Profiles and fluctuations in edge and SOL turbulence

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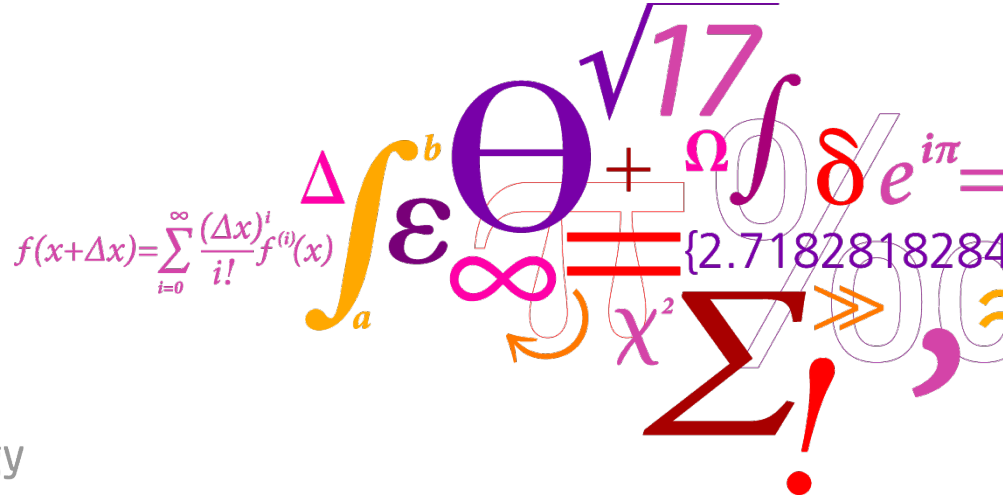


Risø DTU
National Laboratory for Sustainable Energy

Contents

Less a collection of final results than a collection of insight into new questions we need to address

- **Problems**
- **Edge parameters**
- **Flux tube simulations**
- **SOL simulations (profile feedback)**
- **FLR effects**
- **Current filaments and PTM**
- **Conclusion(?)**

After many years of research we still have no conclusive theory/simulation answer to:

- LH transition, mechanism, thresholds?
- ELM dynamics
- Density limits
- SOL width

What is missing?
What is it we are doing wrong?

Edge parameters

$$\widehat{\beta} = \beta \left(\frac{L_\parallel}{L_\perp} \right)^2 \qquad \widehat{\mu} = \frac{m_e}{m_i} \left(\frac{L_\parallel}{L_\perp} \right)^2 \qquad C = 0.51 \nu_* \left(\frac{m_e}{m_i} \right)^{1/2} \left(\frac{L_\parallel}{L_\perp} \right)$$

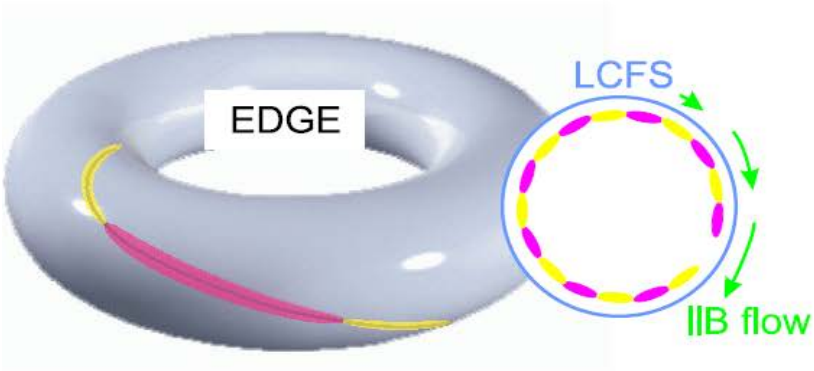
Have been discussed in detail last PET conferences

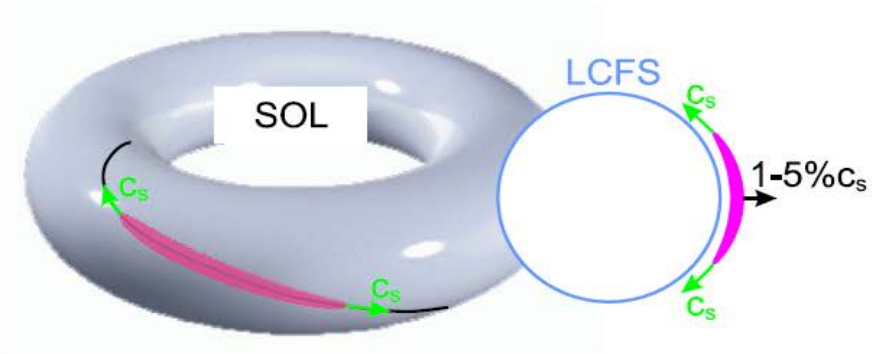
Important point: Variation in Edge and SOL and across machines (Militello & Fundamenski, PPCF, 2011)

Variation of parameters by several orders of magnitude.

-> any global code has do deal with that range of parameter change

Edge and SOL





Edge turbulence is of drift-Alfvén type, SOL is interchange driven [Naulin et al., EPS 2003, Ribeiro and Scott, PoP, 2005].

Edge: Fluctuations. Curvature *not* main drive.

SOL: Blob parallel structure determined by:

thinning of structure and expansion into near vacuum

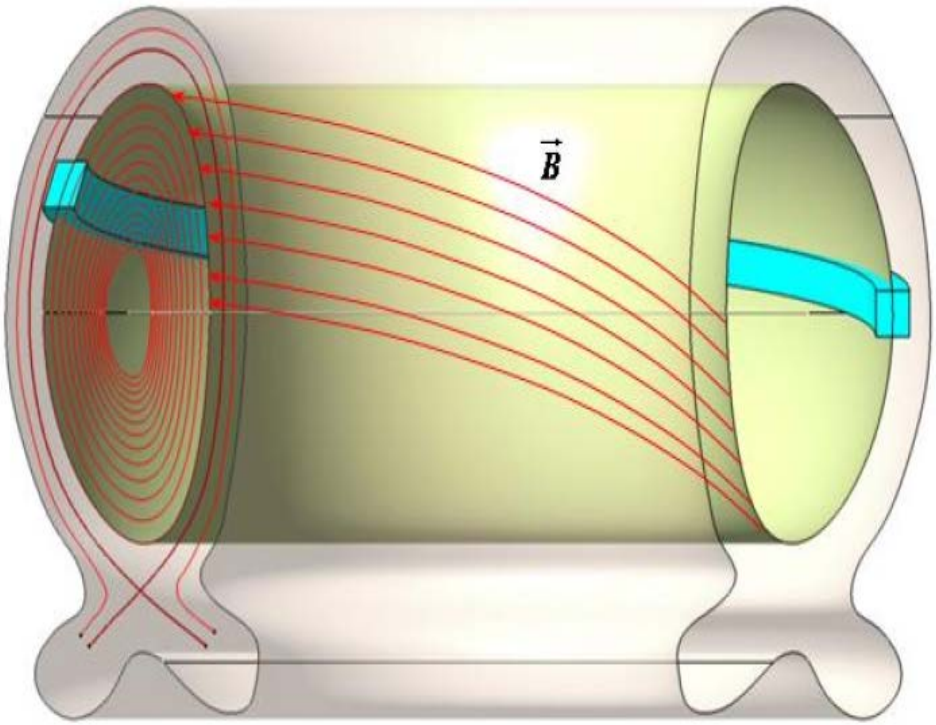
loss to divertor plates. (*Naulin, JNM 2007*)

Fuelling of SOL is poloidally localized (*Gunn, JNM 2007*)

Basic interaction with equilibrium (Scott, CPP 2006)

Geometry for edge turbulence

- Flux tube: x (radial) and y (toroidal) determine drift plane, parallel coordinate follows field line poloidally around the torus
- local magnetic shear
- looses some small n modes, good for microturbulence



Drift Alfvén System

$$\partial_t w + \{\phi, w\} = \mathcal{K}\,(n + T) + \nabla_\parallel J + \mu_w \nabla_\perp^2 w$$

$$\partial_t n + \{\phi, n + n_0\} = \mathcal{K}\,(n + T - \phi) + \nabla_\parallel\,(J - u) + \mu_n \nabla_\perp^2 n$$

$$\frac{3}{2}\partial_t T = \frac{3}{2}\{\phi, T\hat{} + T_0\} + \nabla_\parallel\,((1+\alpha)J - u) + \frac{1.6}{\mu\nu}\nabla_\parallel \cdot \nabla_\parallel T + \hat{\mathcal{K}}\left(n + \frac{7}{2}T - \phi\right)$$

$$\mu\partial_t J + \hat{\beta}\partial_t \Psi + \mu\,\{\phi, J\} = \nabla_\parallel\,(n + n_0 + (1+\alpha)\,(T + T_0) - \phi)\mu\nu J$$

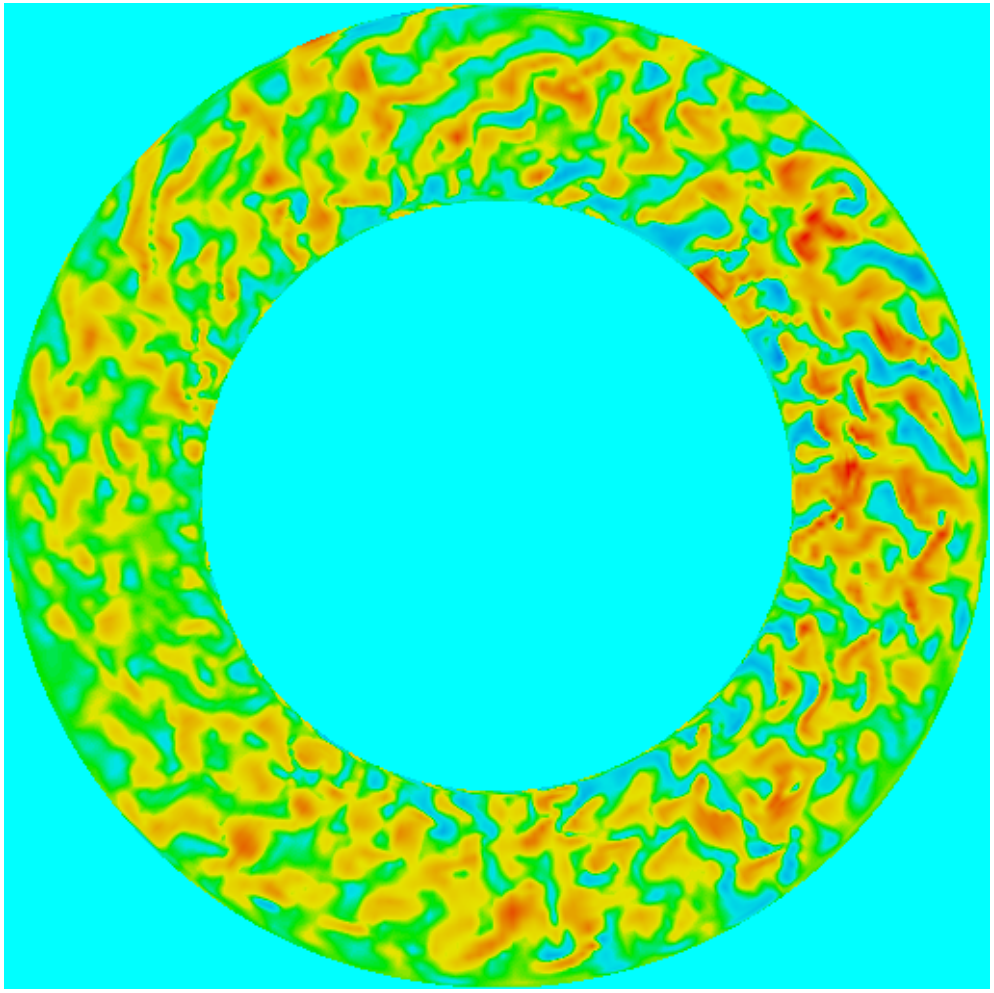
$$\partial_t u + \{\phi, u\} = -1/\mu \nabla_\parallel\,(T + T_0 + n + n_0)$$

$$\{\phi, \cdot\} = \vec{v}_{E\times B} \cdot \nabla \cdot\,, \quad J = -\nabla_\perp^2 \Psi\,, \quad w = \nabla_\perp^2 \phi\,.$$

$$\nabla_\parallel \cdot = \partial_s \cdot + \hat{\beta}\,\{\Psi, \cdot\}\,. \quad \mathcal{K} = \omega_B(\sin(z)\partial_x + \cos(z)\partial_y)$$

$$\hat{\beta} = \frac{4\pi p_e}{B^2}\left(\frac{qR}{L_\perp}\right)^2, \quad \mu = \frac{m}{M}\left(\frac{qR}{L_\perp}\right)^2, \quad \nu = 0.51\,\frac{L_\perp}{\tau_e c_s}$$

Typical result from drift turbulence



Representation of resistive equilibrium

What makes background quantities special?

$$0 = \mathcal{K}\,(n_0 + T_0) + \nabla_{\parallel} J_{PS}$$

$$0 = \mathcal{K}\,(n_0 + T_0) + \nabla_{\parallel}\,(J_{PS})$$

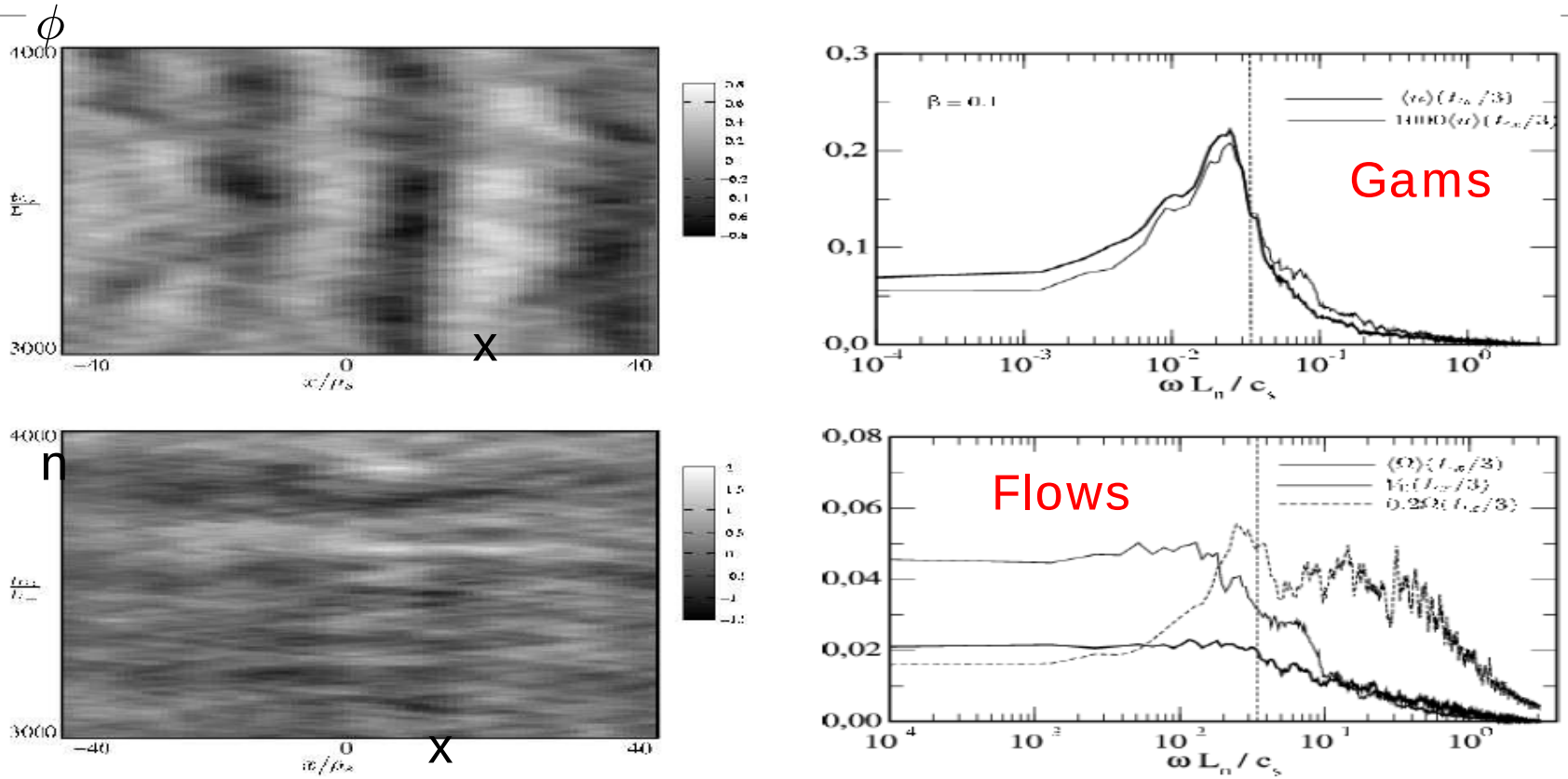
$$0 = \nabla_{\parallel}\,((1+\alpha)J_{PS}) + \hat{\mathcal{K}}\left(n_0 + \frac{7}{2}T_0\right)$$

$$-\nabla_{\parallel}\phi_{PS} = \mu\nu J_{PS}$$

Changes in background quantities must be reflected in changes to resistive equilibrium

Good approach for GAM dynamic

Generation of flows (low $\hat{\beta}$)

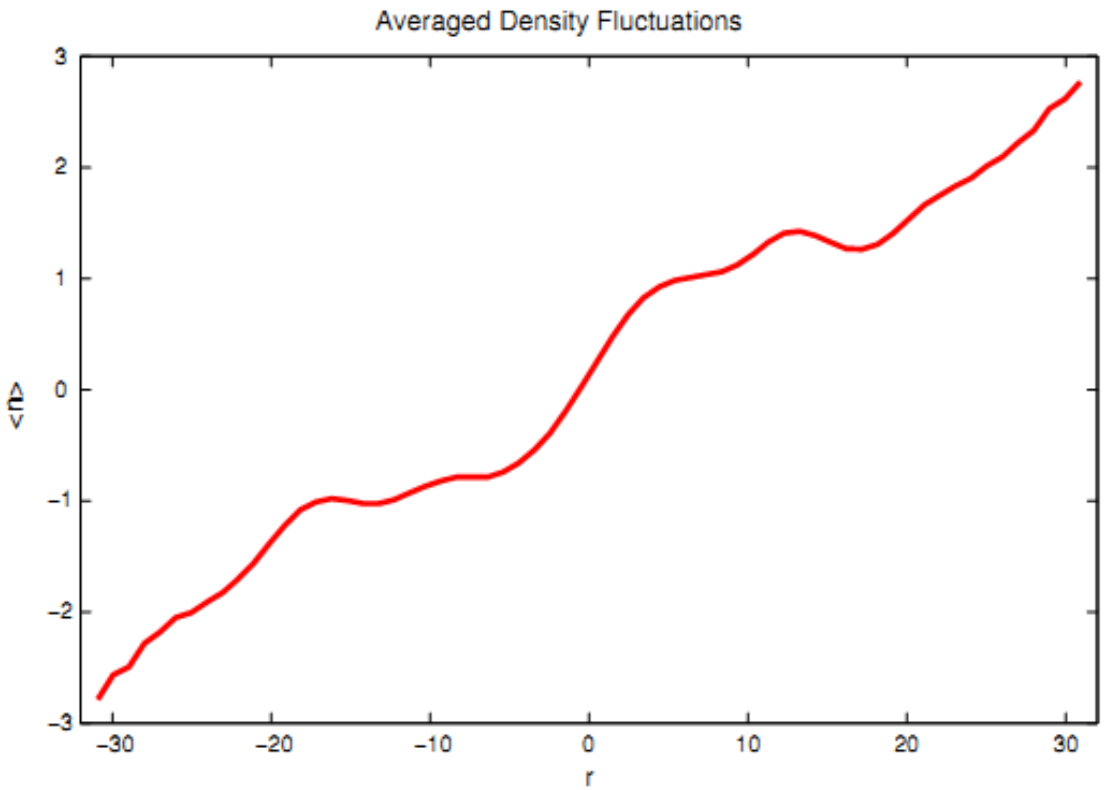


Frequency spectra and time evolution of flow profiles in electrostatic case (flux-tube simulation).

V. Naulin, A. Kendl, O. E. Garcia, A. H. Nielsen, and J. Juul Rasmussen, Phys. Plasmas, **12**, *2005.*

Change in profiles

Flux surface and time averaged density profile:



n_0 ranges from [+32:-32] in this variables.
Turbulent modifications modest, at 10%

Consequences

o driftwave fluxtube simulations allow for small changes in gradients

o magnetic configuration changes not included

o no bootstrap current

o no equilibrium flows

o working in thin layer approximation

Go to 2D for ease of operation

Retain full density, 2D is sufficient as SOL dynamics is concerned (used by a number of codes worldwide)

$$\frac{dn}{dt} + nC(\phi) - C(nT) = \nu_n \nabla_\perp^2 n - \sigma_n (n-1) + S_n,$$

$$\frac{dT}{dt} + \frac{2T}{3} C(\phi) - \frac{7T}{3} C(T) - \frac{2T^2}{3n} C(n) = \nu_T \nabla_\perp^2 T - \sigma_T (T-1) + S_T,$$

$$\frac{d\Omega}{dt} - C(nT) = \nu_\Omega \nabla_\perp^2 \Omega - \sigma_\Omega \Omega, \quad \Omega = \nabla_\perp^2 \phi.$$

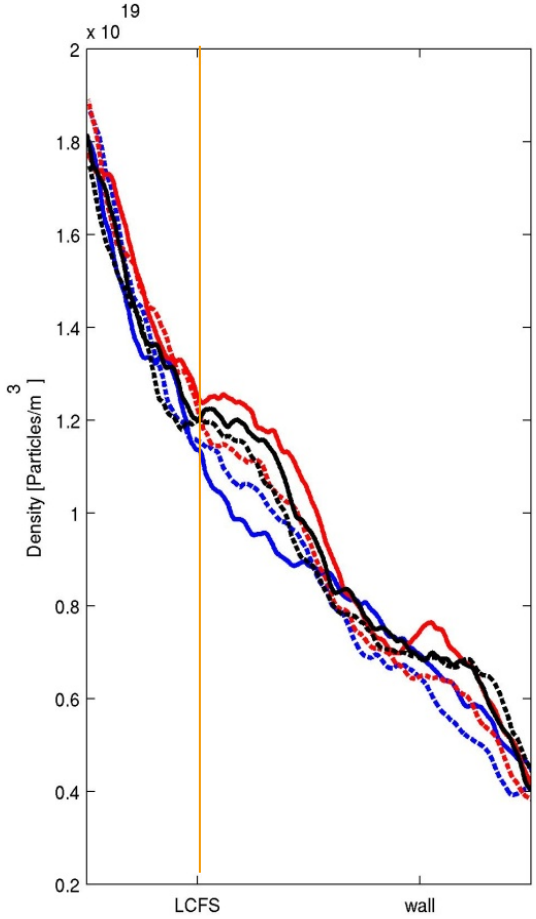
Advective derivative and curvature operators defined by

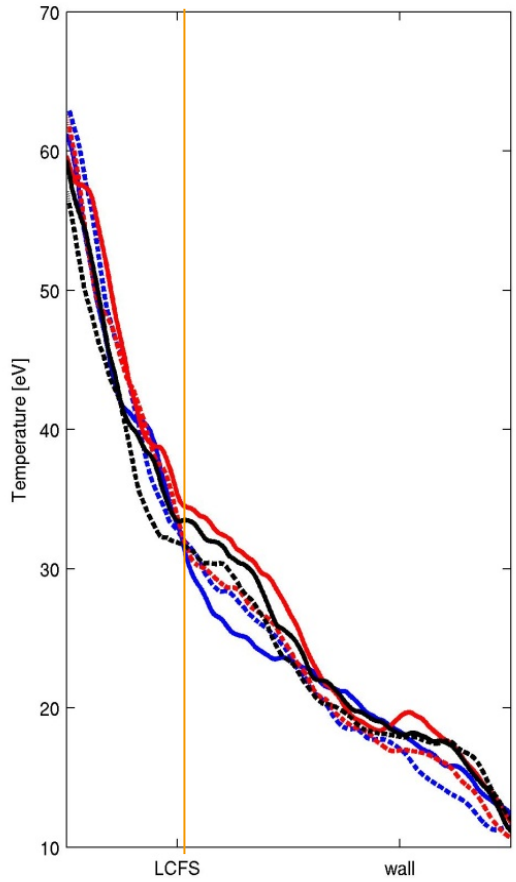
$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{1}{B} \hat{\mathbf{z}} \times \nabla\phi \cdot \nabla, \quad C = \nabla \left(\frac{1}{B} \right) \cdot \hat{\mathbf{z}} \times \nabla, \quad B(x) = \frac{1}{1 + \varepsilon + \zeta x}.$$

Conservation of particles and global energy (lowest order in ζ)

$$E(t) = \int d\mathbf{x} \left[\frac{1}{2} (\nabla_\perp \phi)^2 + \frac{3}{2} nT \right].$$

Profile development for AUG parameters according to ESEL simulations, averaged poloidally and over autocorrelation times

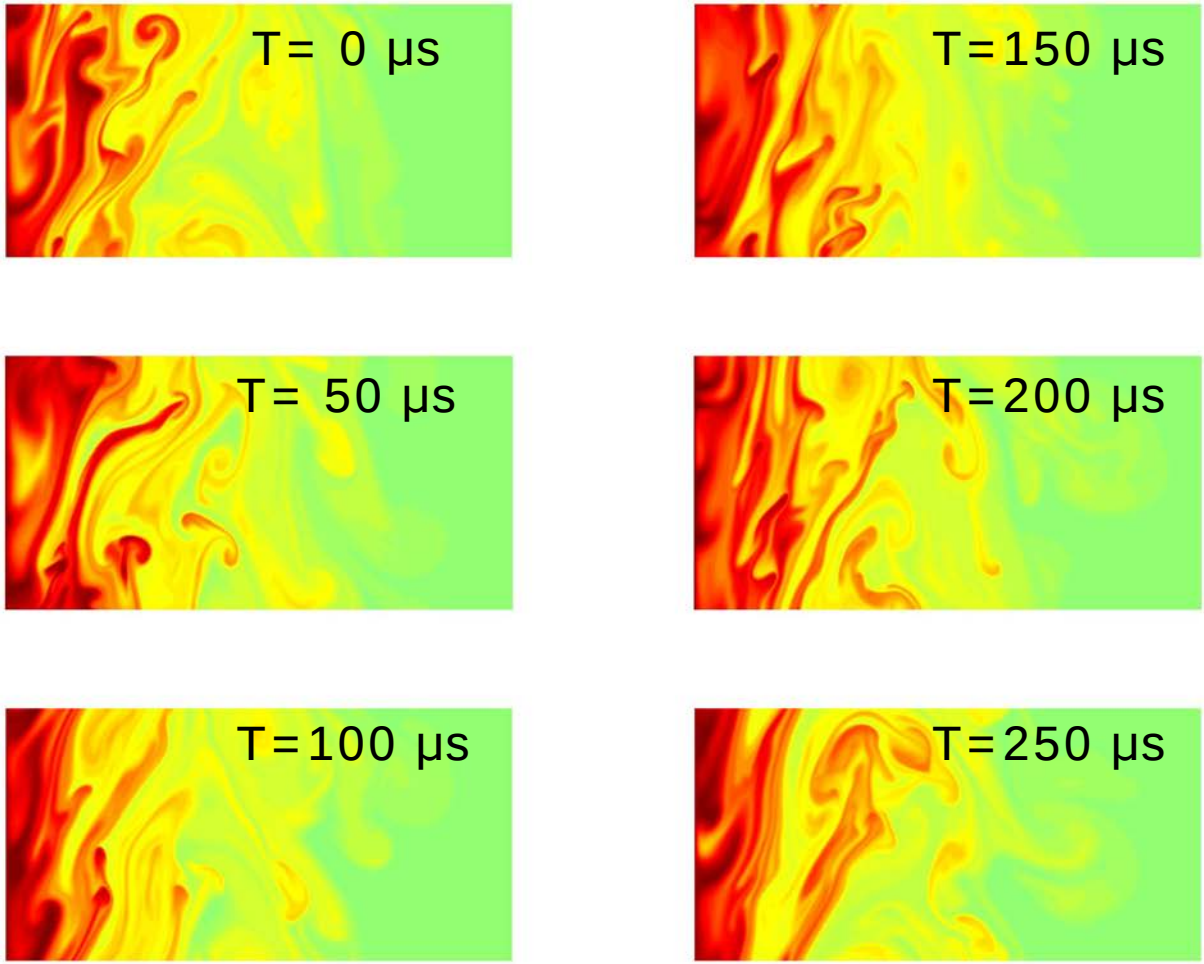




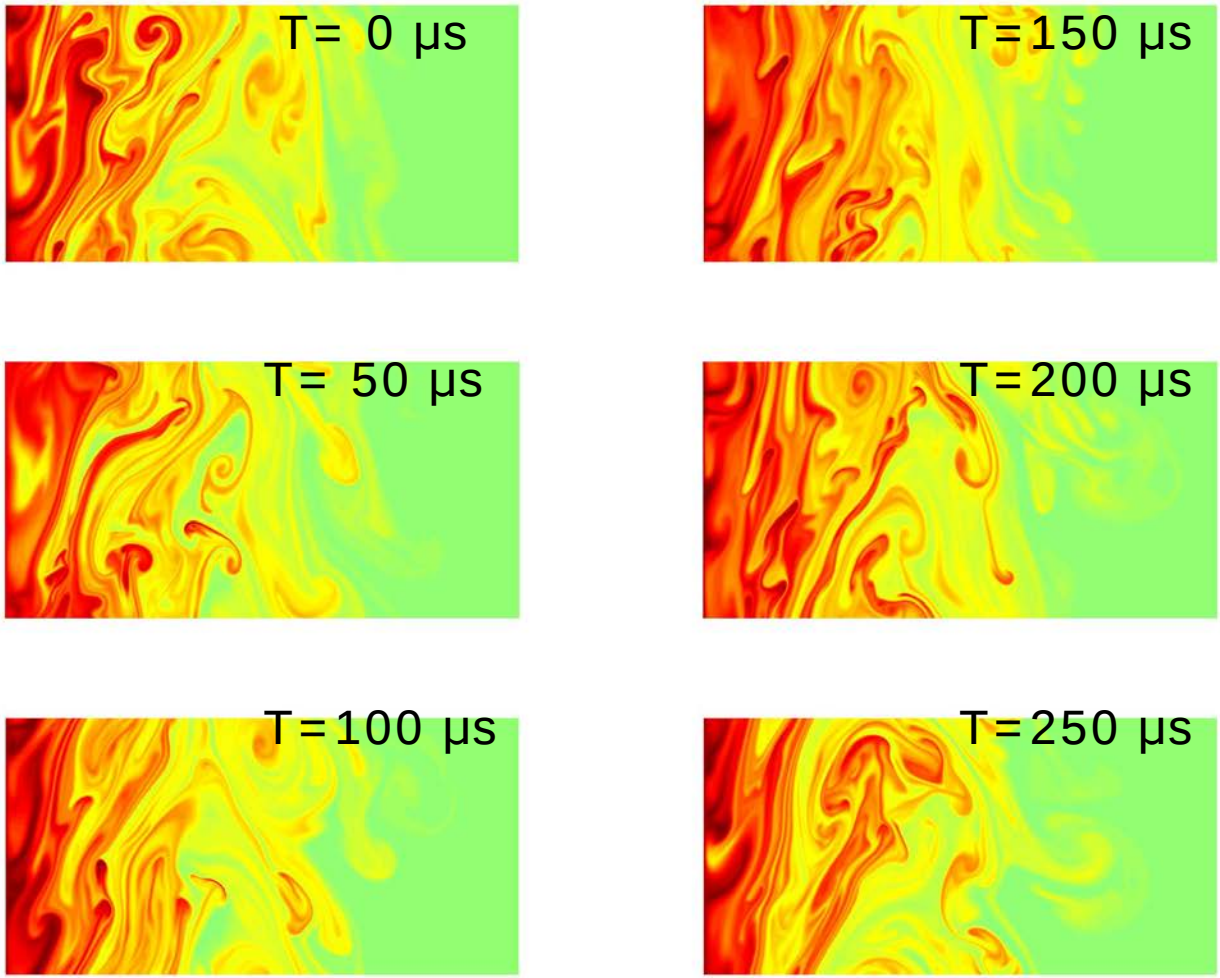
#A = 2
#Z = 1
#q = 4.5
#B0 = 2.34 T
#r0 = 0.5 m
#R0 = 1.64 m
#ne0 = 1.5 10^19
#Te0 = 50 eV
#Ti0 = 50 eV

Variation in profile ca. a factor 10

Temperature at the LCFS/SOL Transition



Density at the LCFS/SOL Transition



Consequences

- can do blobs
- fails on parallel dynamics (sheath connected or not)
- no parallel kinetics
- no FLR effects
- ion temperature

The influence of FLR effects on interchange driven blob motions

- Isothermal, electrostatic two-moment gyrofluid model

$$\frac{dn_e}{dt} = -n_{e0}\mathcal{K}(\phi) + \frac{T_e}{e}\mathcal{K}(n_e) + D\nabla_\perp^2 n_e,$$
$$\frac{\bar{d}N_i}{dt} = -N_{i0}\mathcal{K}(\Gamma_1\phi) - \frac{T_i}{e}\mathcal{K}(N_i) + D\nabla_\perp^2 N_i,$$
$$n_e = \Gamma_1 N_i + \frac{eN_{i0}}{T_i}(\Gamma_0 - 1)\phi,$$

Ion and electron gyroradii are different ->

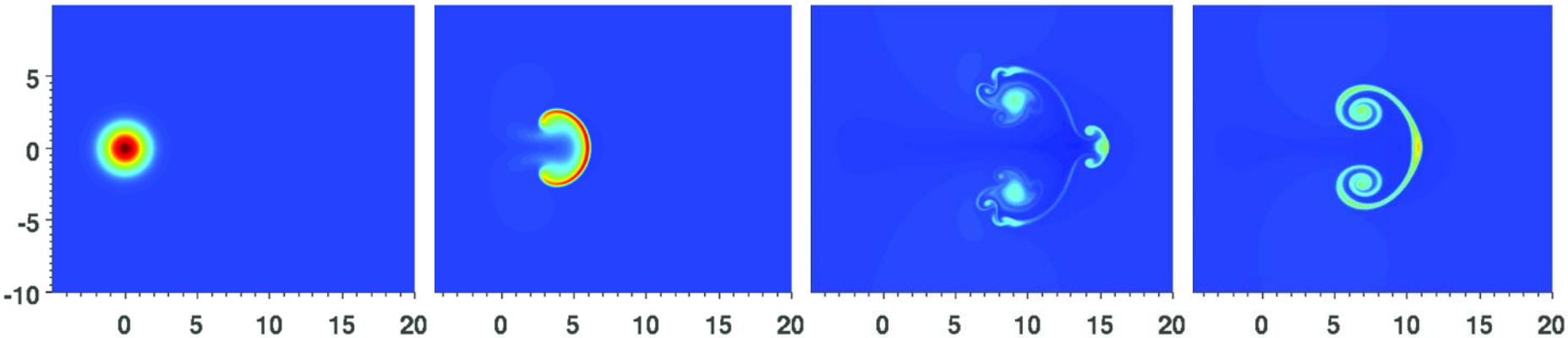
- Gyroradius dependent ExB-advection
- Gyroradius dependent charge contribution
- Model is identical to drift fluid equations in ZLR limit

$$\left[\frac{\partial}{\partial t} + \hat{\boldsymbol{z}} \times \nabla\phi \cdot \nabla\right] n = -\mathcal{C}(\phi) + \mathcal{C}(n) + D\nabla_\perp^2 n,$$
$$\left[\frac{\partial}{\partial t} + \hat{\boldsymbol{z}} \times \nabla\phi \cdot \nabla\right] \nabla_\perp^2\phi = \mathcal{C}(n) + D\nabla_\perp^2\nabla_\perp^2\phi,$$

Particle density contour plots

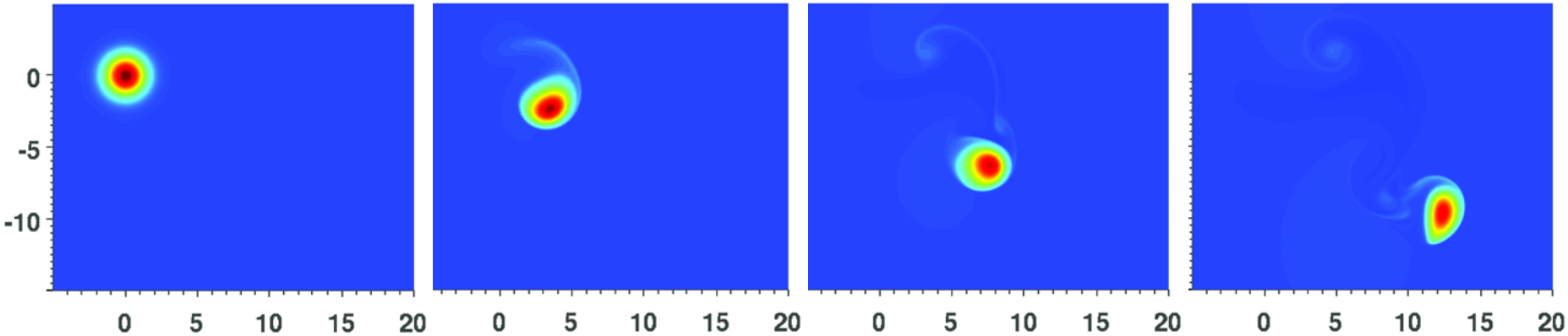
- Formation of mushroom shaped plume structure
- No poloidal motion of CM
- Mixing and stretching -> braking (collisional losses)

Cold ions Ti = 0.0



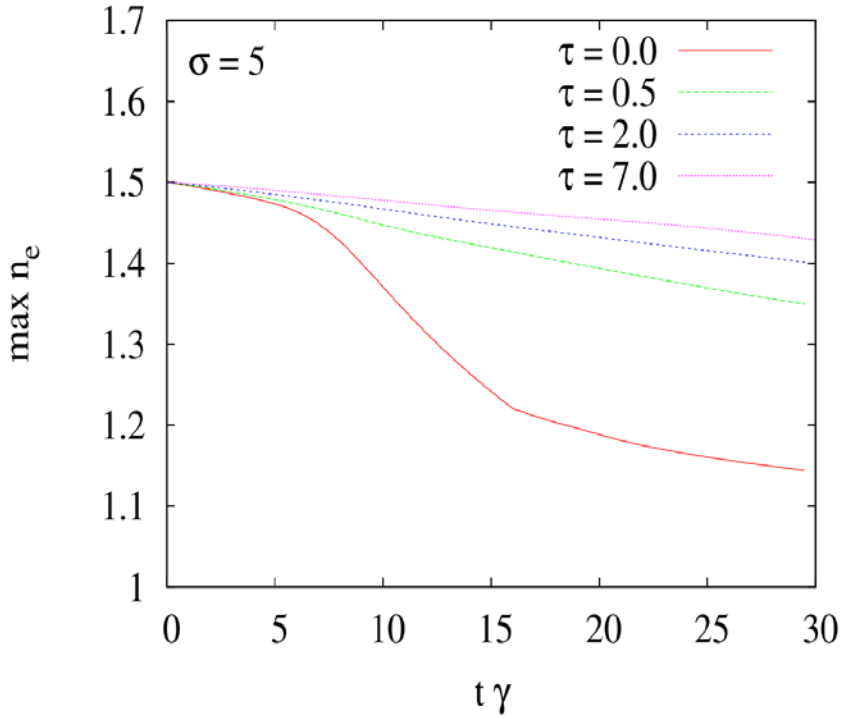
- **Blob spins -> Initial structure approximately conserved**
- **Poloidal motion of CM in B x \nabla B direction**
- **Increased transport**

Hot ions Ti = 7.0

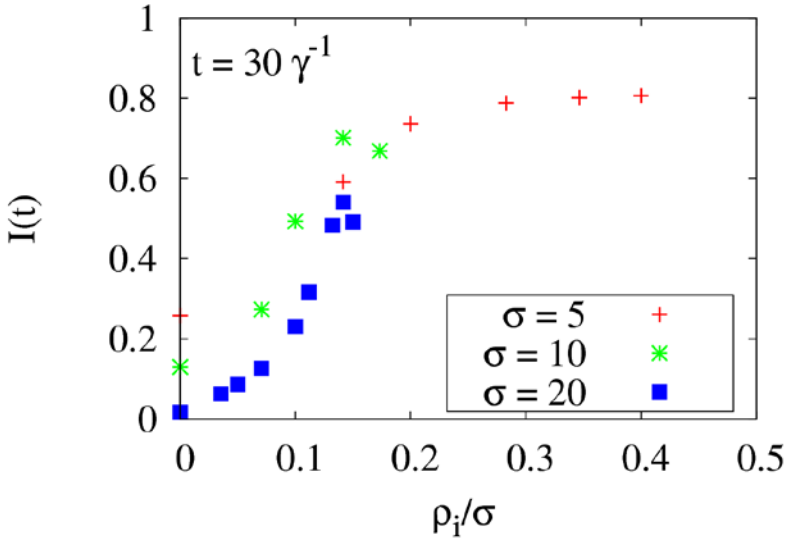


Blob transport

- Time evolution of maximal particle density



- Thermal energy carried by blob after having travelled initial size ~ 10-15 times.
- I = 1, no loss.
- I = 0, initial structur vanished.



Consequences

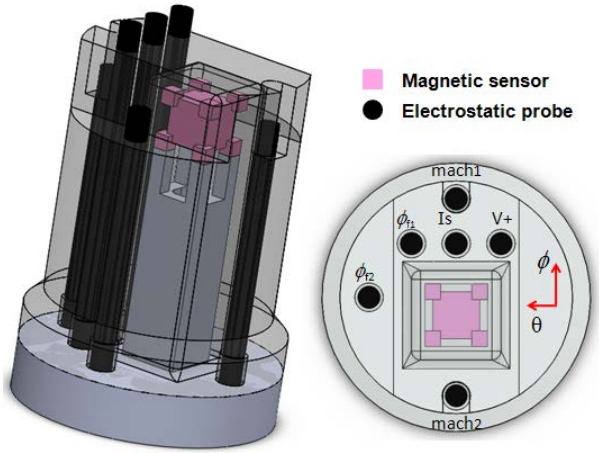
o Gyrokinetic/FLR effects important for blob motion (esp. at high temperatures?)

o Simulations need high resolution

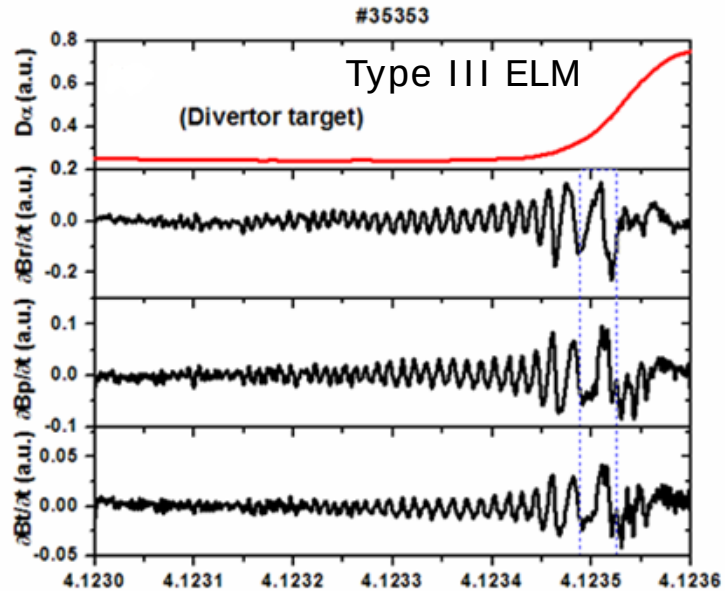
o Equilibrium evolution dictates long runtimes

Other effects/phenomena that we have not yet adressed?

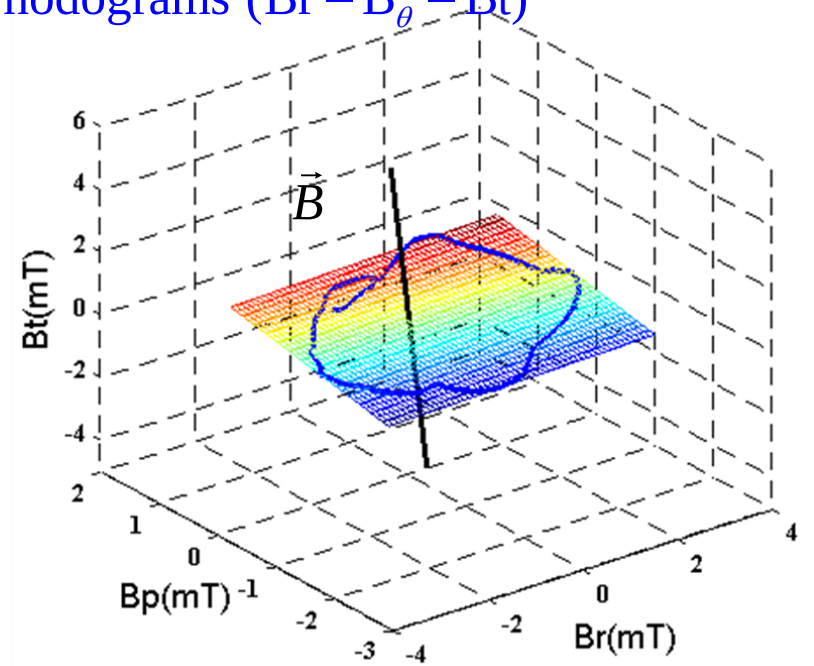
ELM precursor and current filament

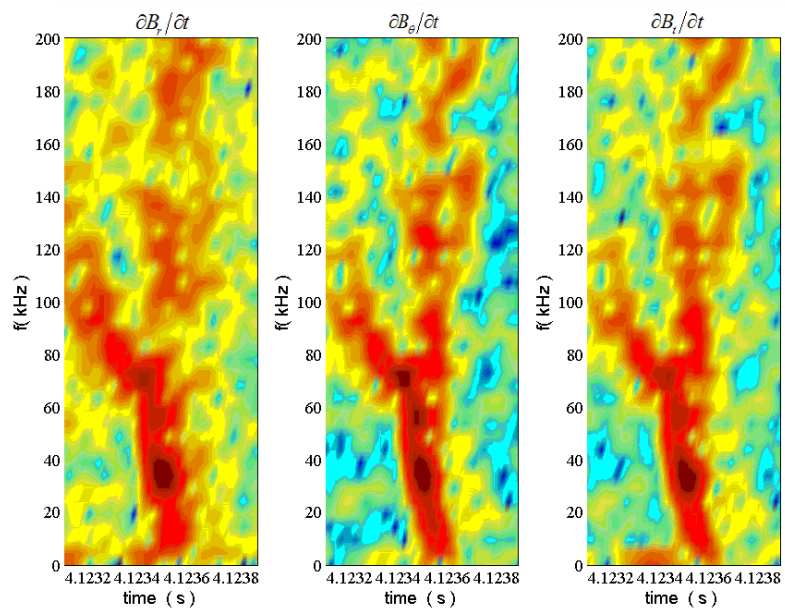


The frequency of precursor decrease from 130KHZ to 70KHZ during 0.4ms

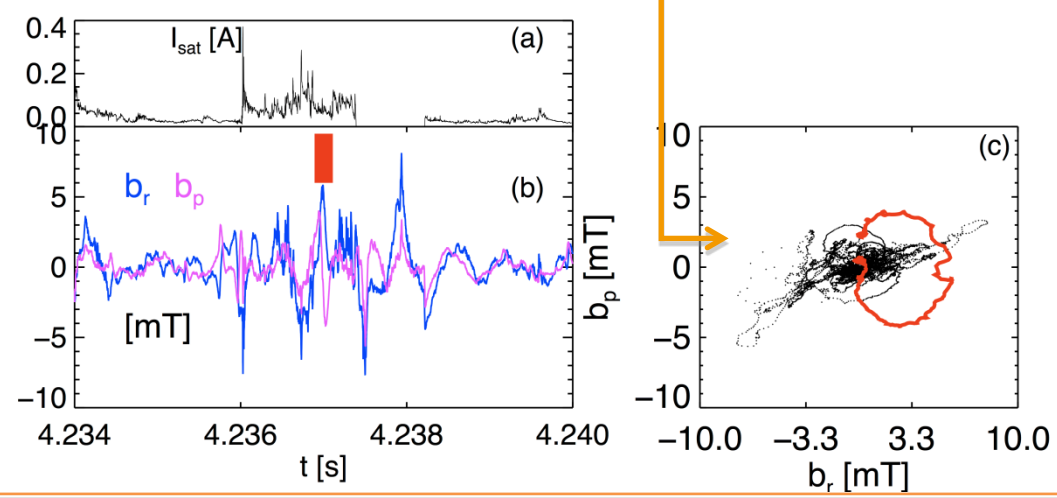


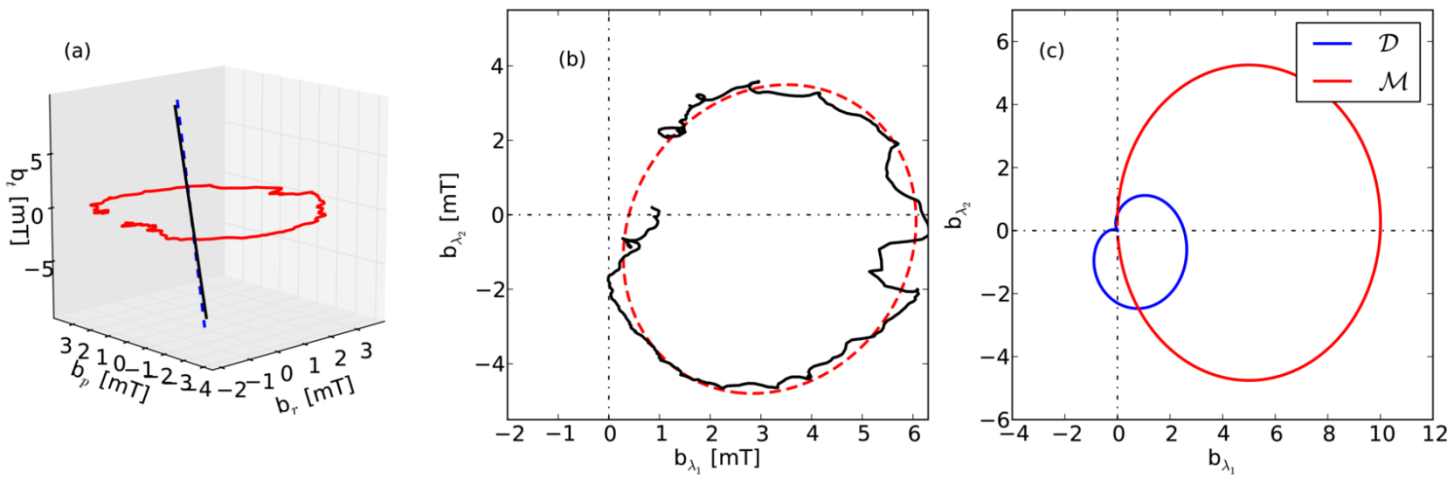
hodograms (Br – B_θ – Bt)





Passing of ELM filament cause a change of phase between radial and poloidal component of the magnetic field

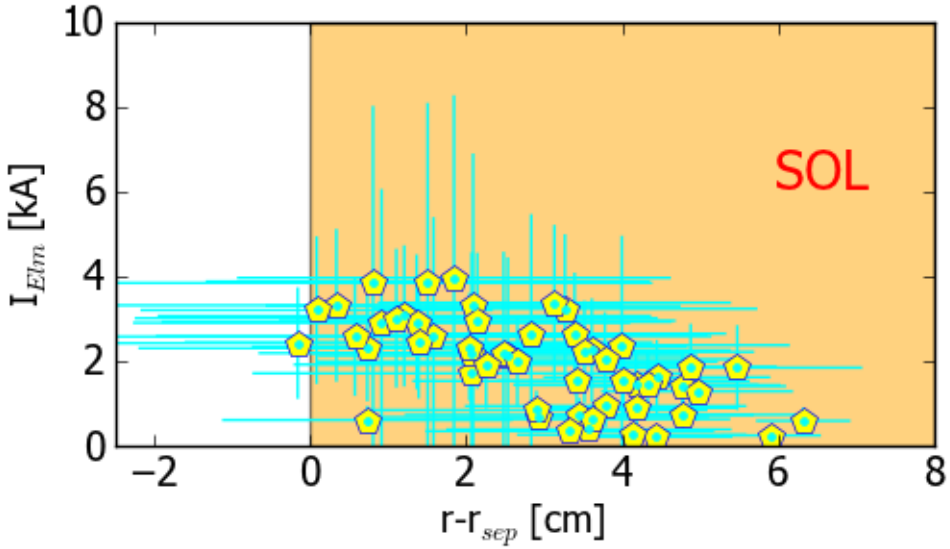




- ✓ In 3D, filaments results in Ellipse lying in a plane perpendicular to the equilibrium field
- ✓ Hodogram compatible with monopolar filamements passing in front of the probe

N. Vianello et al. PRL ***106*** *(2011)*

- ✓ Current carried by the single filaments estimated from the magnetic field perturbation by knowing the filament travelling direction and speed
- ✓ Their absolute position estimated from the knowledge of probe location. Filaments are travelling in the SOL with current up to few kA. Current detected far from the measurement point (≥ 2 cm ~ 100 ρ_s) and decreases in the far SOL. Perturbation of the magnetic field up to 4-5 $\times 10^{-3}$ of the equilibrium field



•What happens to depletions?

•a pressure depression of finite poloidal extend inside the LCFS is connected to the whole flux surface

•Temperature inside the LCFS is high

•Density hole will fill in on the timescale of an ion sound transit time

$$\tau = \frac{L_{\parallel}}{c_s}$$

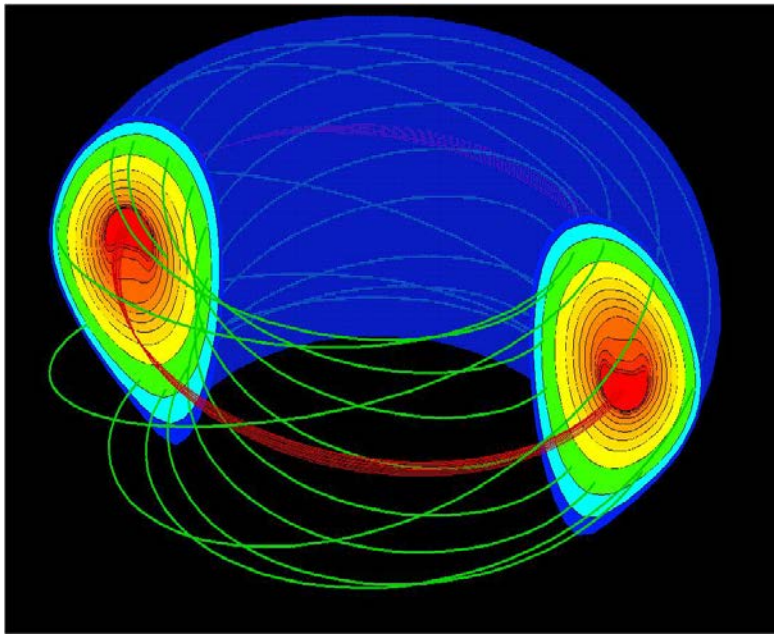
•Pressure hole on conductive thermal timescale

$$\tau_{\mathrm{cond}} \approx L_{\parallel}^2 / \chi_{e\parallel} \sim 20\,\mu s$$

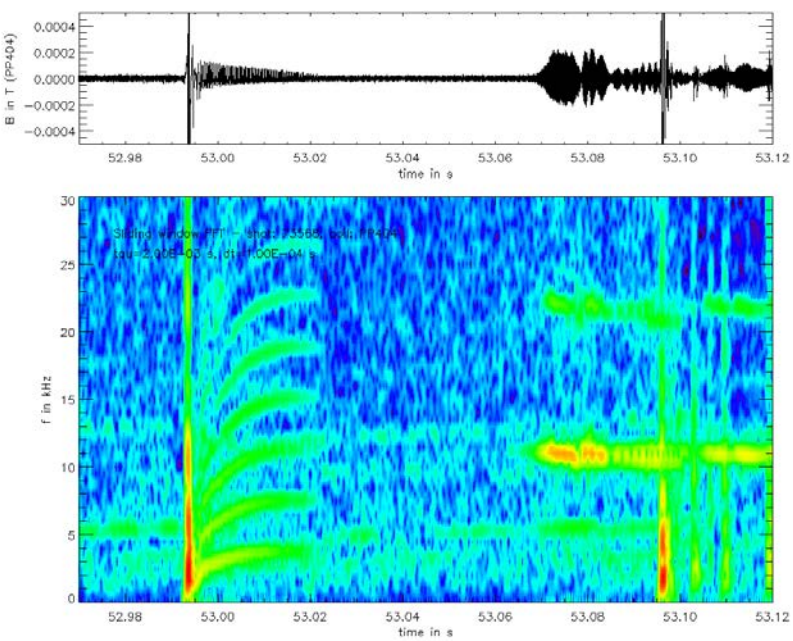
Holes only survive for very short time and are thus able (JET) to move about 2cm inward from their origin

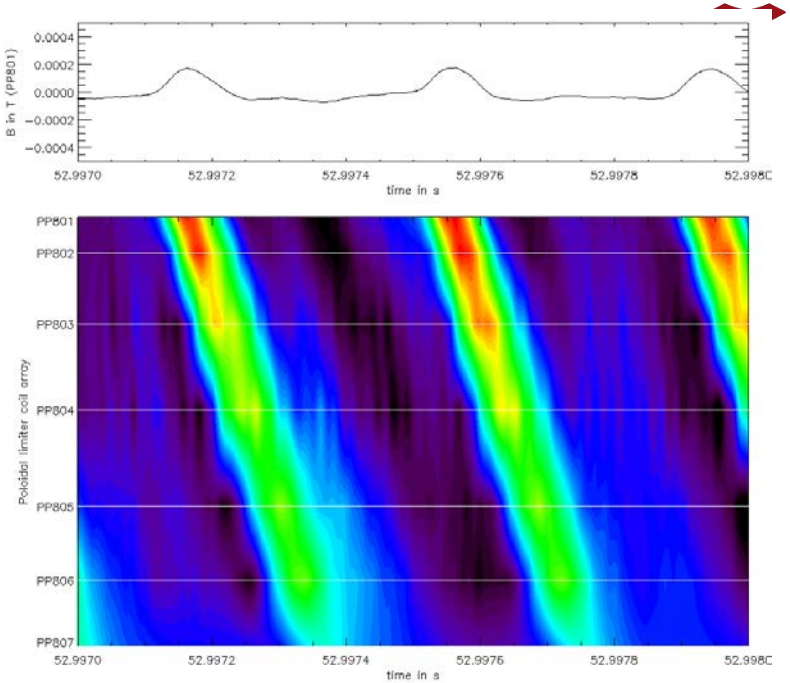
• Arrestment of holes on rationals / Palmtree mode

- If low rational q=3 or 4 is close to edge shear layer, holes are able to reach the rational
- On a rational the filament closes on itself and is no longer in contact with the whole plasma surface
- Interchange charge imbalance then shortcircuited by parallel currents
- Stellarator in a tokamak
- No further radial motion, arrest of filament
- Lets check if this happens at the largest events we have: ELMs



Arrestment of holes on rationals / Palmtree mode





- Large ”hole” after ELM event on JET
- Seen in magnetics, localised (many harmonics), on low q rational (Koslowski, PPCF 2005)
- Rotating current filament
- Decay time much longer than estimates from resistivity

Consequences

o Global current structures with long range fields attached are outside the flux tube formalism

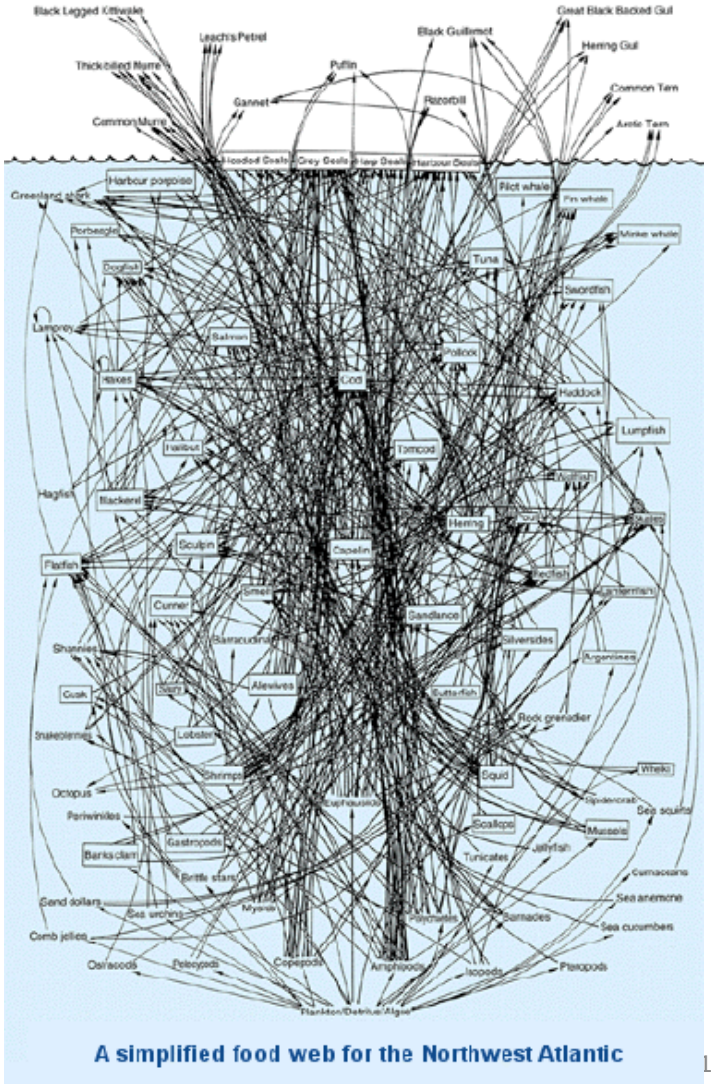
o The reason for this is geometry, not if we are talking electrostatic vs. electromagnetic

o The smaller scales are important for the dynamics of these global structures, which influence equilibrium

Use of reduced models?

Profile – Fluctuations and Predator – Prey

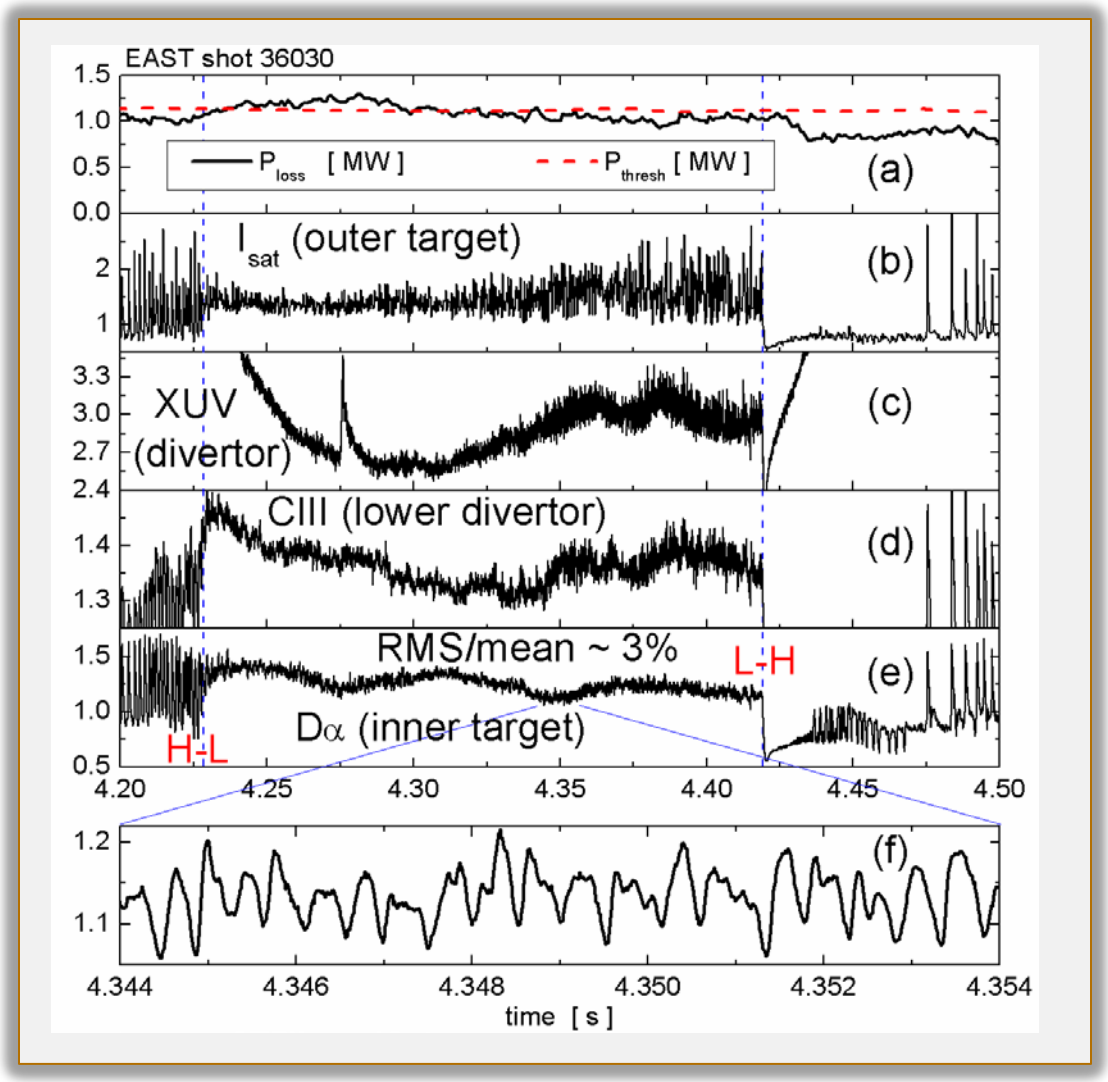
World is more complex, but simplification is part of the process of understanding



A simplified food web for the Northwest Atlantic

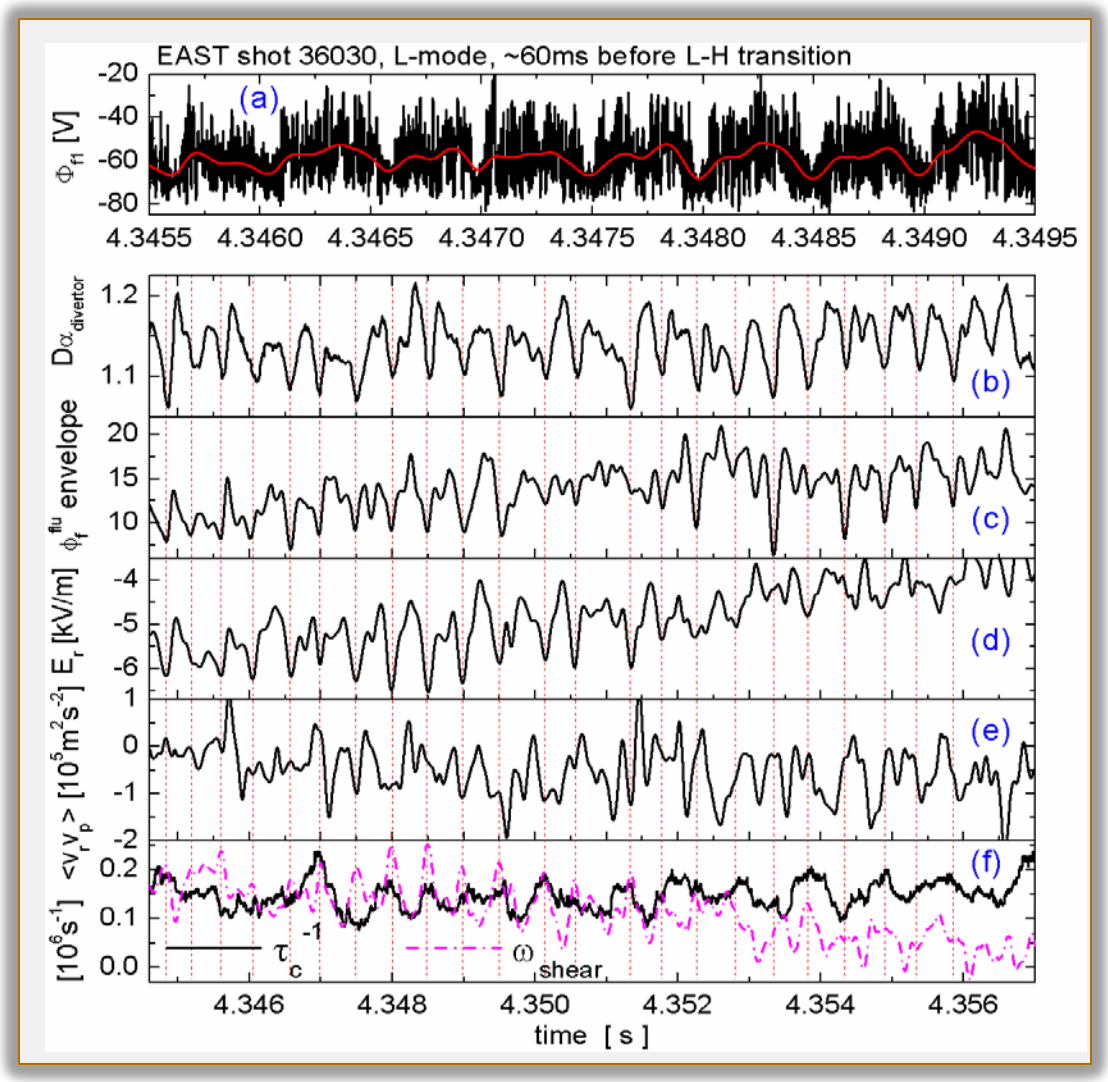
IFAW

First evidence of Role of Zonal Flows for L-H Transition at Low Input Power



- A quasi-periodic edge oscillation preceding and following L-H transition was observed, for the 1st time, in EAST at low input power.
- At frequency < 4 kHz, much lower than GAM, but similar to limit-cycle oscillations predicted by a more recent L-H transition model by Kim/Diamond, which takes into account zonal flow contribution at marginal input power for H-mode access.

Evidence of Role of Zonal Flows for L-H Transition at Low Input Power



- Direct probing inside the separatrix using two toroidally distributed fast moving probes demonstrated a strong coupling between Er and turbulence driven Raynolds stress.
- These new findings not only shed light on the underlying physics mechanism for L-H transition, but also have significant implications for ITER operation close to the L-H transition threshold power.

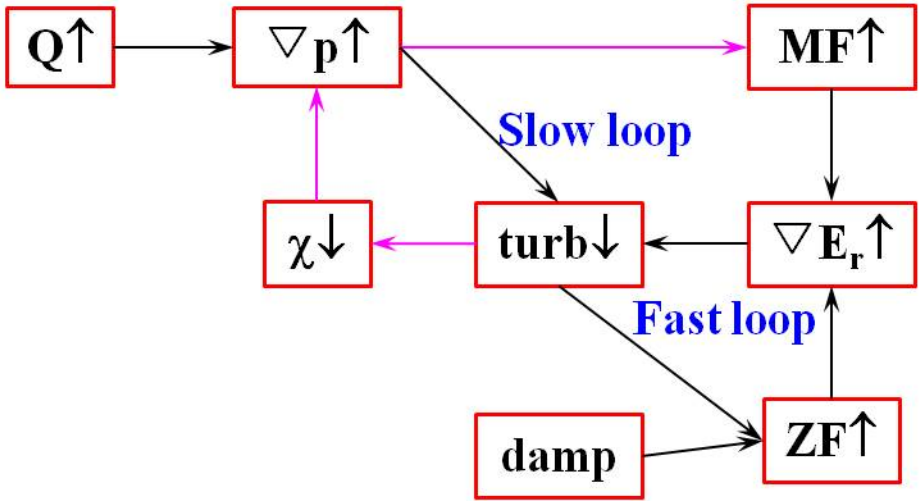
Predator–prey model as a threshold model

$$V_E = V_{NC} + \sqrt{\mathcal{E}_{ZF}}$$

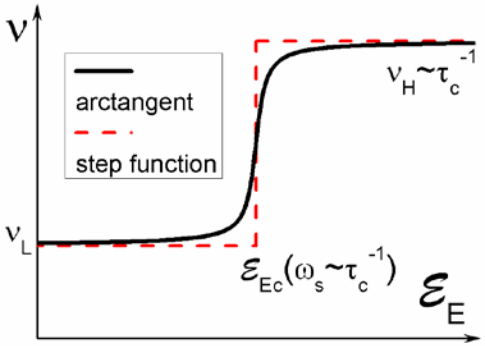
Fast $$\partial_t \mathcal{E}_T = Q\mathcal{E}_T - \alpha \mathcal{E}_T^2 - \nu \mathcal{E}_T$$

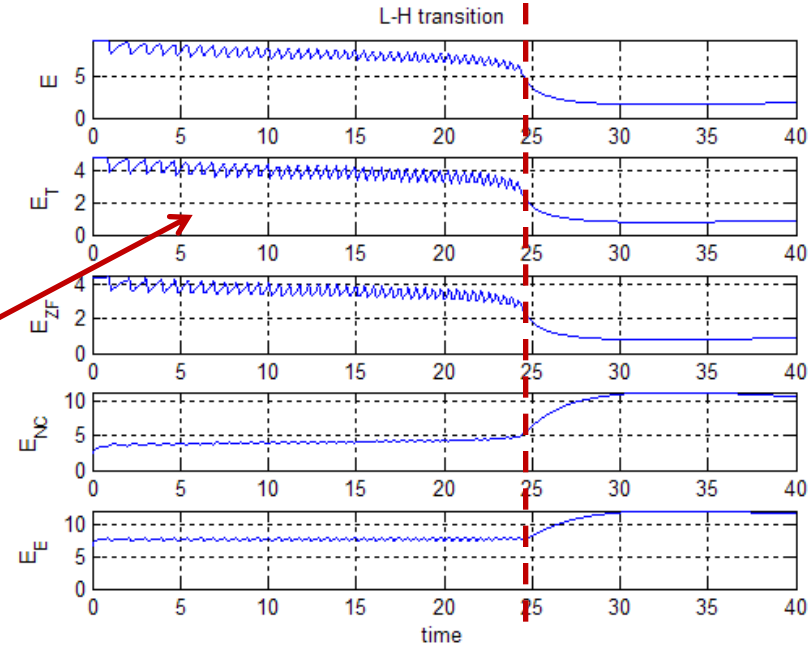
Fast $$\partial_t \mathcal{E}_{ZF} = \nu \mathcal{E}_T - \mu \mathcal{E}_{ZF}$$

Slow $$\partial_t V_{NC} = Q - V_{NC} - \chi \mathcal{E}_T V_{NC}$$



$$\nu = \begin{cases} \nu_H & (V_E' > V_{Ec}') \\ \nu_L & (V_E' \le V_{Ec}') \end{cases}$$





Low frequency oscillations

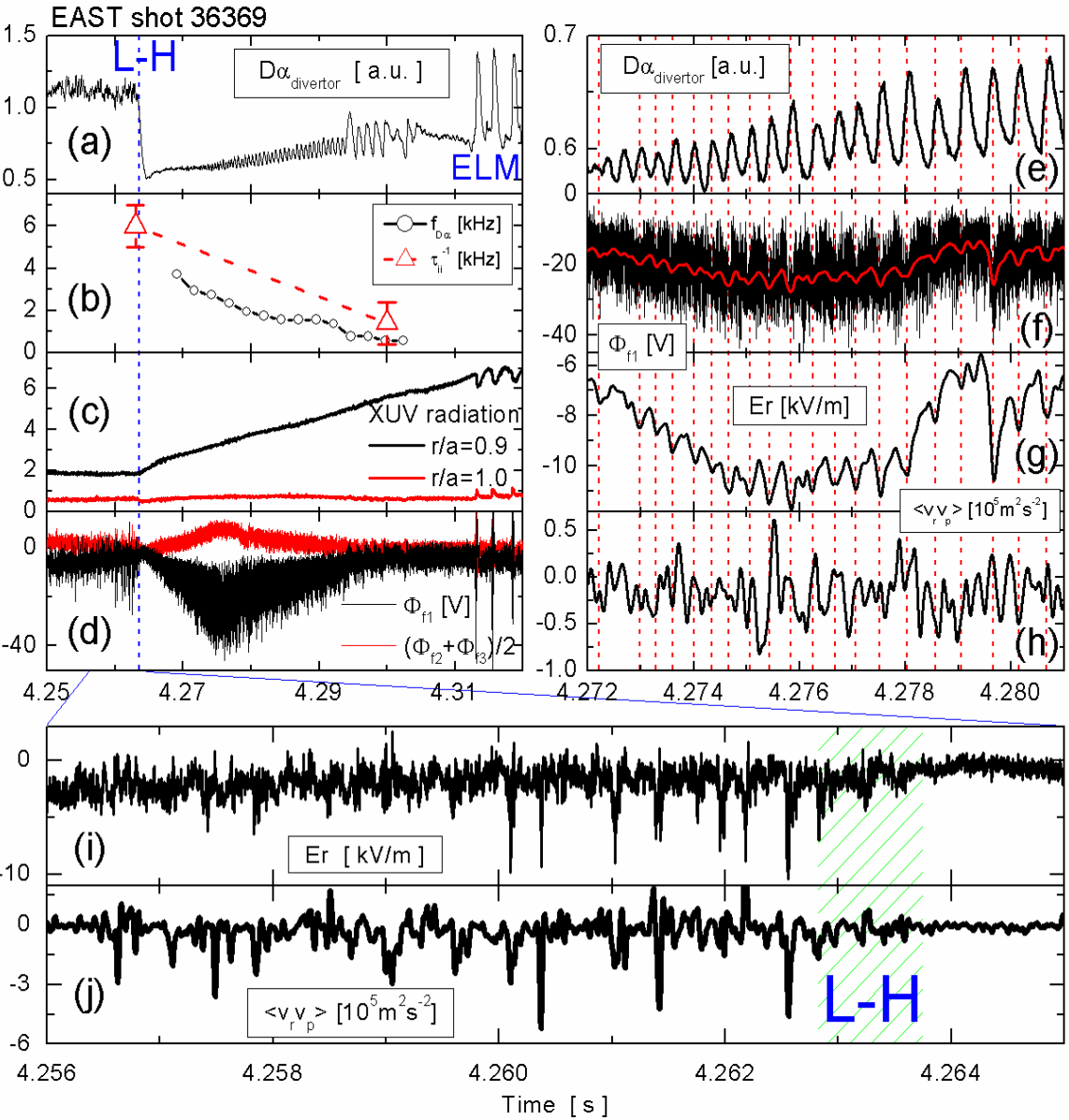
L - H

Turbulence decorrelation rate $\nu = \tau_c^{-1}$

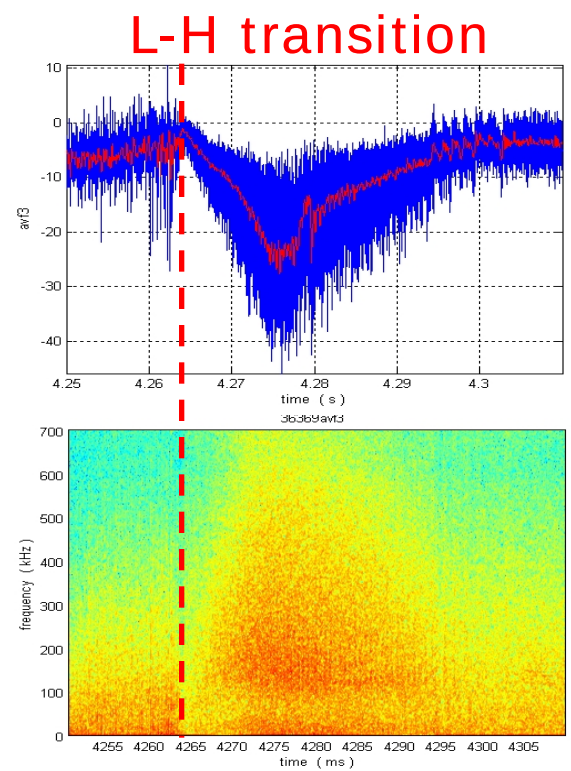
Poloidal flow damping rate μ

Turbulent transport rate χ

The role of zonal flows for the L-H transition at marginal input power in the EAST tokamak



- Er oscillations were not only observed preceding the transition but also following the transition.
- frequency gradually decreased from ~4 to below 1 kHz.



Introduce an equation describing the ITG-like high frequency turbulence to reproduce the oscillation in ELM-free phase

$$\partial_t \mathcal{E} = \kappa Q \mathcal{E} - \nu \mathcal{E} - \alpha \mathcal{E}^2$$

$$\partial_t \mathcal{E}_{ITG} = \gamma V_{NC} \mathcal{E}_{ITG} - \nu_{ITG} \mathcal{E}_{ITG} - \alpha_{ITG} \mathcal{E}_{ITG}^2$$

ITG-like high frequency turbulence

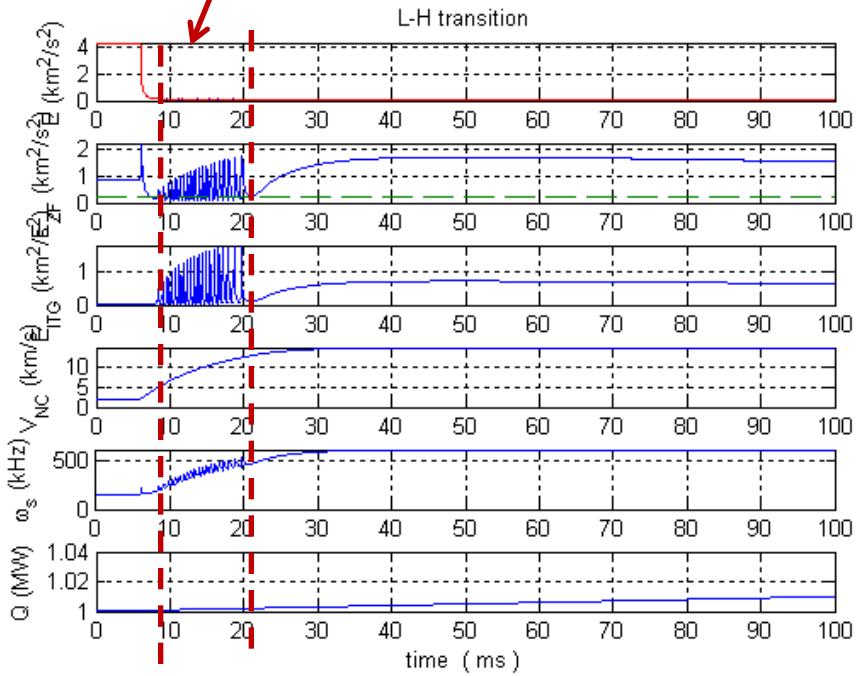
$$\partial_t \mathcal{E}_{ZF} = \nu \mathcal{E} + \nu_{ITG} \mathcal{E}_{ITG} - \mu \mathcal{E}_{ZF}$$

$$\partial_t V_{NC} = \sigma Q - \tau_{NC}^{-1} V_{NC} - \chi \mathcal{E} V_{NC} - \chi_{ITG} \mathcal{E}_{ITG} V_{NC}$$

$$\omega_s \equiv \left| V_E' \right| = V_{NC} / L_{MF} + \sqrt{\mathcal{E}_{ZF}} / L_{ZF}$$

$$\nu = \begin{cases} K_H \tau_c^{-1} & \left(\omega_s \geq \tau_c^{-1} \right) \\ K_L \omega_s & \left(\omega_s < \tau_c^{-1} \right) \end{cases}$$

$$\nu_{ITG} = \begin{cases} K_{ITGH} \tau_{ITGc}^{-1} & \left(\omega_{ZFs} \geq \tau_{ITGc}^{-1} \right) \\ K_{ITGL} \omega_{ZFs} & \left(\omega_{ZFs} < \tau_{ITGc}^{-1} \right) \end{cases}$$



Conclusions

- Global simulations are a necessity
- Global means a variety of things:
  - Spatial and temporal variation in parameters by orders of magnitude
  - Allow relaxations/changes to equilibrium
  - Allow for fields (potentials, electric and magnetic) on system size scale
  - Resolve small scales (below ρ_s)
  - Consider currents
- Reduced models useful for understanding of parts of the ”food web”

We now are getting closer to know what we have to put together!