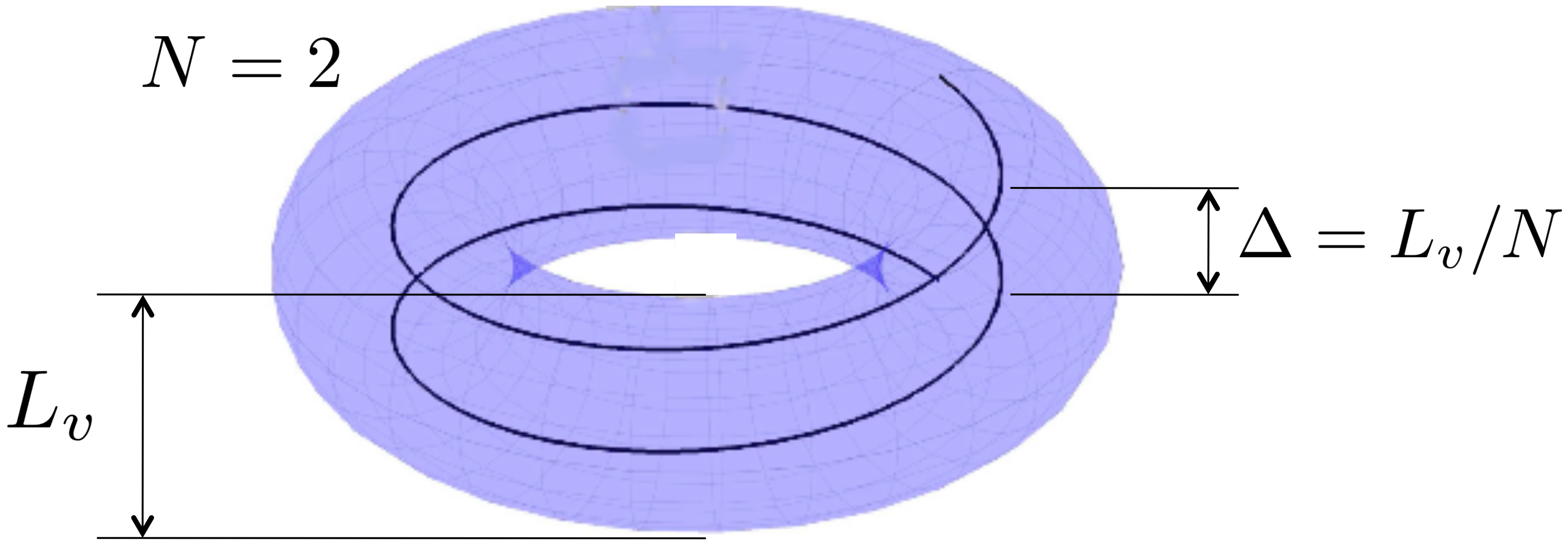
$k_{\|} = 0$ ➡

$n + T_e$ eqs. ⟶ $$\frac{\partial p_e}{\partial t} = \frac{c}{B}\left[\phi, p_e\right]$$

Vorticity eq. ⟶ $$\frac{\partial \nabla_\perp^2 \phi}{\partial t} = \frac{2B}{c m_i R n}\frac{\partial p_e}{\partial y}$$

➡ $$\gamma = \gamma_I \qquad \gamma_I = c_s\sqrt{\frac{2}{L_p R}}$$

Anatomy of a $k_{\|} = 0$ perturbation



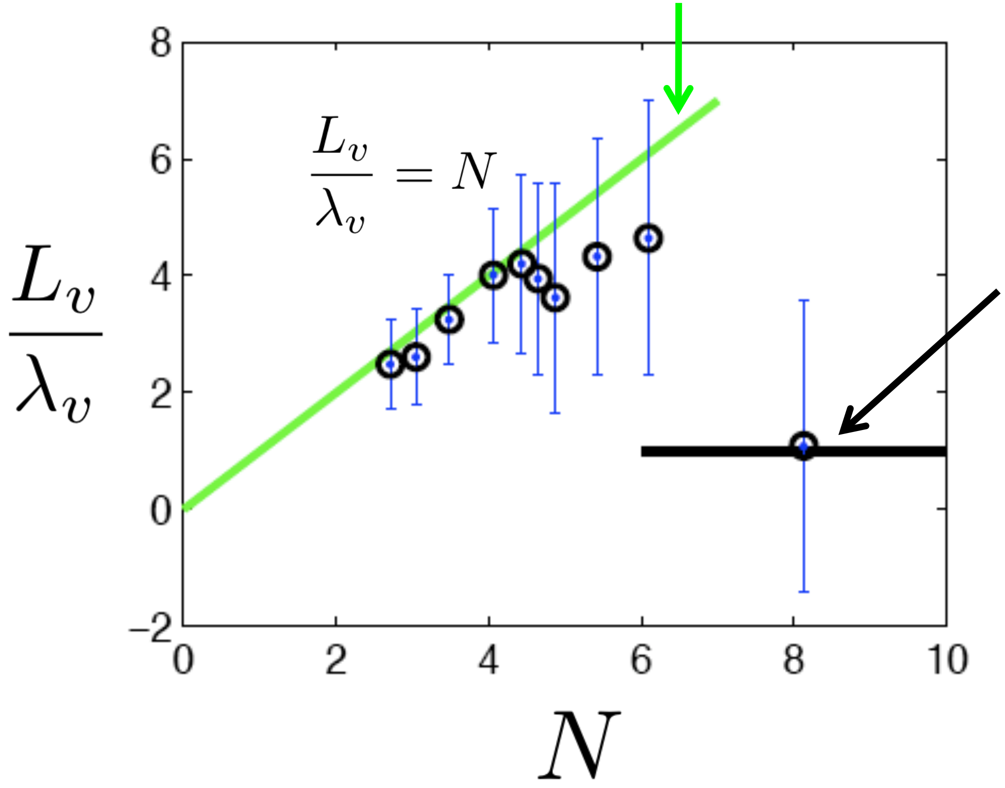
λ_v : longest possible vertical wavelength of a perturbation

If $k_{\|} = 0$ then $\lambda_v = \Delta = \dfrac{L_v}{N}$

TORPEX shows $k_\parallel = 0$ turbulence at low N

$$k_\parallel = 0 \quad (\lambda_v = L_v/N)$$

Ideal interchange regime

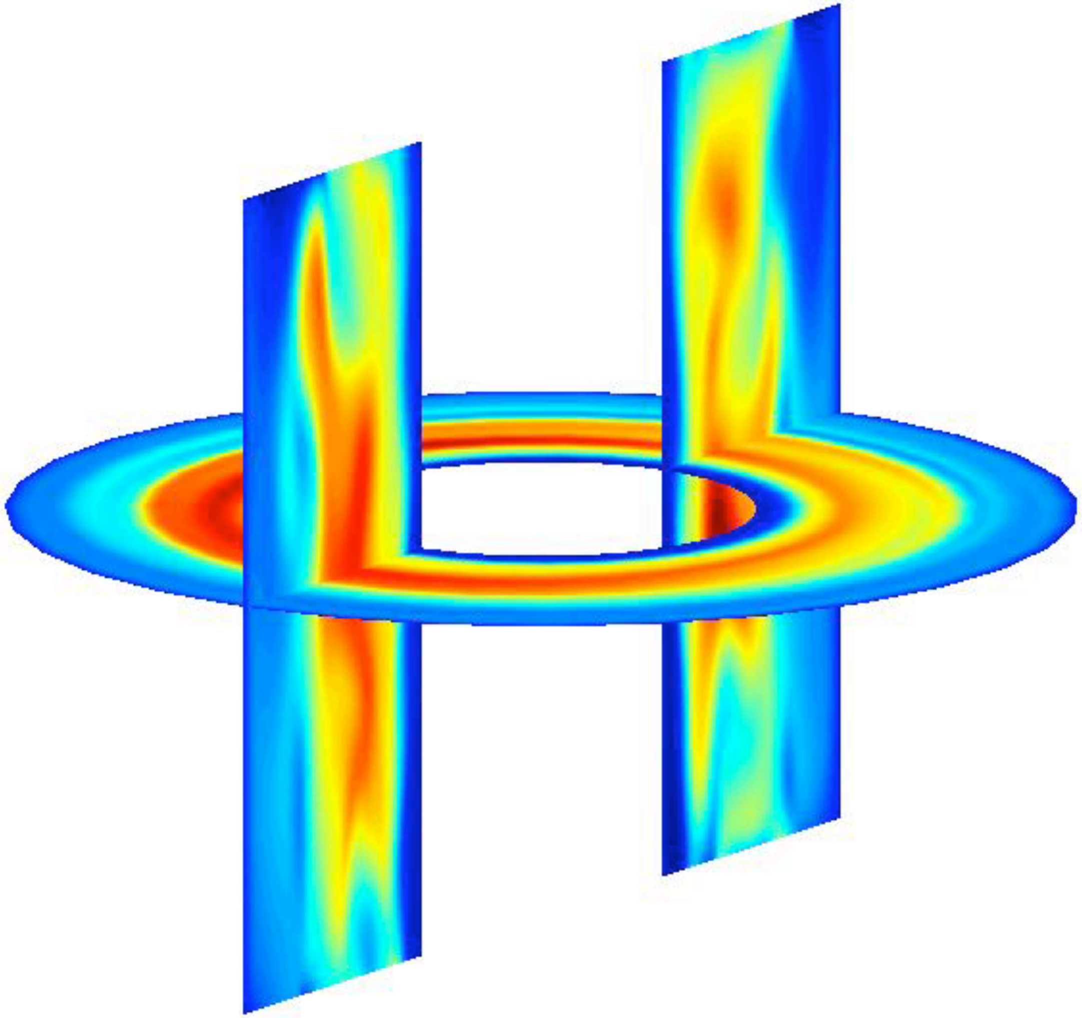


$$k_\parallel \neq 0 \;\; (\lambda_v = L_v)$$

Resistive interchange regime – return to this later

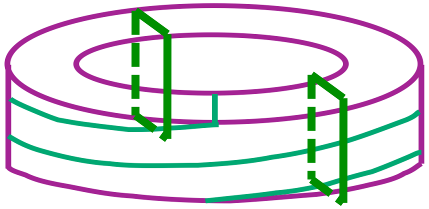
Poli et *al*., PoP 2006, 2008

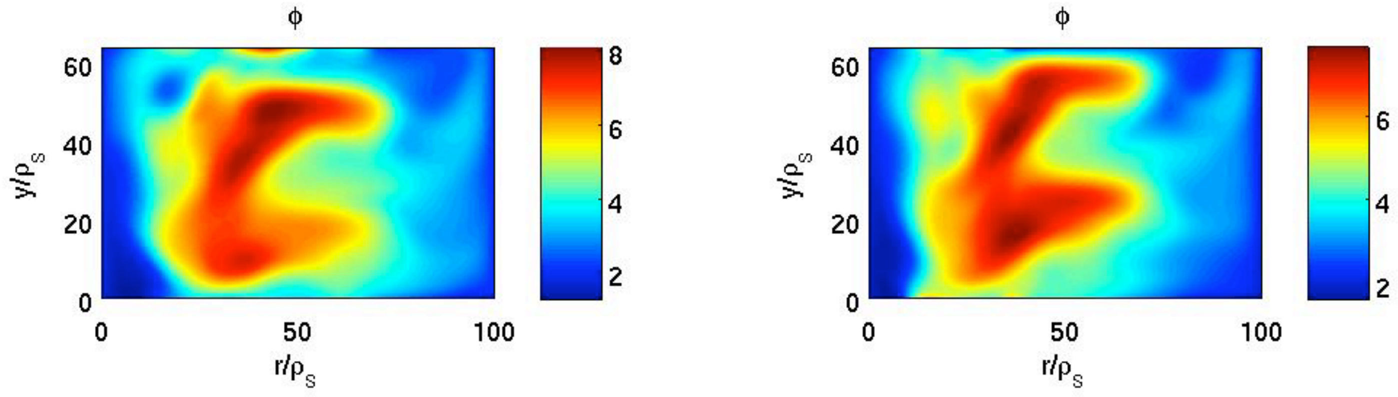
For N~1-6, ideal $(k_\parallel = 0)$ interchange modes dominant

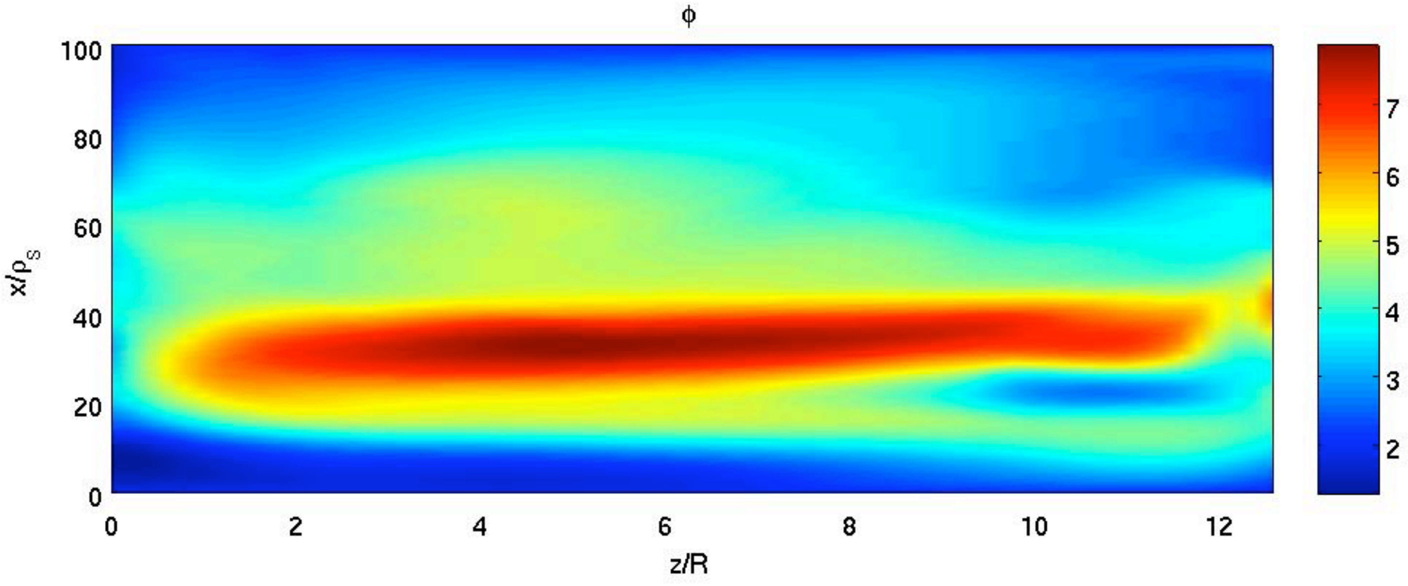


N=2

Ideal interchange (*N*=2)

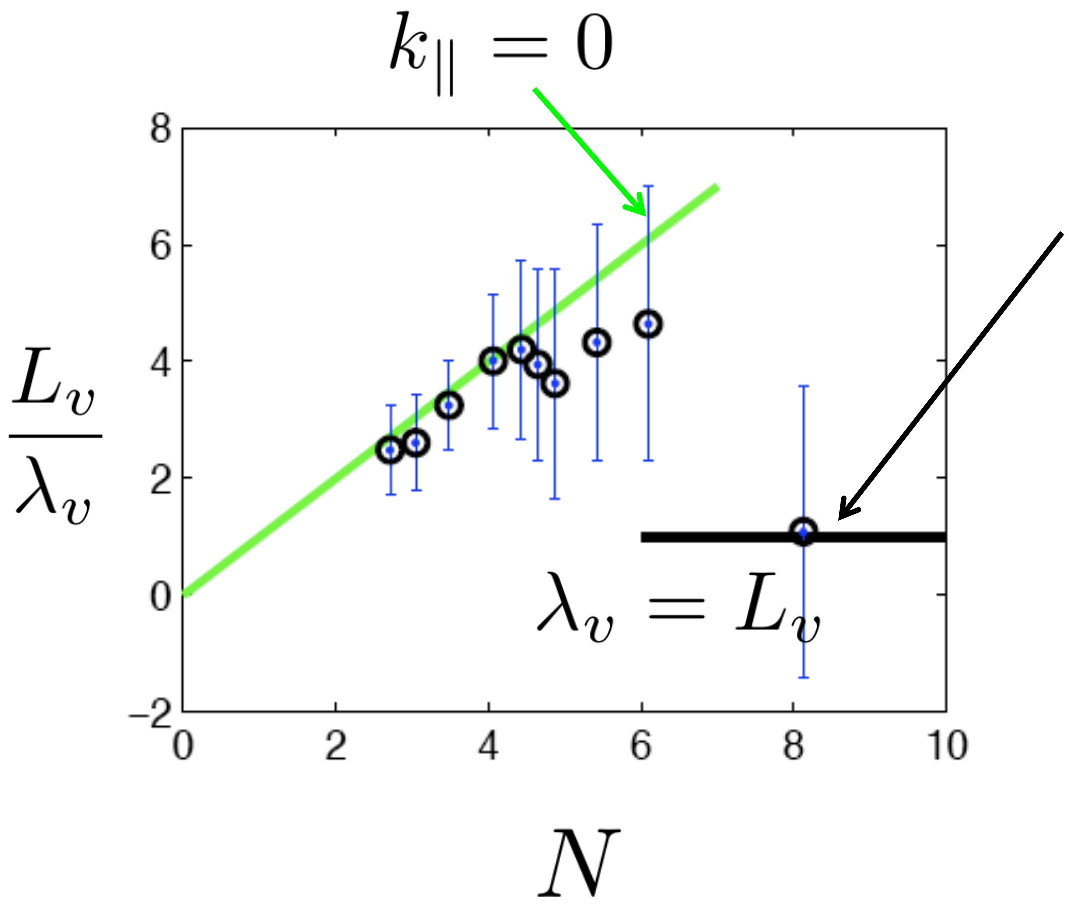






High $N>7$

Simulations and TORPEX experiments dominated by $k_\| \neq 0$ toroidally symmetric turbulence.



Resistive interchange

$k_\| \neq 0$

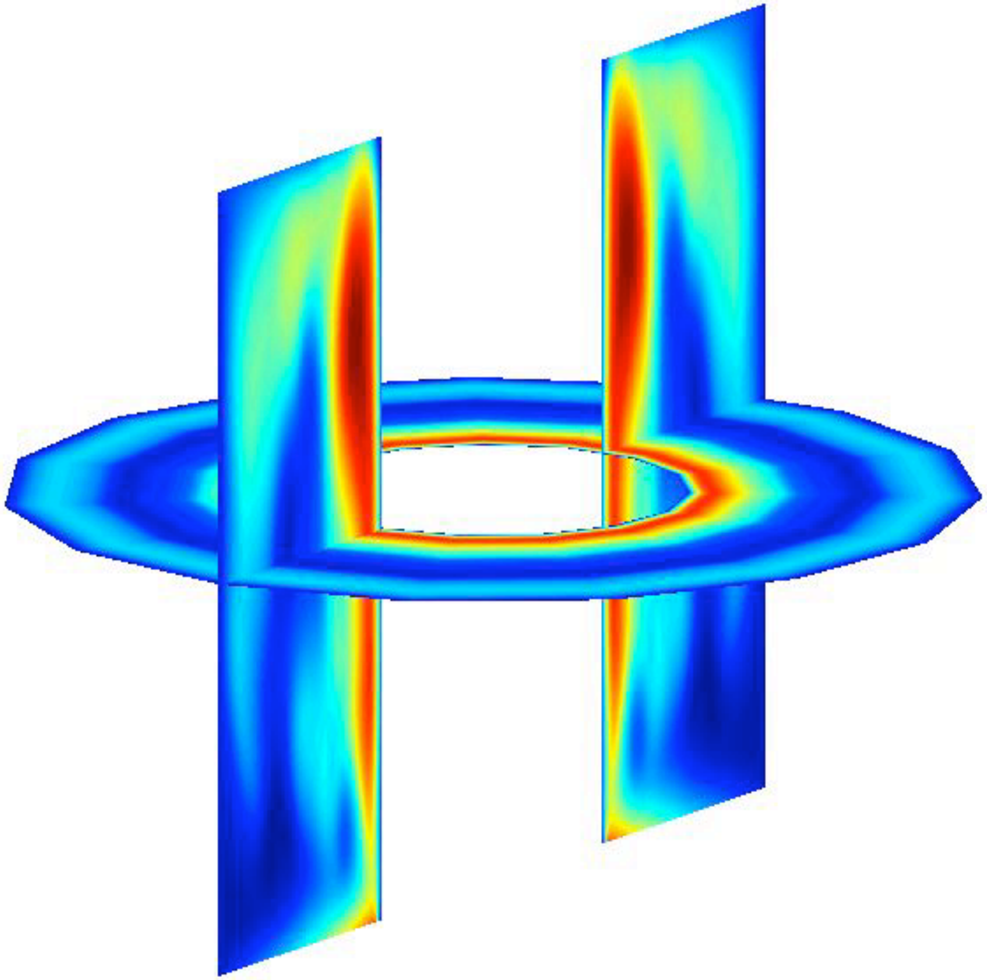
Why $\lambda = L_v$? $N > 6$?

Toroidally symmetric?

Explain in a moment.

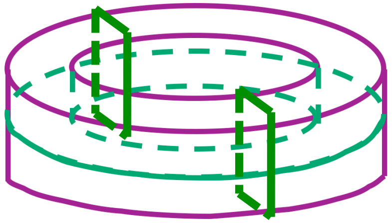
Poli *et al.*, PoP 2006, 2008

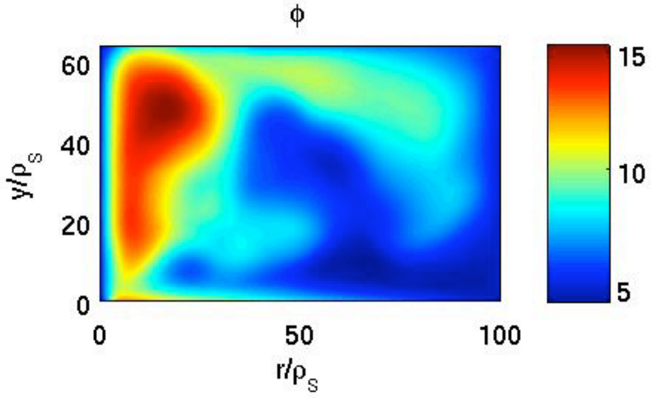
At high N>7, toroidal $\lambda_v \sim L_v$ symmetric turbulence

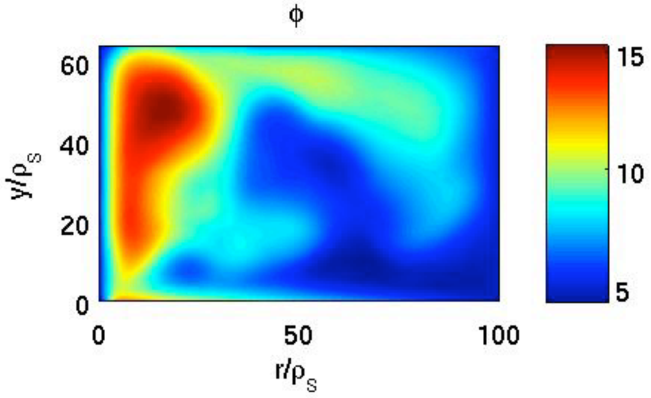


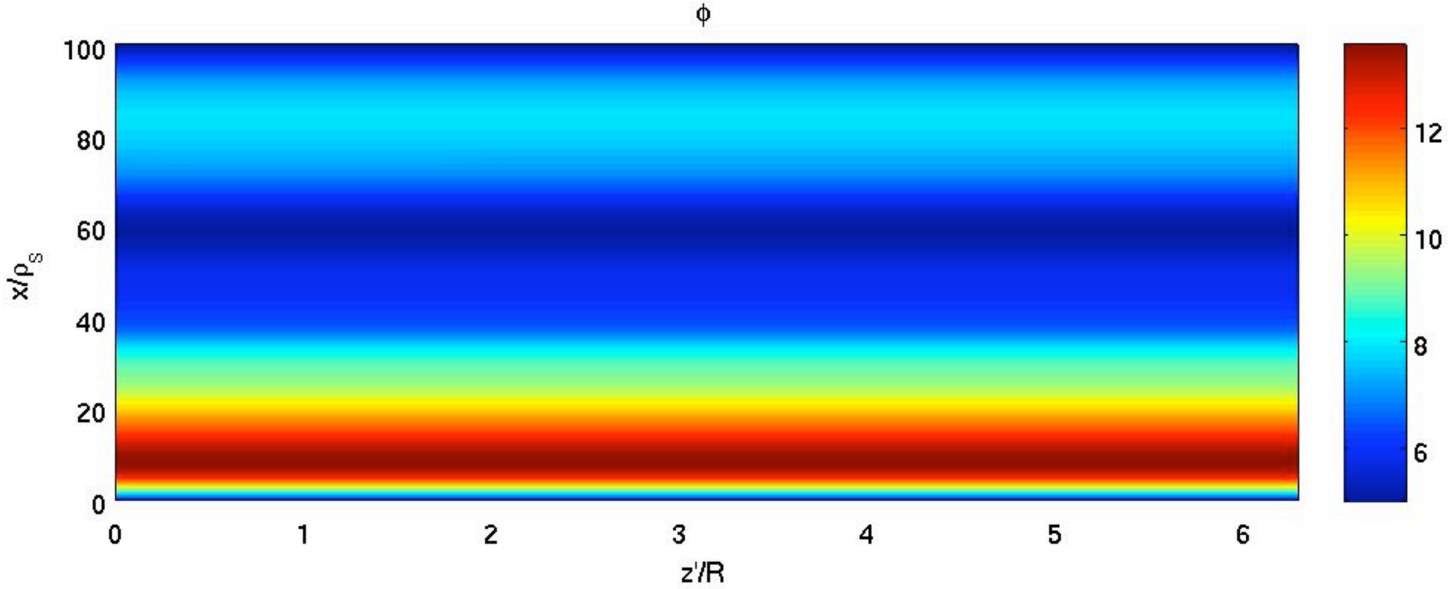
N=16

Resistive interchange (N=16)









Resistive interchange modes

n + *T*$_e$ eqs. →

$$\frac{\partial p_e}{\partial t} = \frac{c}{B}\left[\phi, p_e\right]$$

Vorticity eq. →

$$\frac{\partial \nabla_\perp^2 \phi}{\partial t} = \frac{2B}{c m_i R n}\frac{\partial p_e}{\partial y} + \frac{4\pi V_A^2}{c^2}\frac{\partial j_{||}}{\partial z}$$

Ohm's law →

$$\eta_{||} j_{||} = -\frac{\partial \phi}{\partial z}$$

→

$$\gamma^2 = \gamma_I^2 - \gamma \frac{4\pi V_A^2 k_{||}^2}{\eta_{||} c^2 k_y^2}, \qquad \gamma_I = c_s\sqrt{\frac{2}{R L_p}}$$

$$\gamma \simeq \gamma_I \quad \rightarrow \quad \frac{k_{||}^2}{k_y^2} < \frac{\gamma_I \eta_{||} c^2}{4\pi V_A^2} \quad \text{or} \quad \eta_{||} > \frac{4\pi V_A^2 k_{||}^2}{\gamma_I c^2 k_y^2}$$

Two cases:

- → $k_{||} = 0$ Ideal interchange mode
- → $k_{||} \neq 0$ Resistive interchange mode (requires $\eta_{||} \neq 0$)

Parameters of the resistive interchange mode

$$k_{\|} = \frac{\mathbf{k}\cdot\mathbf{B}}{B} = \frac{(k_v B_v + k_\varphi B_\varphi)}{B}$$

Define: $k_v = 2\pi l/L_v \;,\quad k_\varphi = -n/R\ (= -2\pi n/(2\pi R))$:

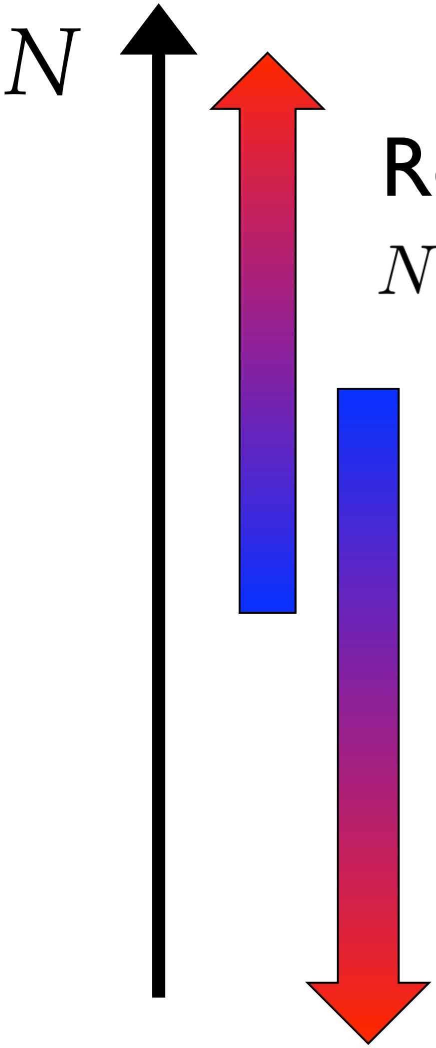
$$k_{\|} = \frac{l}{RN} - \frac{n}{R} \quad \text{and} \quad \frac{k_{\|}}{k_v} = \frac{L_v}{2\pi R}\left(\frac{1}{N} - \frac{n}{l}\right)$$

Since the RI needs $k_{\|}^2/k_v^2 < \gamma_I \eta_{\|} c^2/(4\pi V_A^2)$

→ The most unstable mode is for $N \gg 1$ is $n = 0,\ l = 1$

In TORPEX the RI mode has $k_{\|} = 1/(RN)\ ,\ k_v = 2\pi/L_v$
and requires $N^2 > V_A^2 L_v^2/(\gamma_I \eta_{\|} c^2 \pi R^2)$

Why does TORPEX transition from ideal to resistive interchange for large N?



Resistive interchange requires high N:

$$N^2 > V_A^2 L_v^2/(\pi \gamma_I \eta_\| c^2 R^2).$$

Ideal interchange requires low N:

$$\lambda_v = \frac{L_v}{N} \quad \text{thus} \quad k_v = \frac{2\pi N}{L_v}$$

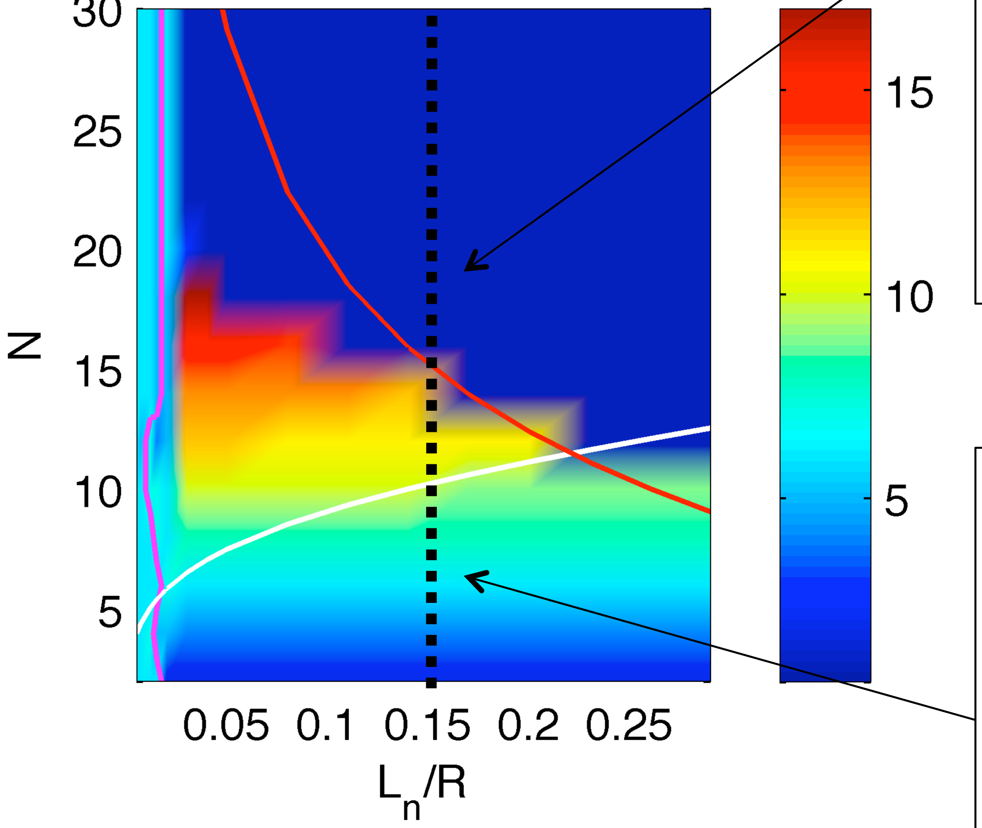
stable: $k_v \rho_s > 0.3 R \gamma_I / c_s \sim 0.2\sqrt{R/L_p}$

Transport less effective at high k

Threshold: N~10 TORPEX

Linear stability analysis: TORPEX

Vertical mode number l of fastest mode



Resistive Interchange :

$$l = 1$$

$$k_\perp = 2\pi/L_v$$

$$k_\parallel = 1/(RN)$$

Ideal Interchange :

$$l = N$$

$$k_\perp = 2\pi N/L_v$$

$$k_\parallel = 0$$

Ricci & Rogers, PRL 2010

Resistive Driftwaves

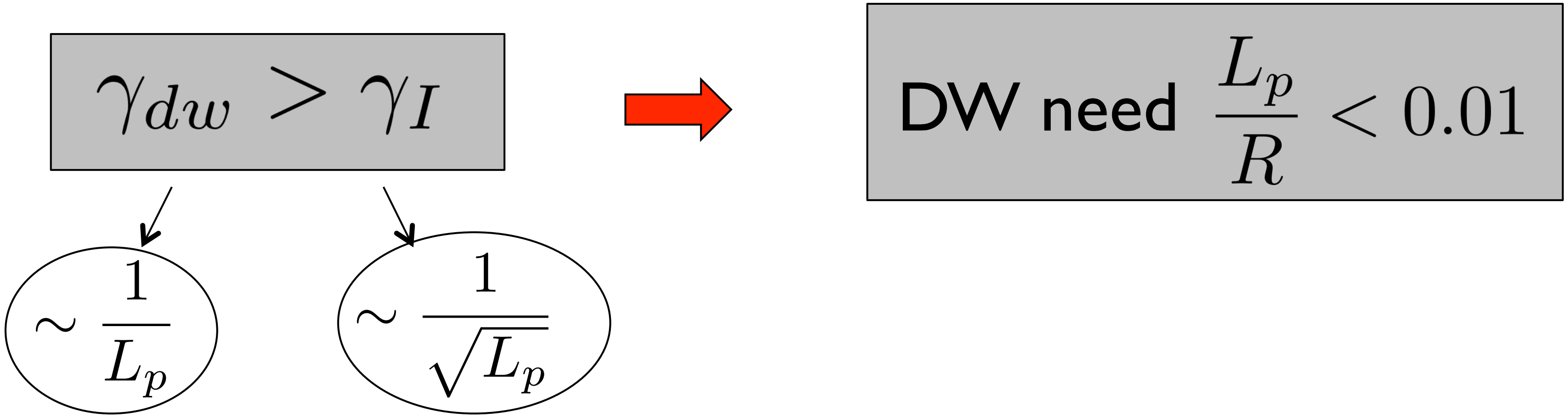
Neglecting the curvature terms, soundwaves, and m_e/m_i :

$$\nu_e k_y^2 \rho_s^2 \gamma^2 + k_{||}^2 c_s^2 (1 + 2.94 k_y^2 \rho_s^2)\gamma + i k_{||}^2 c_s^2 \omega_* = 0 \qquad (\nu_e = e^2 n \eta_{||}/m_i)$$

Fastest mode:

$$\gamma_{dw} \simeq 0.1 c_s/L_p \quad \text{for} \quad k_\perp \rho_s \simeq 0.5, \quad k_{||} \simeq 0.2\sqrt{\nu_e/(c_s L_p)}$$

Define DW regime as:

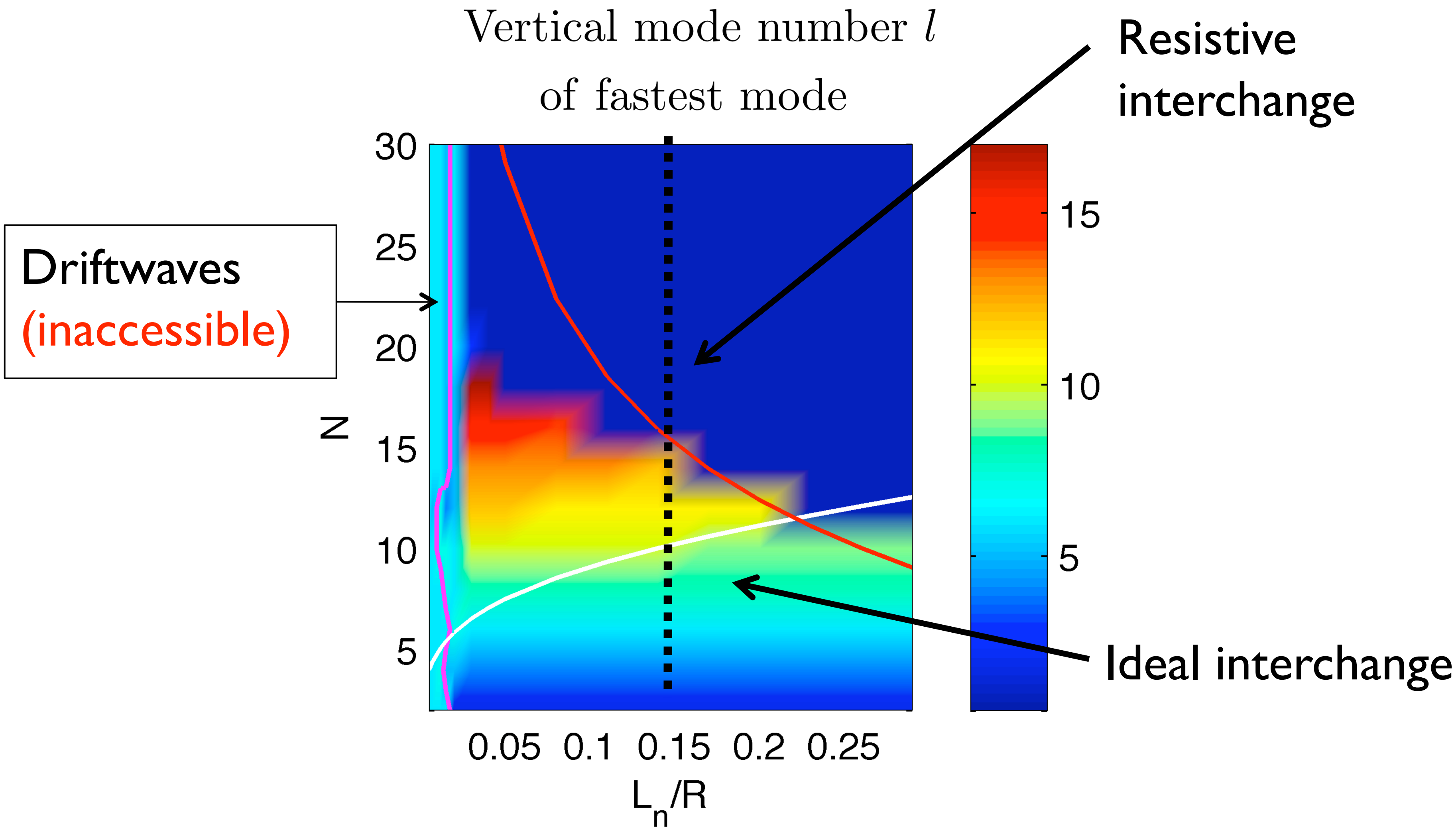


$$\boxed{\gamma_{dw} > \gamma_I}$$

$$\sim \frac{1}{L_p} \qquad \sim \frac{1}{\sqrt{L_p}}$$

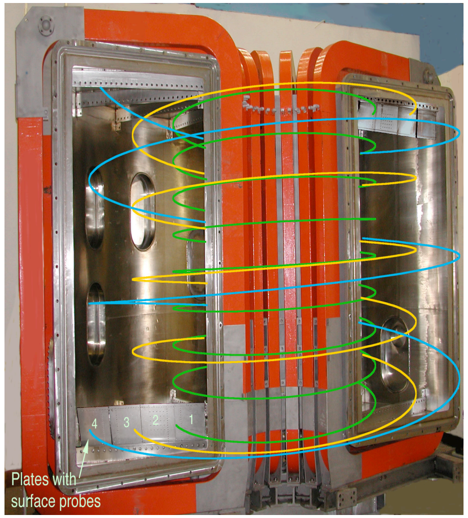
DW need $\dfrac{L_p}{R} < 0.01$

Linear stability analysis of TORPEX

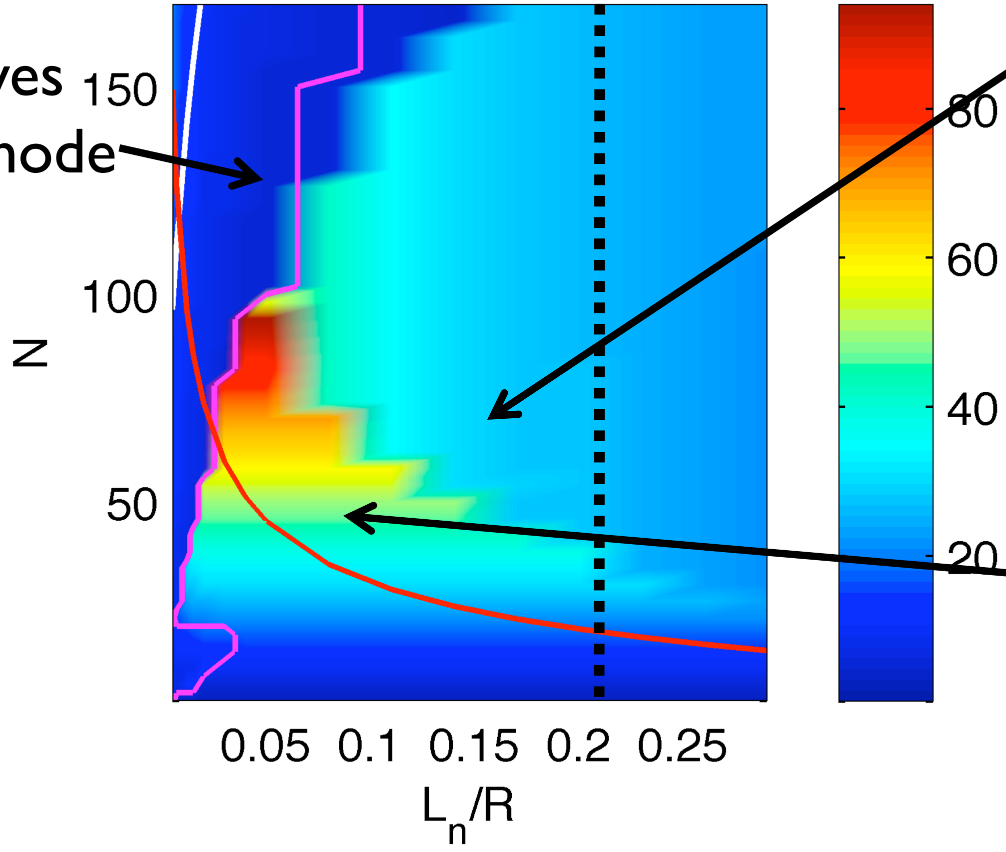


Interchange transport prevents access to DW regime in TORPEX for realistic parameters (as in tokamak SOL)

Analysis of other devices: Helimak



Vertical mode number l
of fastest mode



Driftwaves
and RI mode

Non-MHD drift-interchange

$k_\perp \rho_s \sim 1 \quad (l \sim 30)$

$\eta_\parallel = m_e = 0$

$k_\parallel \neq 0$

Adiabatic electrons

Ideal interchange

Li *et al.*, in preparation

Non-MHD drift-interchange mode

Braginskii equations with $\eta_\parallel = m_e = T_i = V_{\parallel i} = 0$:

$$\frac{\partial \nabla_\perp^2 \phi}{\partial t} = \frac{2B}{c m_i R n}\frac{\partial p_e}{\partial y} + \frac{4\pi V_A^2}{c^2}\frac{\partial j_\parallel}{\partial z} \qquad (\text{where } p_e = nT_e)$$

$$\frac{\partial n}{\partial t} = \frac{c}{B}[\phi, n] + \frac{2c}{eRB}\left(\frac{\partial p_e}{\partial y} - ne\frac{\partial \phi}{\partial y}\right) + \frac{1}{e}\frac{\partial j_\parallel}{\partial z}$$

$$\frac{\partial T_e}{\partial t} = \frac{c}{B}[\phi, T_e] + \frac{4cT_e}{3eRB}\left(\frac{7}{2}\frac{\partial T_e}{\partial y} + \frac{T_e}{n}\frac{\partial n}{\partial y} - e\frac{\partial \phi}{\partial y}\right) + \frac{2T_e}{3ne}\frac{\partial j_\parallel}{\partial z}$$

$$-\frac{\partial \phi}{\partial z} + \frac{1}{ne}\frac{\partial p_e}{\partial z} = \eta_\parallel j_\parallel \simeq 0 \;\rightarrow\; \tilde{p}_e \simeq n_0 e\tilde{\phi} \quad (\text{adiabatic electrons})$$

These give $(\omega_{*n} = k_\perp \rho_s c_s / L_n \;, \omega_{*p} = k_\perp \rho_s c_s / L_p \;,\; \omega_d = k_\perp \rho_s c_s / R)$:

$$\left(1 + \frac{5}{3}k_\perp^2 \rho_s^2\right)\gamma^2 - i\gamma\left(\omega_{*p} + \frac{10}{3}\omega_d k_\perp^2 \rho_s^2\right) - \frac{10}{3}\omega_d(\omega_{*n} - 2\omega_d) = 0$$

$$\boxed{\gamma \sim \sqrt{\omega_d \omega_{*n}} \sim c_s/\sqrt{RL_n} \quad \text{for} \quad k_\perp \rho_s \sim 1}$$

What are we really learning from TORPEX simulations?

- How to characterize turbulence in a relatively simple system
- Need of global simulations

  Flux tube simulations are not appropriate

  to describe a certain set of instabilities

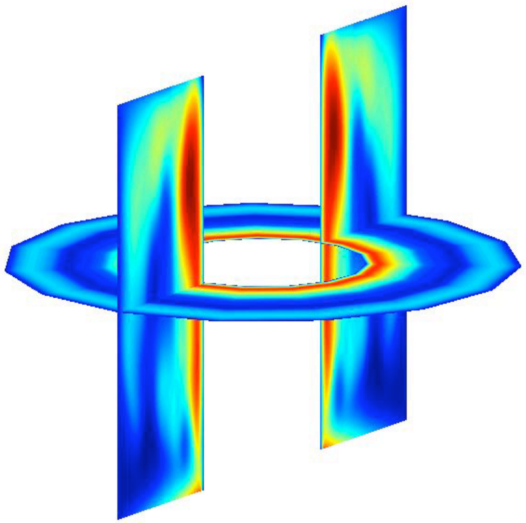
- Need of non-local simulations

  E.g., required by the saturation mechanism

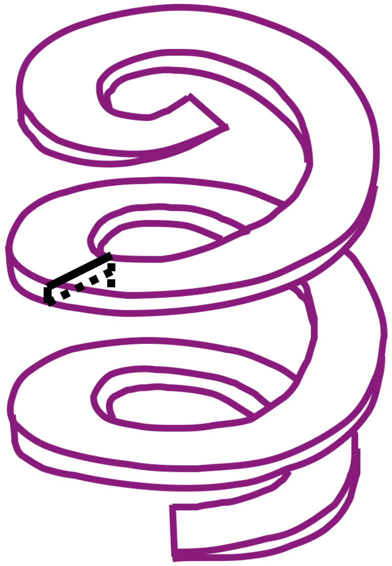
- How to perform comparison between experiments and simulations

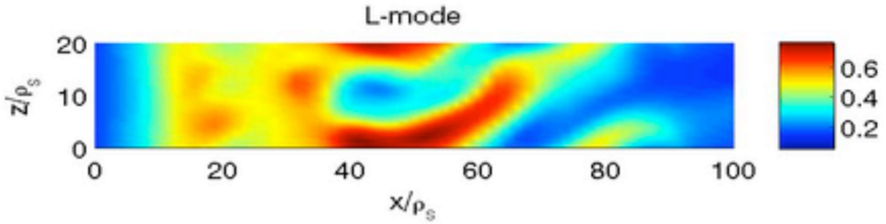
Need of global simulations

To describe instabilities like the resistive interchange mode

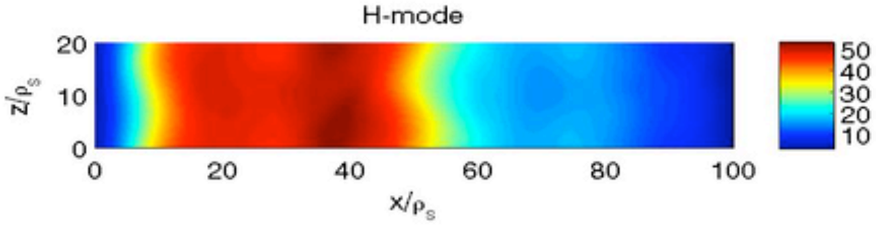


3D Flux tube simulations:





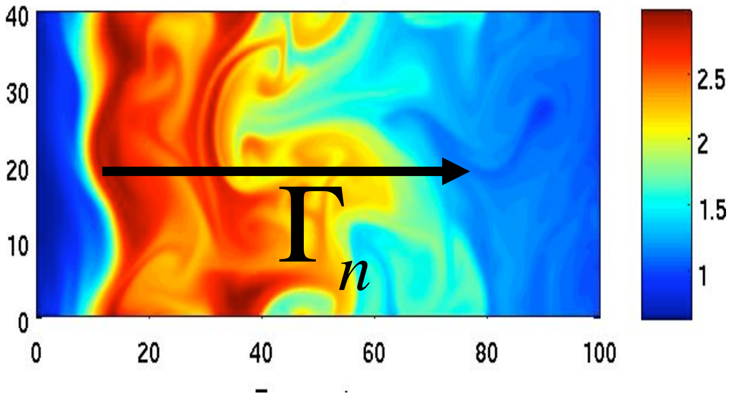
B_v decreased
(*N* increased)



Ricci & Rogers, PoP 2009

Need of non-local simulations

Radial transport:
analytical estimate
no shear flow, $\partial_r^2 \phi \sim 0$



$$\Gamma_n = \left\langle \delta n \frac{\partial \delta\phi}{\partial z} \right\rangle_{z,t}$$

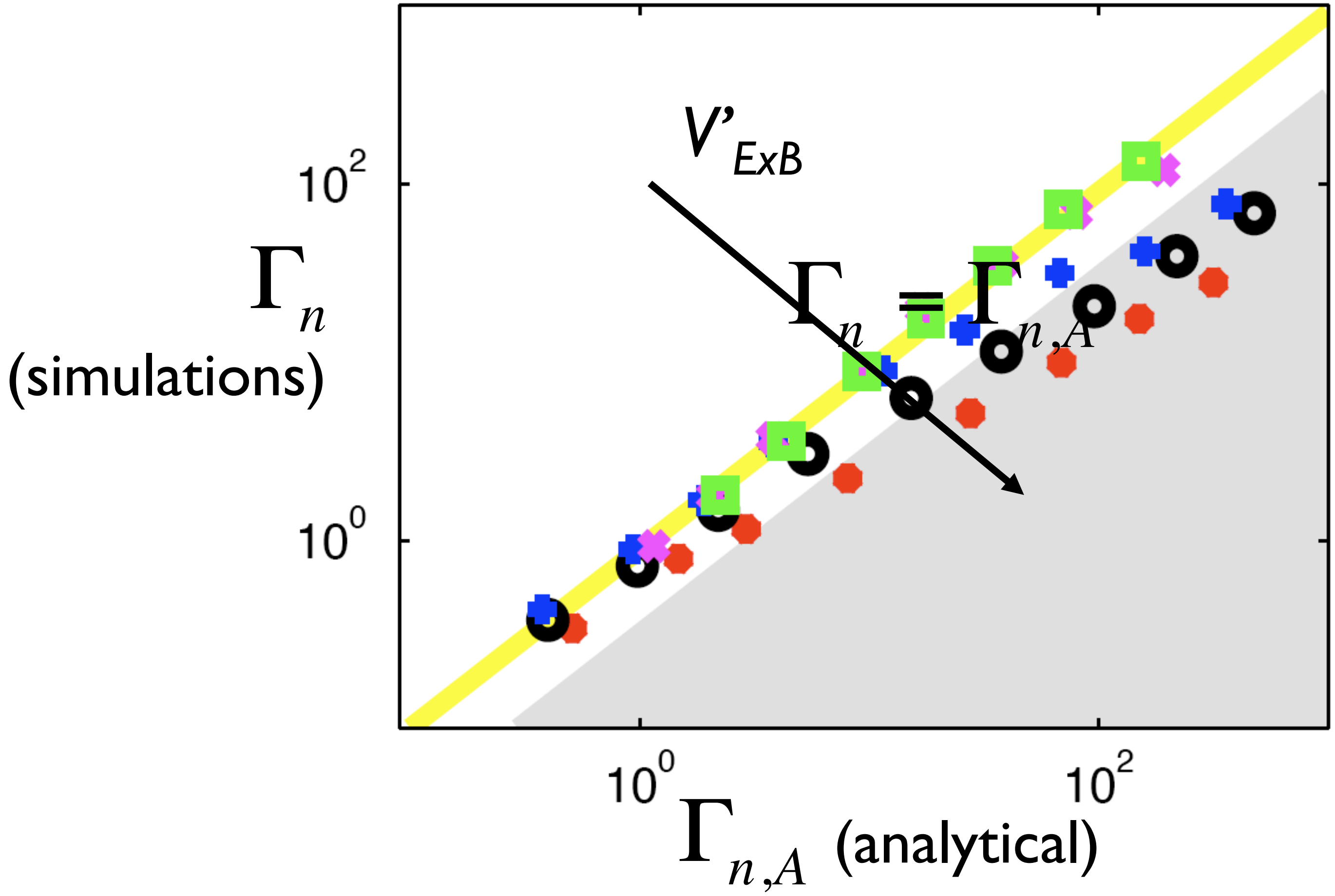
$$\frac{\partial \delta n}{\partial r} \sim \frac{\partial n_0}{\partial r} \longrightarrow \delta n \sim \frac{n_0}{k_r L_n}$$

$$k_r \sim \sqrt{k_y / L_n}$$

$$\frac{\partial n}{\partial t} + [\phi, n] \approx 0 \longrightarrow \frac{\partial \delta\phi}{\partial z} \sim \gamma \delta n \frac{L_n}{n_0}$$

$$\Rightarrow \boxed{\Gamma_{n,A} = \Gamma_{n,A}(n_0, T_0, L_p, B_z)}$$

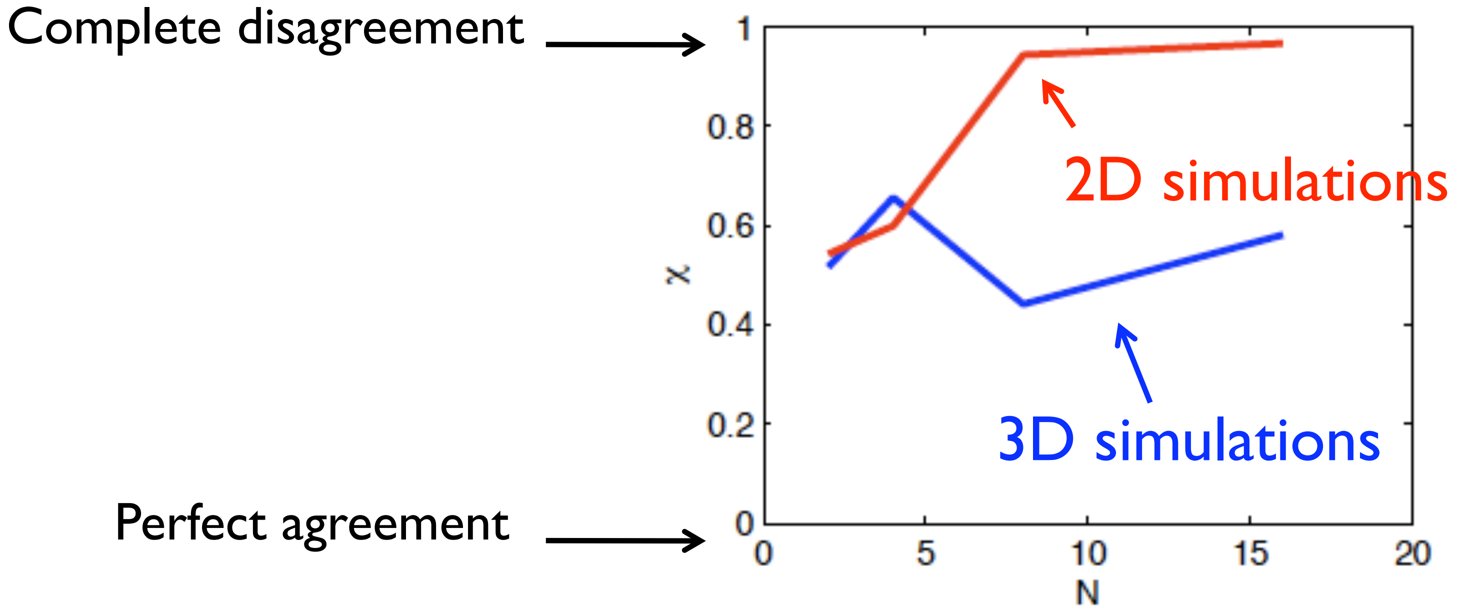
Comparison of analytical and simulation results



Ricci & Rogers, PRL 2008, PoP 2009

How to make experiment/simulation comparison

- Comparison performed using observables across different hierarchy levels.
- A composite metric that takes into account the agreement of each observable is introduced.
- The “quality” of the comparison has to be defined.



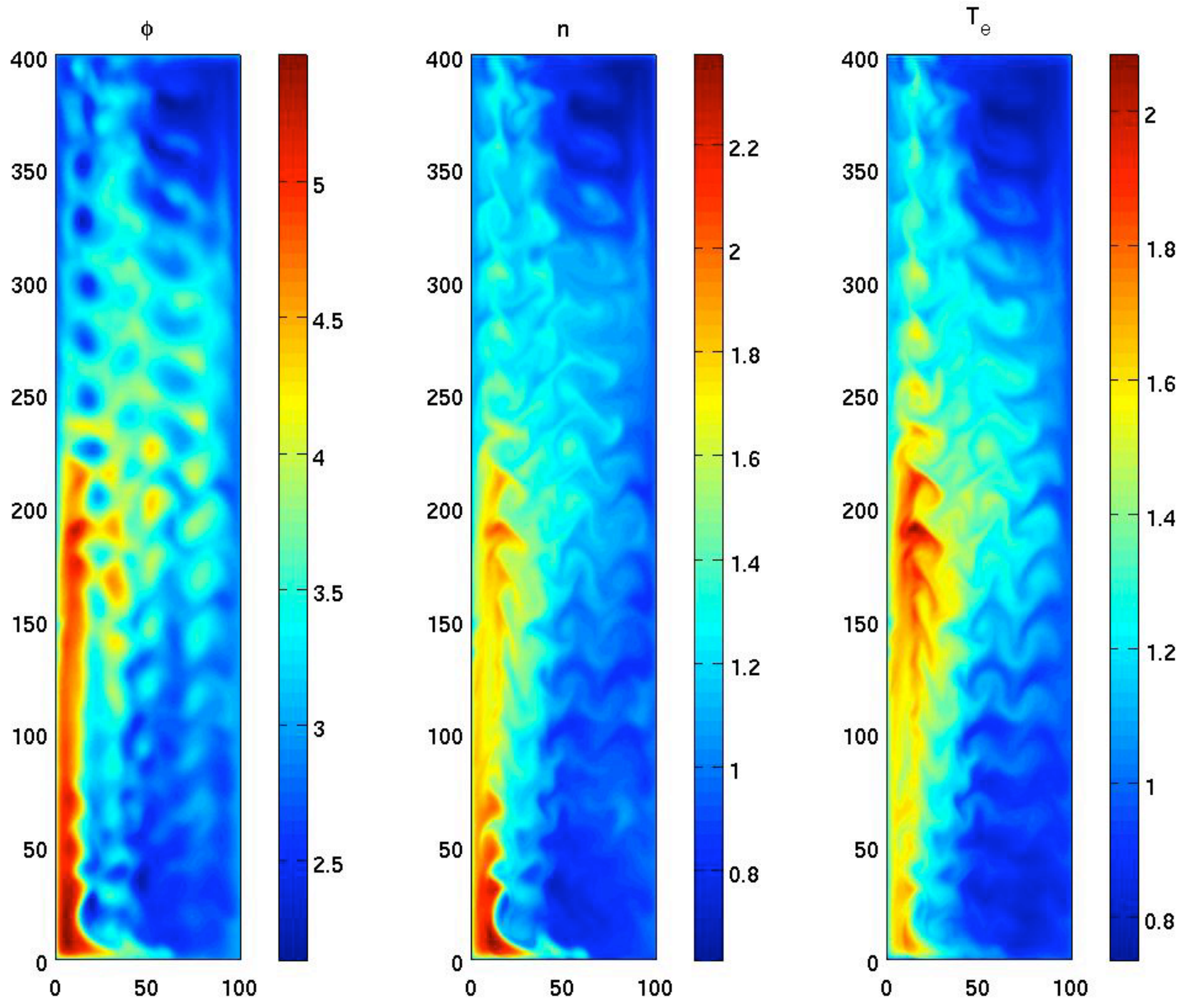
Ricci *et al.*, PoP 2009, and to be submitted

Concluding remarks

What are we learning from TORPEX modeling?

- By using global simulations and evolving both plasma equilibrium and fluctuations, it is possible to interpret the experimental results.
- The turbulence is subject to a number of driving mechanisms, as a competition between ideal interchange, drift waves, and resistive interchange.
- The properties of plasma turbulence reflect the different linear drives.
- Similar analysis can be carried out in other basic plasma devices.
- TORPEX is providing an ideal test-bed to study techniques and assumptions to be used for edge plasma turbulence simulations.

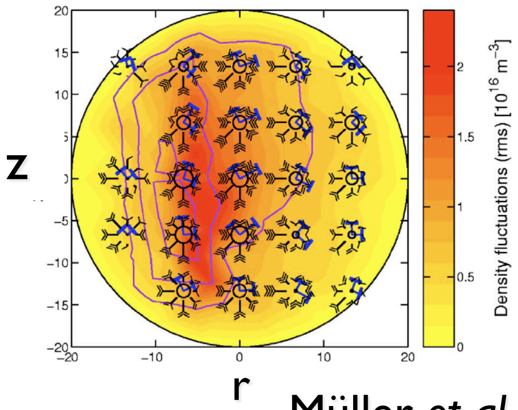
What's next?



SOL simulations

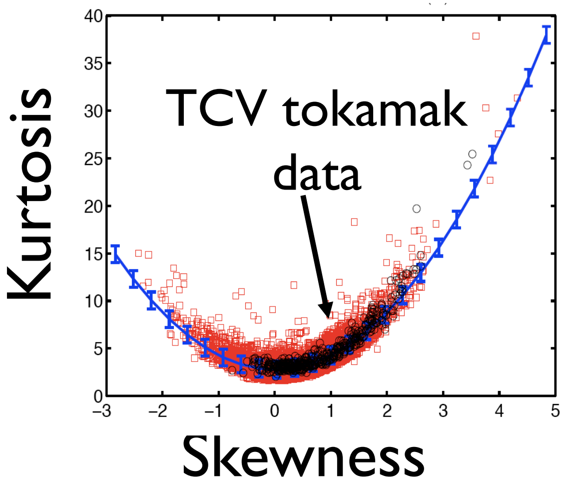
Some of the recent experimental results

Identification of transport mechanism, quantification of turbulent structures



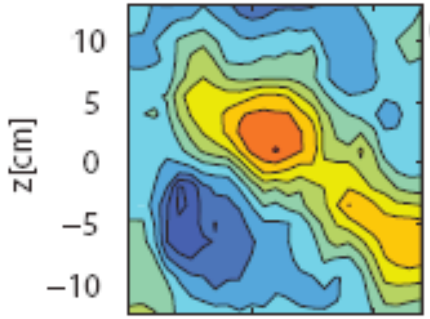
Müller *et al.*, PoP 2007
Podestà *et al.*, PRL 2008

Universal properties of turbulence



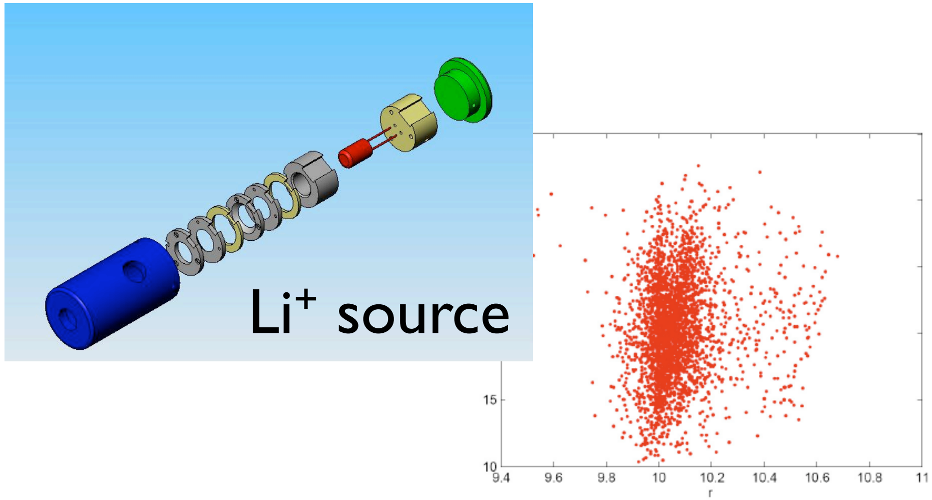
Labit *et al.*, PRL 2007

Blob generation mechanism and dynamics



Furno *et al.*, PRL 2008
Theiler *et al.*, PRL 2009
Diallo *et al.*, PRL 2008

Fast ion dynamics



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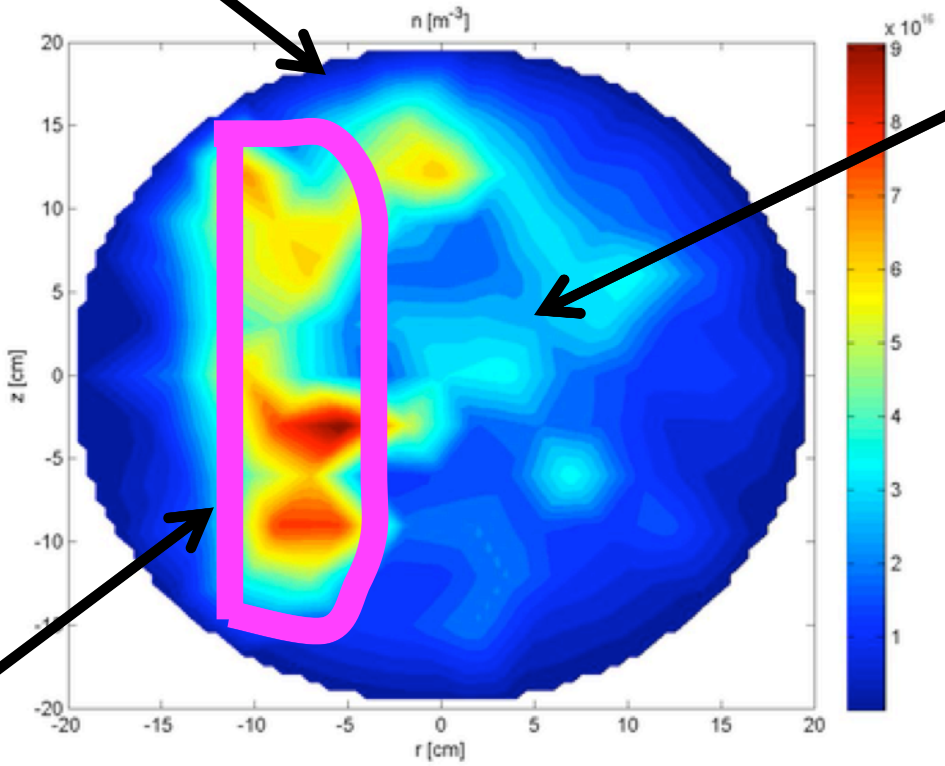
- The turbulence is subject to a number of driving mechanisms, as a competition between ideal interchange, drift waves, and resistive interchange.
- The properties of plasma turbulence reflect the different linear drives.
- Similar analysis can be carried out in other basic plasma devices.
- TORPEX is providing an ideal test-bed for a close comparison between experiments and simulations, in plasma edge conditions.

What needs to be done…



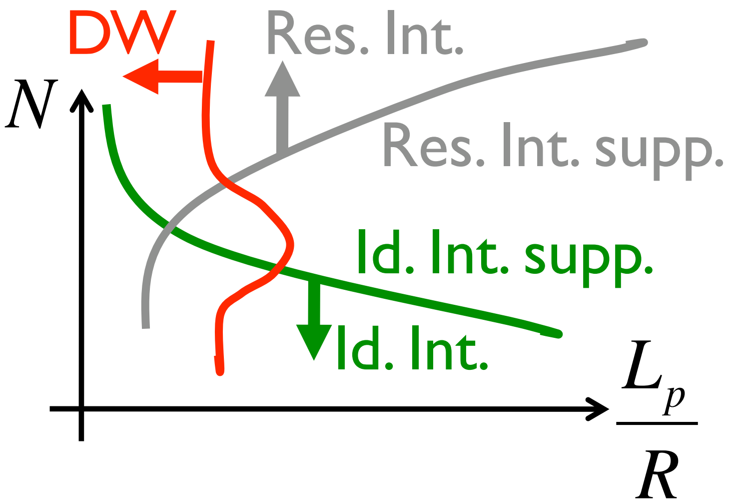
Better boundary conditions

Physics of neutrals

Better source modeling

Turbulence phase space

$$m = l - nN$$

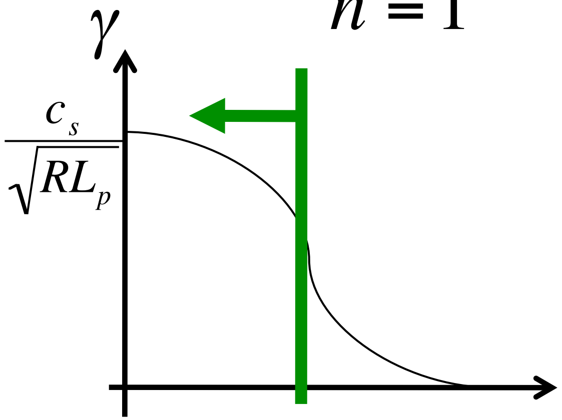


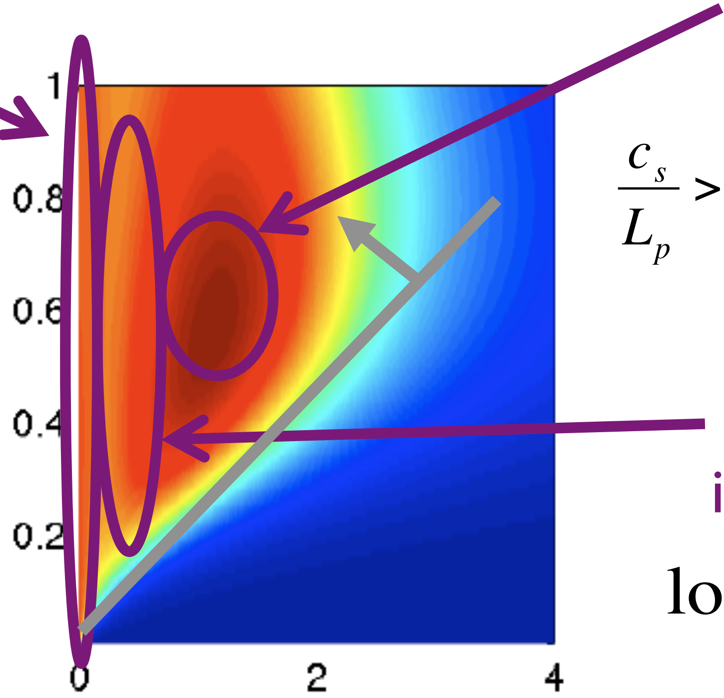
Ideal interchange

$k_{\|} = 0$ ➡ $m = 0$

$l = nN$

$n = 1$





Drift waves

$\gamma \sim \frac{c_s}{L_p}$

$\frac{c_s}{L_p} > \frac{c_s}{\sqrt{RL_p}}$ ➡ $L_p < L_{p,crit}$

Resistive interchange

low m ➡ $n = 0$

$l = 1$

Turbulence phase space

$$k_\parallel = \mathbf{k}\cdot\mathbf{b} = k_v \frac{B_v}{B} + k_\varphi \frac{B_\varphi}{B} \Longrightarrow m = l - nN$$

Parallel mode number

Vertical mode number

Toroidal mode number $= 0, 1, 2, 3, \ldots$

Non-MHD drift-interchange mode

Braginskii equations with $\eta_\parallel = m_e = T_i = V_{\parallel i} = 0$:

$$\frac{\partial \nabla_\perp^2 \phi}{\partial t} = \frac{2B}{cm_i R n}\frac{\partial p_e}{\partial y} + \frac{4\pi V_A^2}{c^2}\frac{\partial j_\parallel}{\partial z} \qquad (\text{where } p_e = nT_e)$$

$$\frac{\partial n}{\partial t} = \frac{c}{B}[\phi, n] + \frac{2c}{eRB}\left(\frac{\partial p_e}{\partial y} - ne\frac{\partial \phi}{\partial y}\right) + \frac{1}{e}\frac{\partial j_\parallel}{\partial z}$$

$$\frac{\partial T_e}{\partial t} = \frac{c}{B}[\phi, T_e] + \frac{4cT_e}{3eRB}\left(\frac{7}{2}\frac{\partial T_e}{\partial y} + \frac{T_e}{n}\frac{\partial n}{\partial y} - e\frac{\partial \phi}{\partial y}\right) + \frac{2T_e}{3ne}\frac{\partial j_\parallel}{\partial z}$$

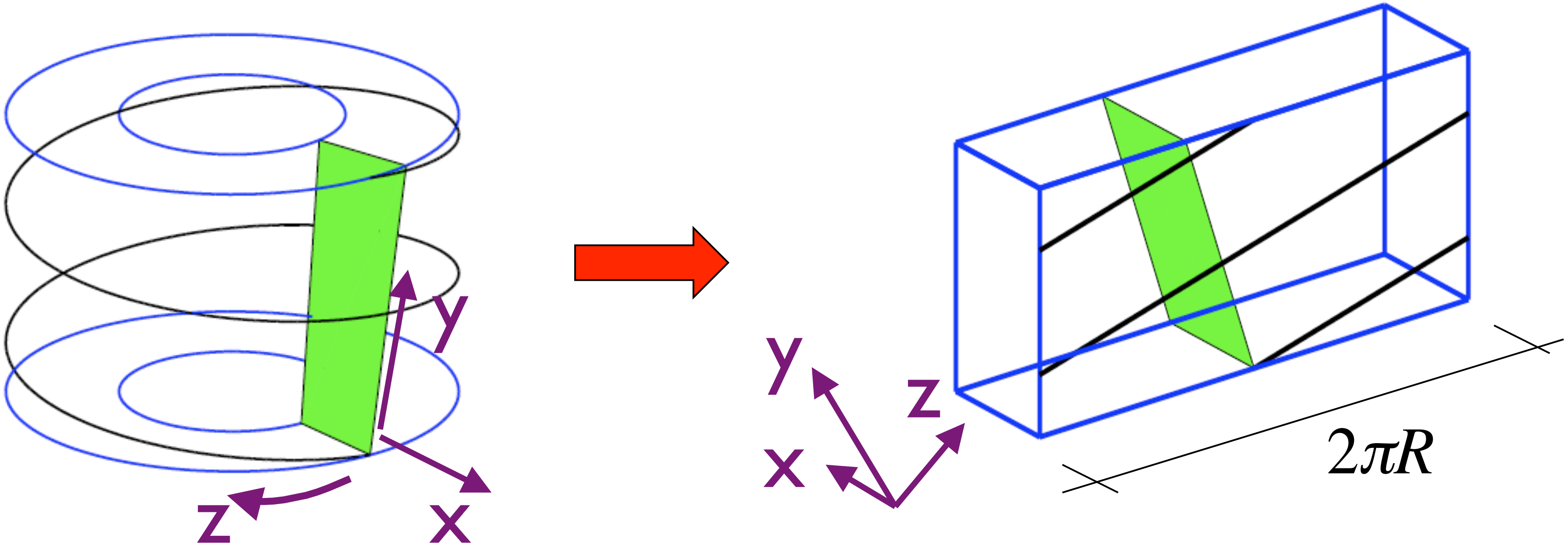
$$-\frac{\partial \phi}{\partial z} + \frac{1}{ne}\frac{\partial p_e}{\partial z} = \eta_\parallel j_\parallel \simeq 0 \;\rightarrow\; \tilde{p}_e \simeq n_0 e\tilde{\phi} \quad (\text{adiabatic electrons})$$

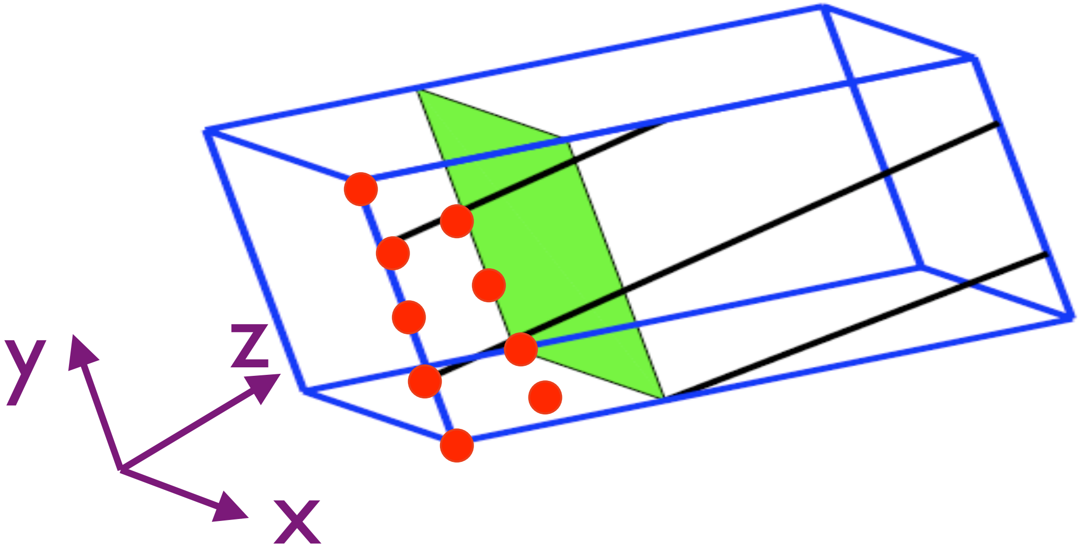
These give $(\omega_{*n} = k_\perp \rho_s c_s / L_n \;, \omega_{*p} = k_\perp \rho_s c_s / L_p \;,\; \omega_d = k_\perp \rho_s c_s / R)$:

$$\left(1 + \frac{5}{3}k_\perp^2 \rho_s^2\right)\gamma^2 - i\gamma\left(\omega_{*p} + \frac{10}{3}\omega_d k_\perp^2 \rho_s^2\right) - \frac{10}{3}\omega_d(\omega_{*n} - 2\omega_d) = 0$$

$$\boxed{\gamma \sim \sqrt{\omega_d \omega_{*n}} \sim c_s/\sqrt{RL_n} \quad \text{for} \quad k_\perp \rho_s \sim 1}$$

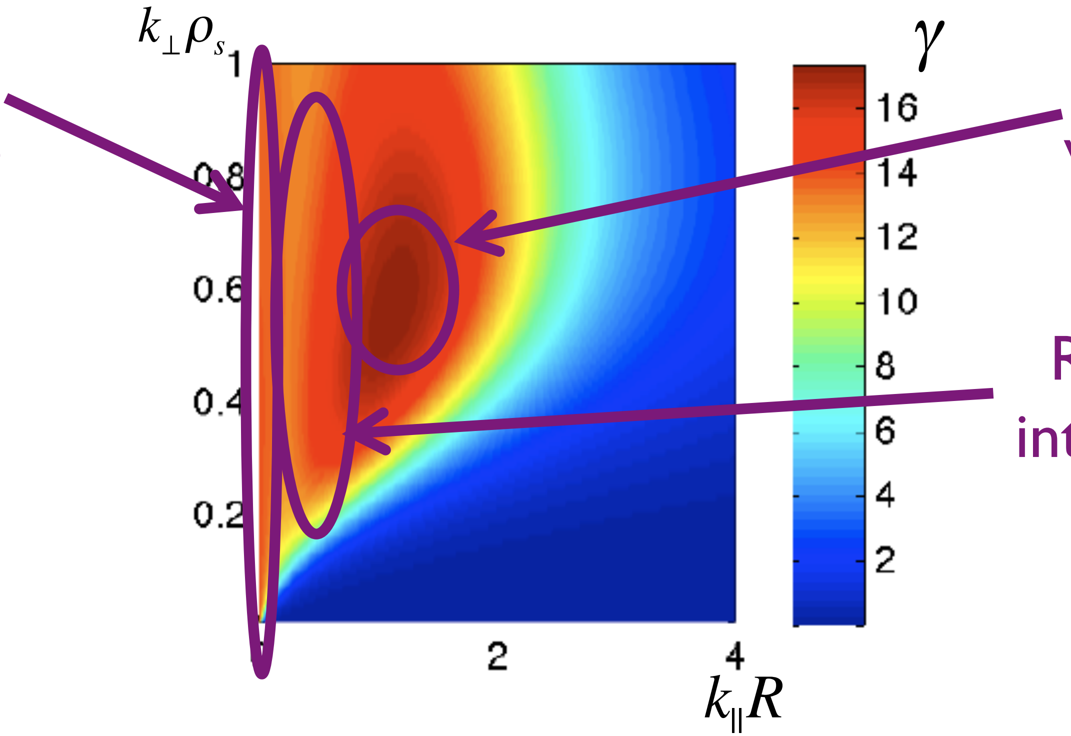
Field-aligned computational grid





Non-orthogonal
field-aligned grid
in the whole
domain

Turbulence phase space



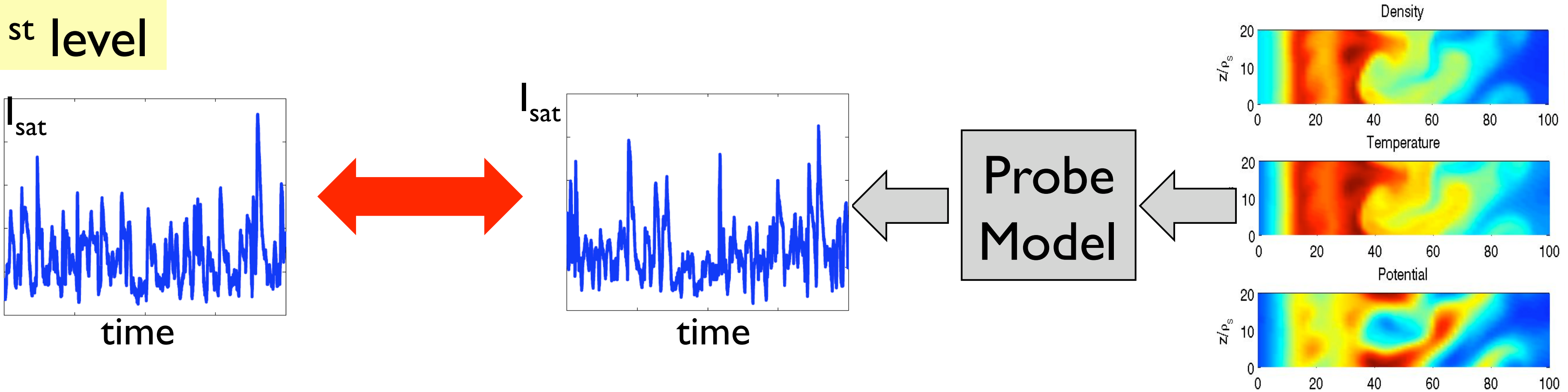
Ideal interchange

Drift waves

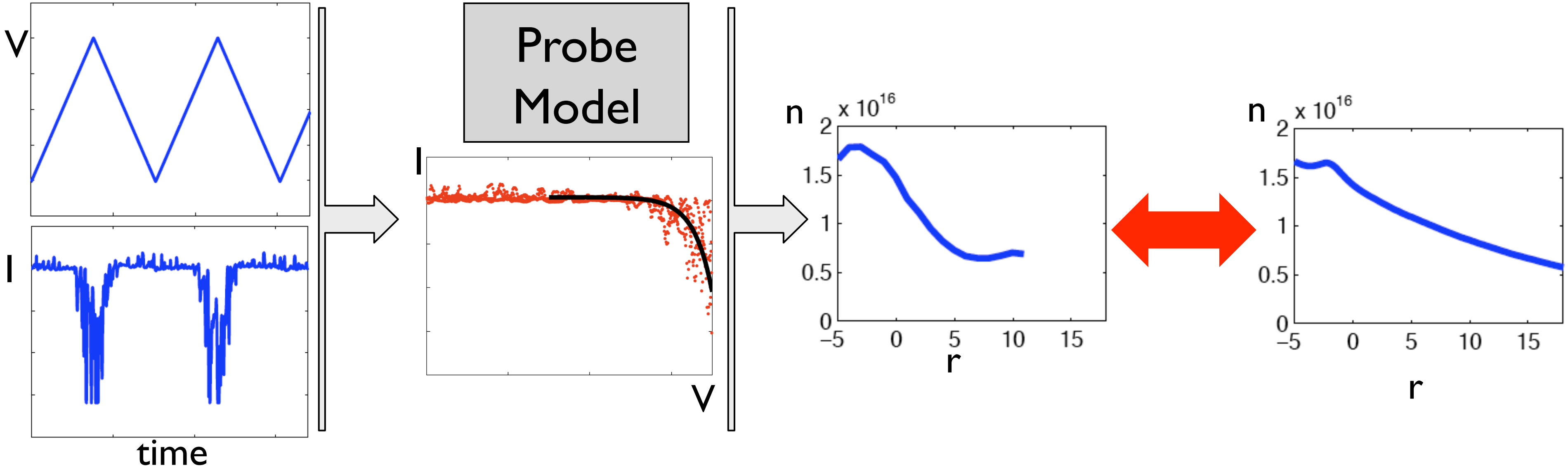
Resistive interchange

Outlook: methodology for comparison

1st level



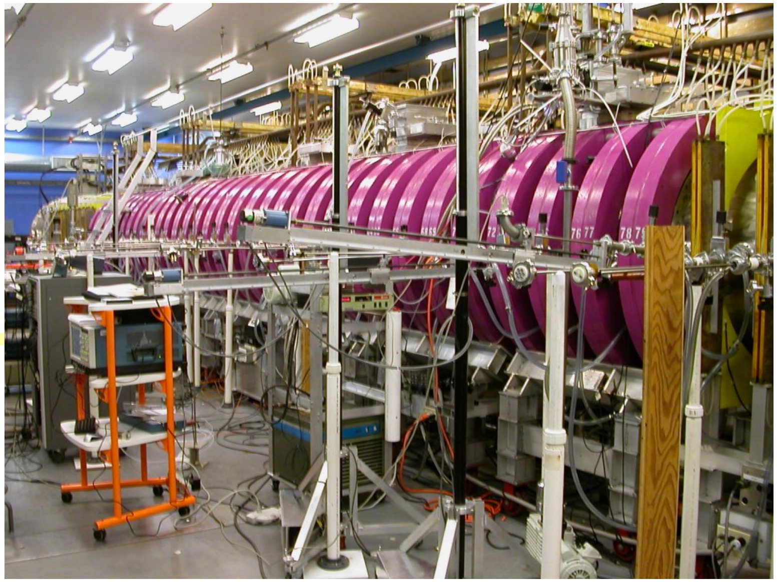
2nd level



3rd, … levels

Transport, etc…

Analysis of other devices: LAPD



$$\overbrace{\frac{\partial n}{\partial t}+[\phi,n]}^{\text{Convection}} = \overbrace{D_n\nabla^2 n}^{\text{Diffusion}} + \overbrace{\cancel{\frac{2}{R}\left(n\frac{\partial T_e}{\partial y}+T_e\frac{\partial n}{\partial y}-n\frac{\partial \phi}{\partial y}\right)}}^{\text{Magnetic curvature}} - \overbrace{\nabla_{\parallel}(nV_{\parallel e})}^{\text{Parallel dynamics}} + \overbrace{S}^{\text{Source}}$$

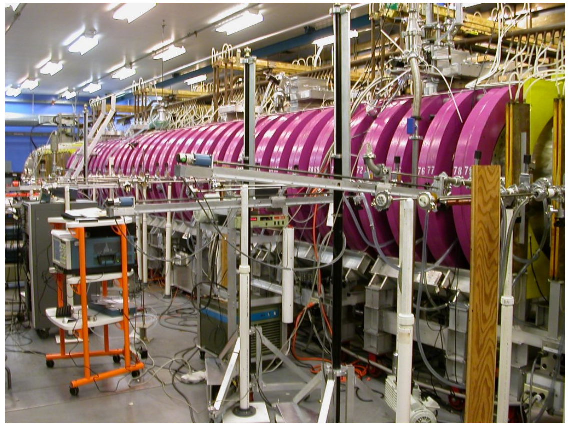
Plasma gradients →

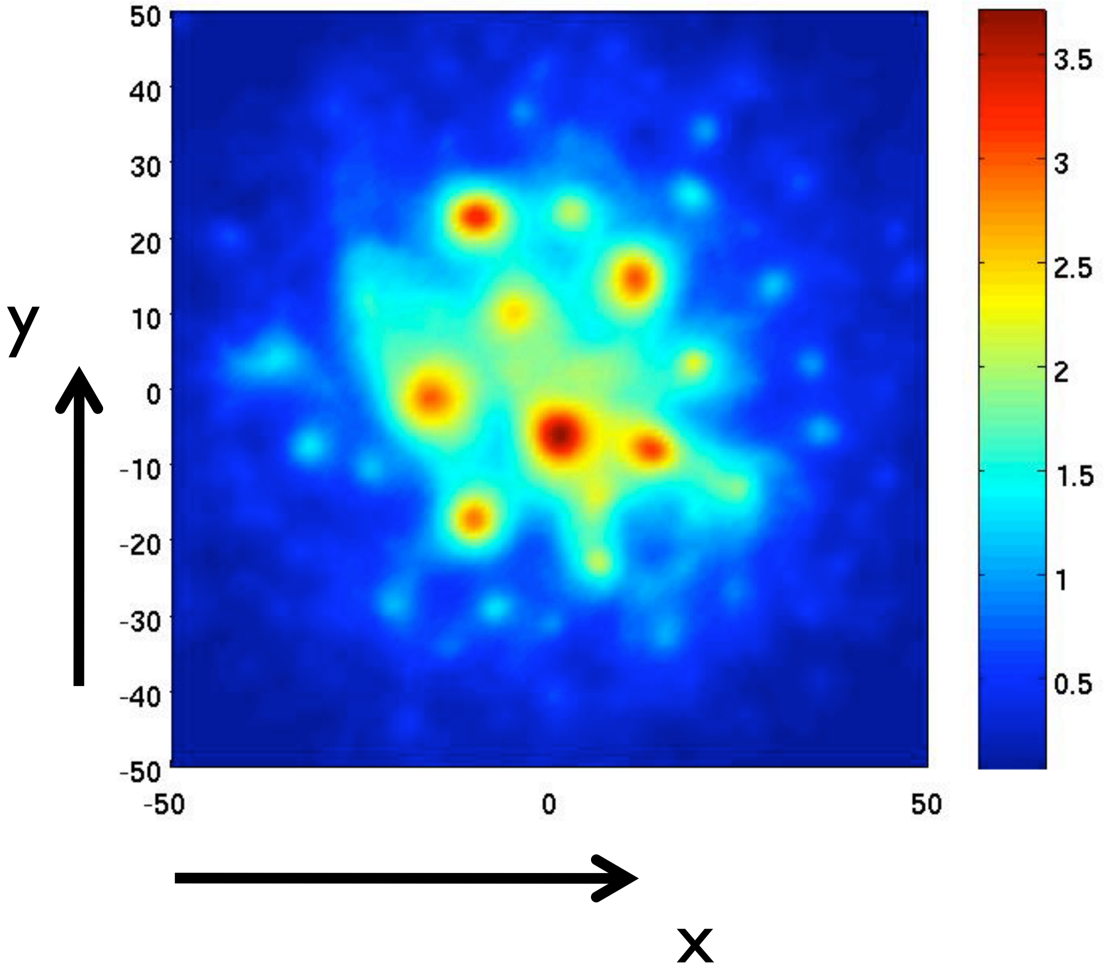
Drift waves

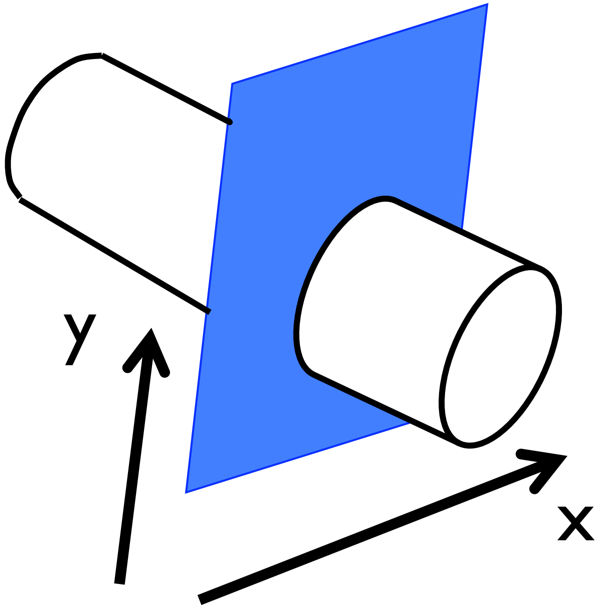
Kelvin-Helmholtz

Sheath mode

Analysis of other devices: LAPD







Rogers & Ricci, PRL, in press

Outline

- *The TORPEX experiment (why? what can it do?)*
- *The simulation approach*
  - *The model used? 2D and 3D*
  - *The turbulent regimes?*

    Low (L) and High (H) confinement regimes
- *How do experimental and simulation result compare?*

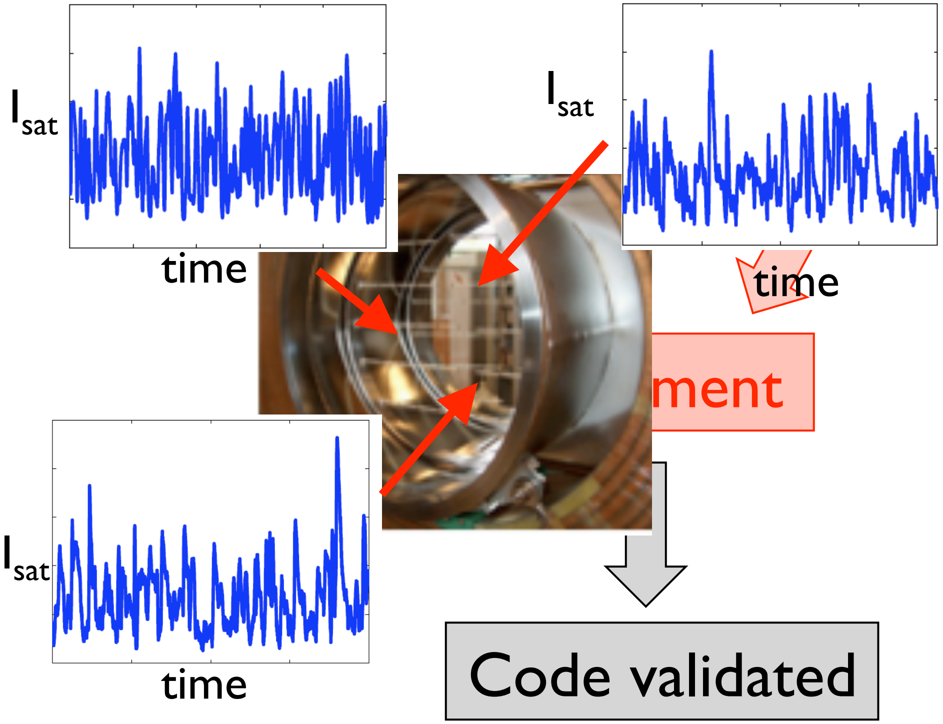
Code Validation

Definition of the observables for the comparison

Experimental data

Simulation results

tric



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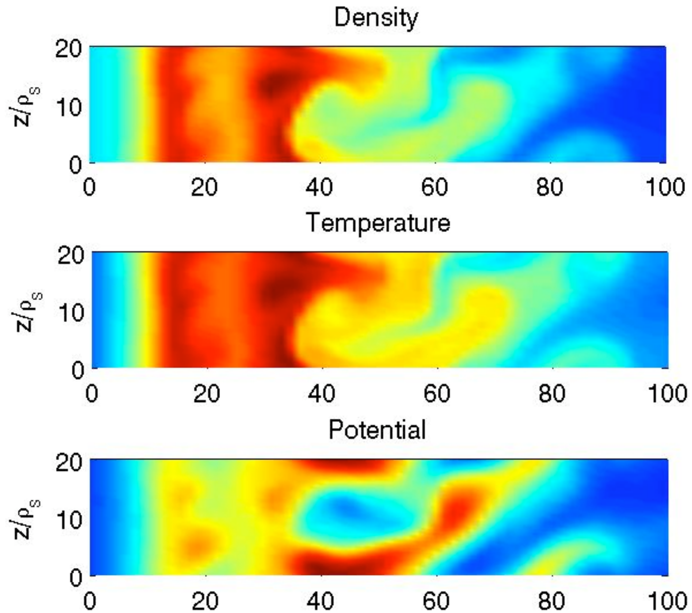

Code validated

Code improvements