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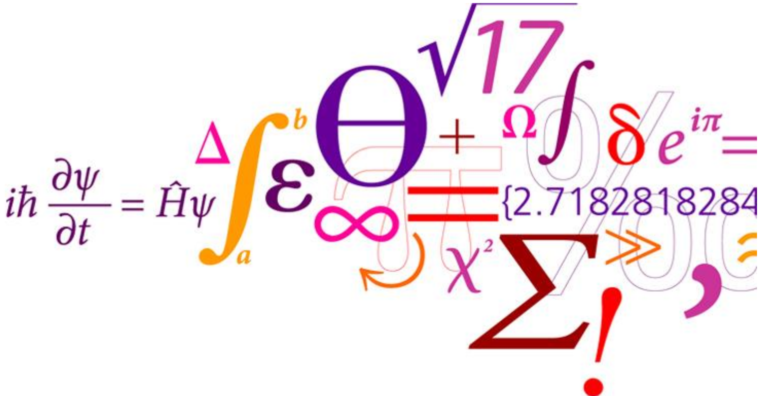
Scrape-off-Layer (SOL) and pedestal physics

V. Naulin, J. Juul Rasmussen, A.H. Nielsen, J. Madsen, L. Tophøj, A.S. Thrysø, and M. Løiten , *PPFE, Dept. Physics, DTU, Kgs. Lyngby, Denmark*
O.E. Garcia, *Dept. Phys.Tech., UiT, Tromsø, Norway*
R. Schrittwieser, C. Ionita, S. Costea, and B.S. Schneider, *Inst. Ion Phys. and Appl. Phys., University of Innsbruck, Innsbruck, Austria*
N.Vianello, *SPC, Ecole Polytechnique Fédérale de Lausanne, Switzerland*
N. Yan and G.S. Xu , *ASIPP, Chinese Academy of Sciences, Hefei, China*
T. Tala and A. Salmi, *VTT, Espoo, Finland*

vona@fysik.dtu.dk

DTU Physics
Department of Physics



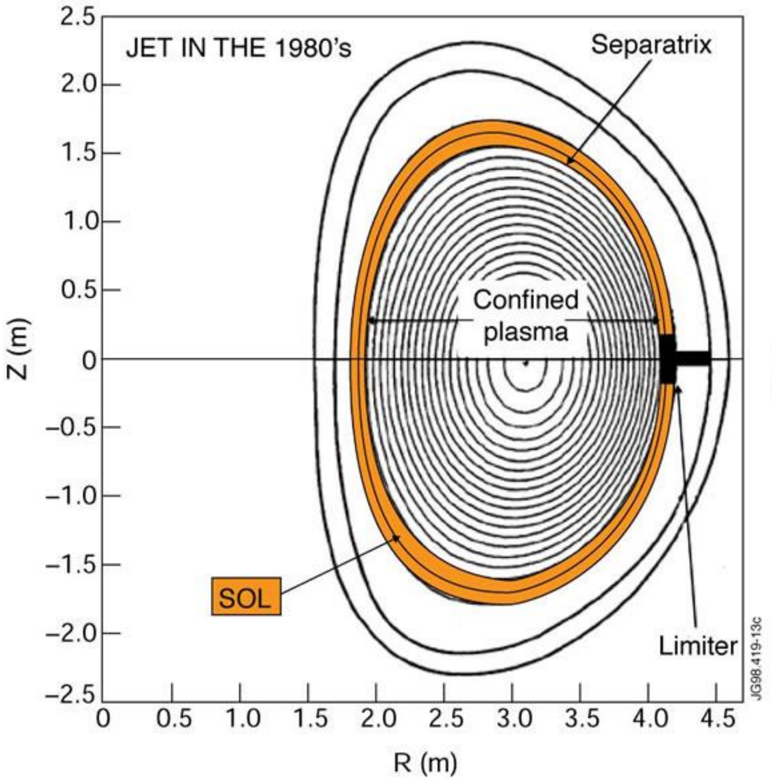
Outline/Motivation

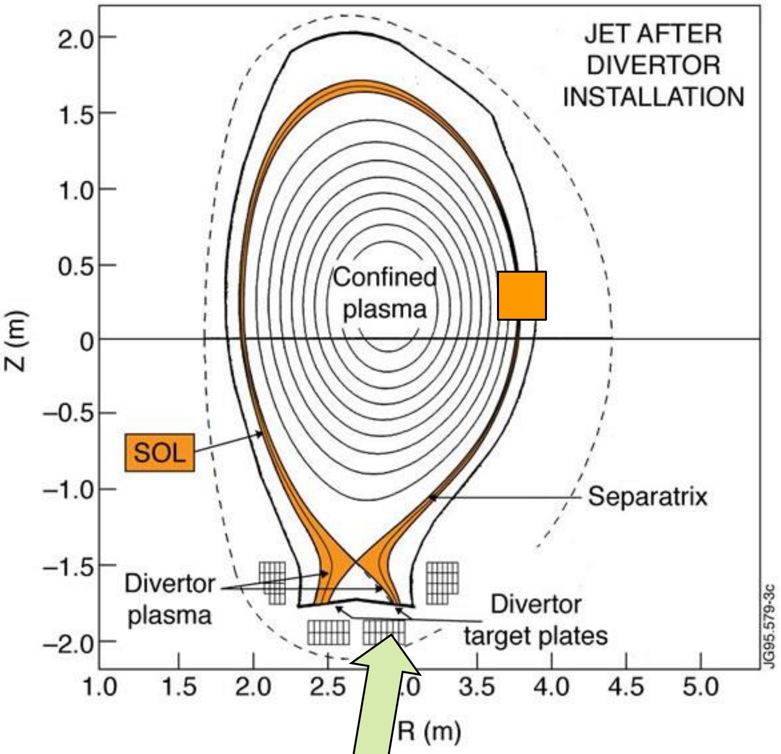
- Plasma dynamics in the Scrape-off-Layer, SOL.
- SOL is the plasma exhaust channel – all plasma goes through the SOL.
- In magnetically confined hot plasmas the **anomalous – turbulent - transport** is the dominant mechanism for transport of particles and energy across the confining magnetic field – orders of magnitude higher than classical collisional transport.
- Understanding and predicting the transport is essential for the viable operation of fusion power plants
- Interplay with SOL and role of turbulence at LCFS for power exhaust not fully clarified

Content

- SOL and Edge
- Nonlocal, non-diffusive transport
- Shoulder formation
- Fuelling and ITER
- LH transition

Scrape Off Layer





from plasma to vacuum

from 200.000.000 degrees to -200 degrees in superconducting coils within a few centimeters

All energy goes through the SOL

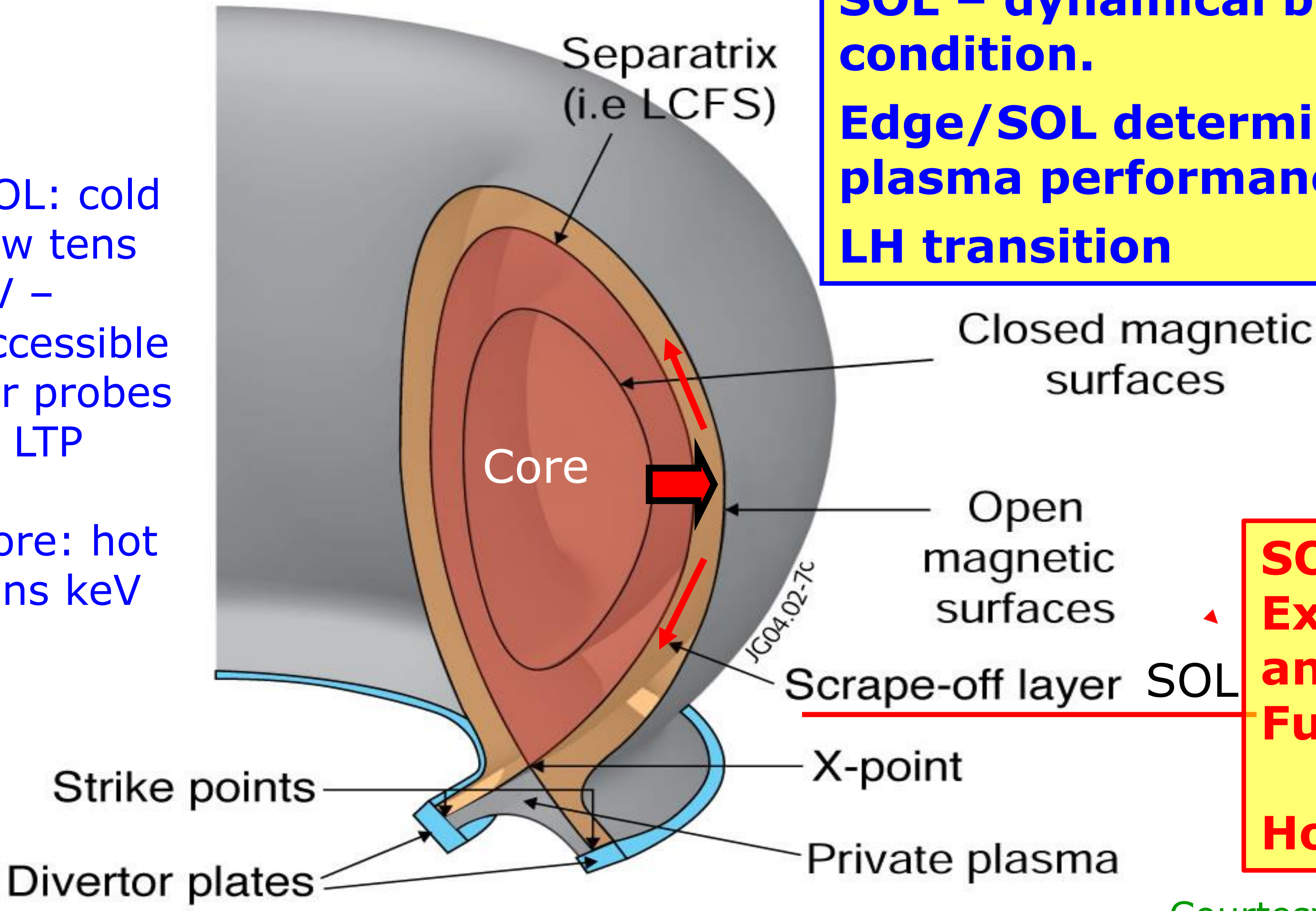
Energy ends up here

From center of a star to earth in a single step

Tokamak divertor configuration – edge/SOL

SOL: cold few tens eV – accessible for probes -- LTP

Core: hot tens keV



SOL – dynamical boundary condition.

Edge/SOL determines plasma performance.

LH transition

SOL – Exhaust and Fuelling

How fast ?

Courtesy EFDA/JET

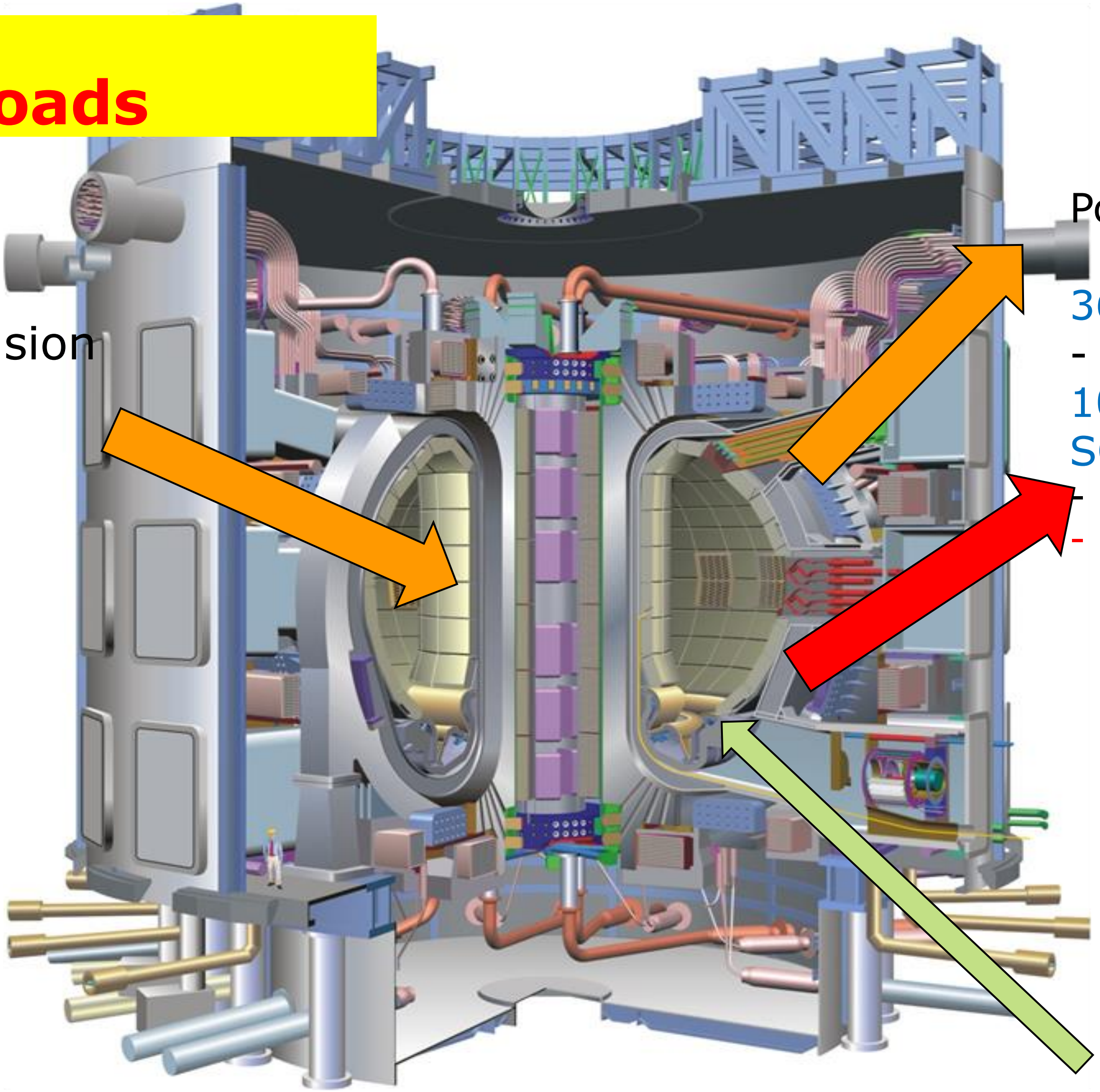
SOL – plasma characteristics

- Cold – few tens of eV –and low density - 10^{18} – 10^{19} m^{-3}. Core: tens of keV and 10^{20} m^{-3}.
- Transport into and through the SOL – strongly intermittent.
- SOL not fully ionized (core fully ionized)
- SOL region involves plasma interaction with solid materials (PMI) - the first wall, plasma facing components (PFC), the divertor plates (erosion)

- …. and interaction with neutral particles.

Complex atomic physics: including ionization and excitation of neutrals, single atoms or molecules -> obstacle to scaling approaches

Power loads



Power IN:
450 MW Fusion
50 MW
Heating

Power OUT:

360 MW Neutrons
- 0.5 MW/sqm Neutrons

10 MW fast particles

SOL 130 MW
- 110 MW radiation
- 20 MW divertor target

Power on target plates: 10 MW/sqm

Surfaces:
1st wall 700 sqm
Divertor wetted area: circumference x 1cm: ca. 2 sqm
or less? Or more? **How wide is the SOL?**

Effective radiative cooling (>110 MW) is a necessity

Extreme heat fluxes in other technologies

PWR fuel element

Rolls-Royce Trent 900

Atmospheric Reentry Demonstrator

Average surface heat flux: 1 MWm-2

max. surface heat flux up to 85 MWm-2 for a few minutes cooled by liquid gas

Ariane 5 /Vulcain 2

Transport across LCFS and in the SOL

Cross field transport of particles and heat in magnetically confined plasmas is dominated by anomalous - turbulent - transport!

In the edge/SOL region the transport is strongly intermittent and characterized by:

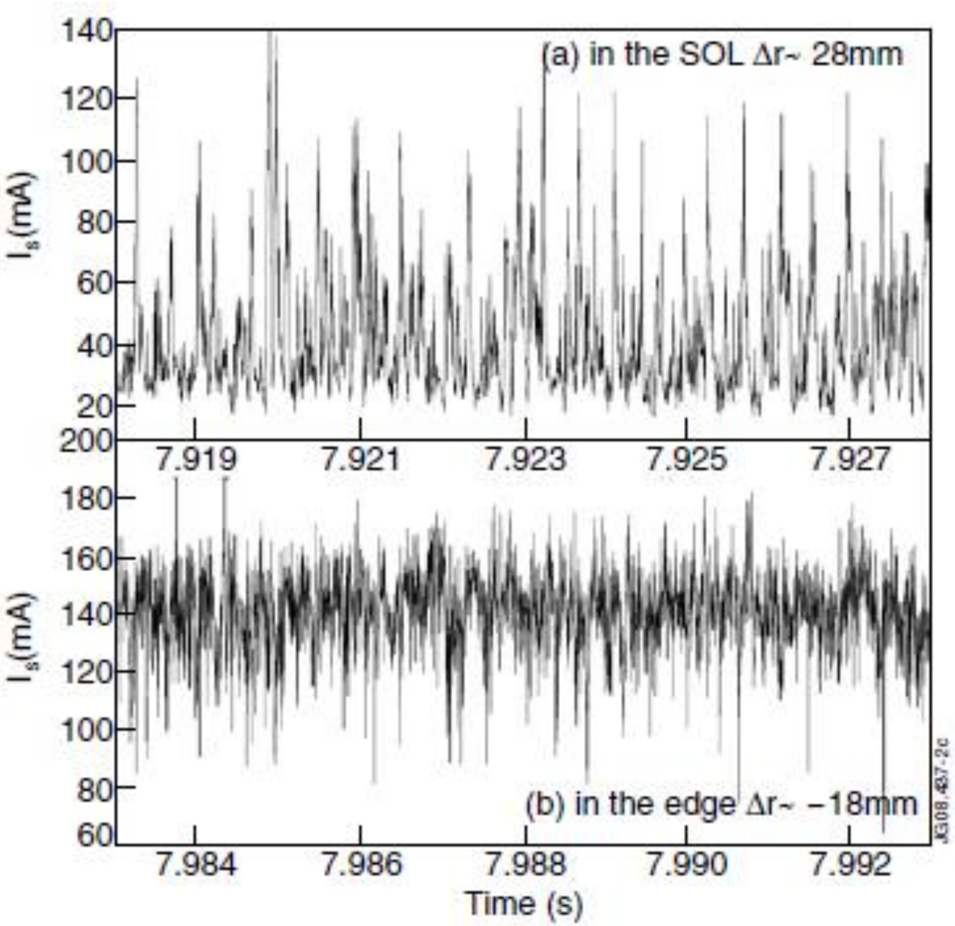
- **large-amplitude, radially propagating blob-like structures of particles and heat, generated close to the last closed flux surface**
- **results in localized power loads at plasma facing components**
- **lasting influence on the chamber wall and other plasma facing components**
- **strong demands on materials**

Observed under a variety of conditions:

Zweben Phys. Fluids **28** 974 (1985); Boedo *et al.* PoP **10**, 1670 (2003); Zweben *et al*. Nucl. Fus. **44**, 134 (2004); Grulke *et al.* PoP **13**, 012306 (2006); Garcia *et al.* PPCF **48**, L1 (2006); Garcia *et al.* PPCF **49**, B47 (2007); Xu *et al.* Nucl. Fus. **49,** 092002 (2009); Nold *et al.* PPCF **52,** 065005 (2010); Garcia *et al.* PoP **20**, 055901 (2013); Yan *et al.* PPCF **55**, 115007 (2013); Carralero *et al.* Nucl, Fus. **54** 123005 (2014)…...

Reviews: Zweben *et al.* PPCF **49**, S1 (2007); Garcia, Plasma Fusion Res. **4,** 019 (2009); D'Ippolito *et al*. Phys Plasmas **18,** 060501 (2011)….

Intermittent density fluctuations



In the SOL

Inside last closed flux surface, LCFS

Typical density fluctuations in JET – Joint European Torus

G. Xu *et al.* Nucl Fusion **49**, 092002 (2009)

Blob cause of intermittency (from NSTX)

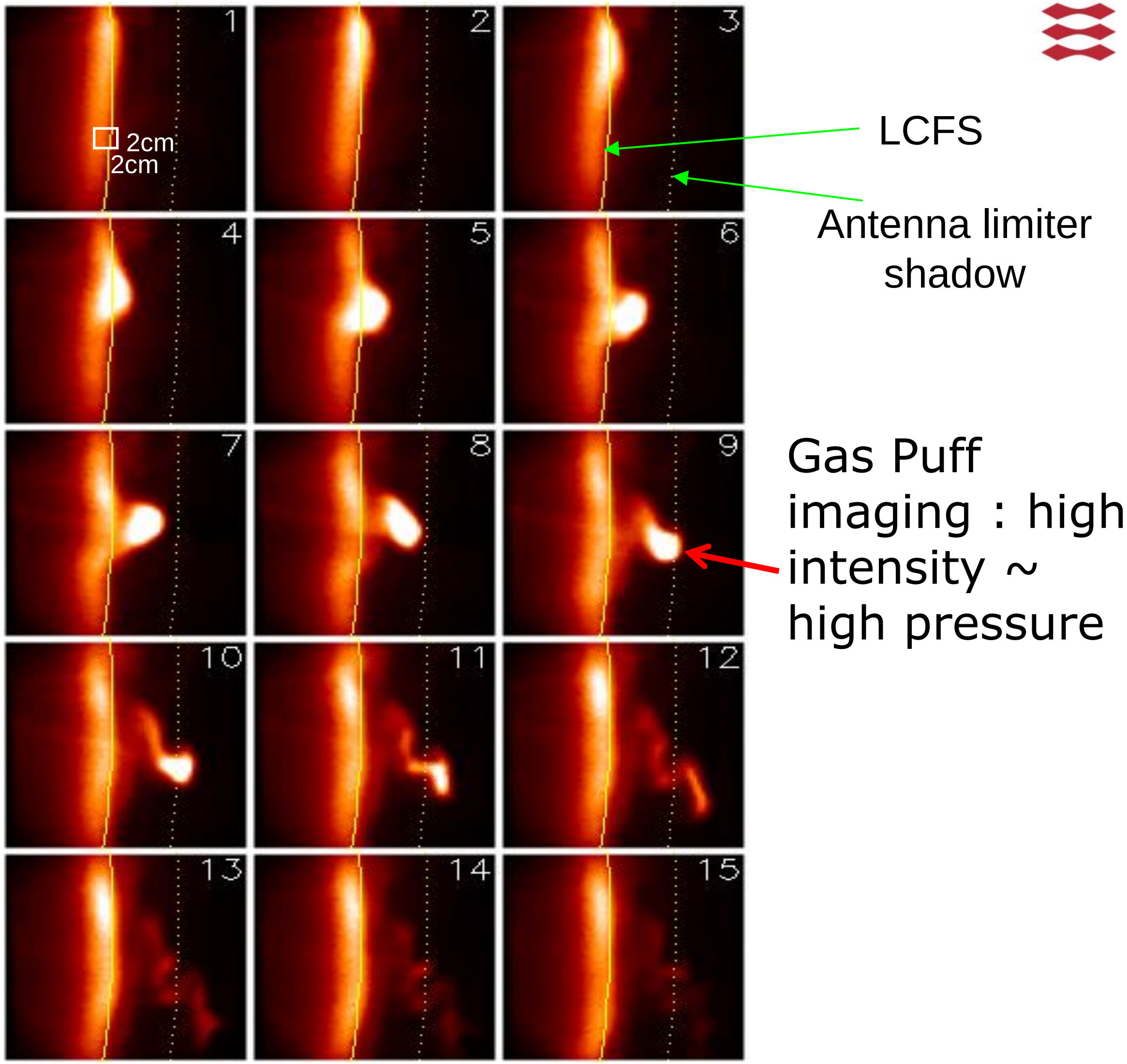
Plasma blobs – field aligned filaments - detaches from confinement region and propagate through the SOL

Zweben *et al.* Phys. Plasma **13**, 056114 (2006); PPCF **49**, S1 (2007).

D'Ippolito *et al*. Phys. Plasmas **18,** 060501 (2011)

Blob investigations in non-fusion devices, e.g., Torpex, Vineta

Theiler *et al.* PRL **103**, 065001 (2009); PoP **18**, 055901 (2011)

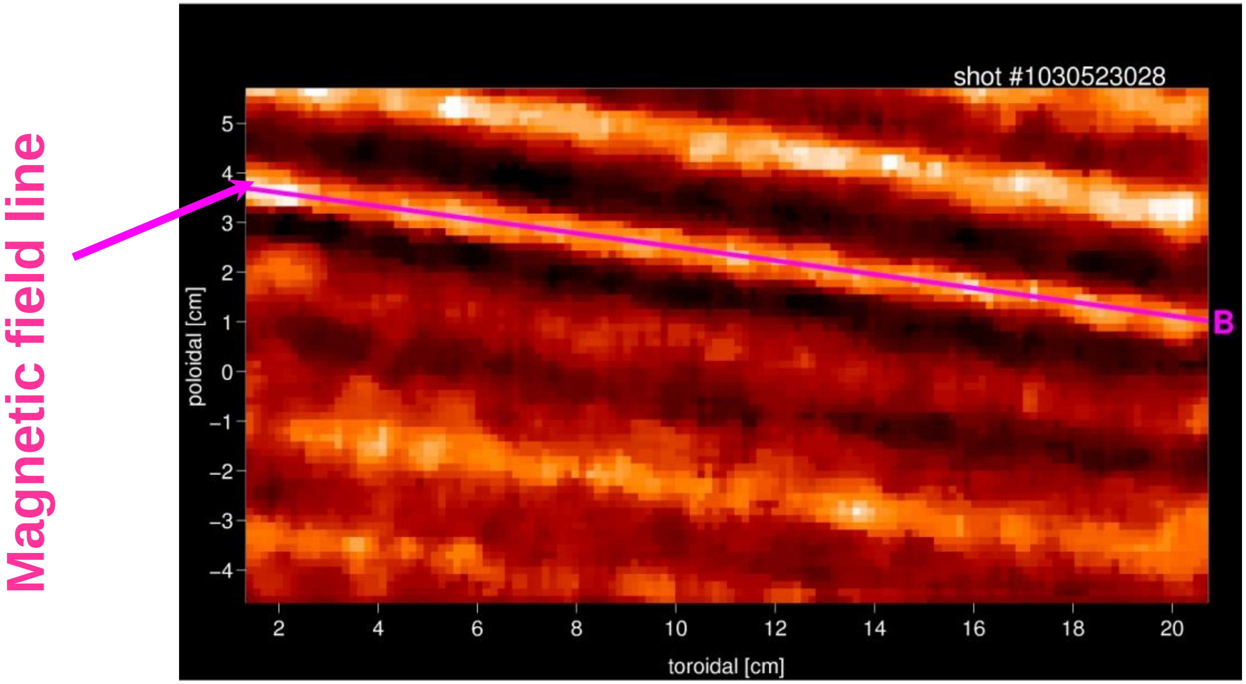


Shot 118152 **208.853 ms**

Maqueda *et al.* IEA Workshop Edge Transport in Fusion Plasmas, Sept. 11 – 13, 2006, Krakow, Poland

Blob: parallel structure: Filaments

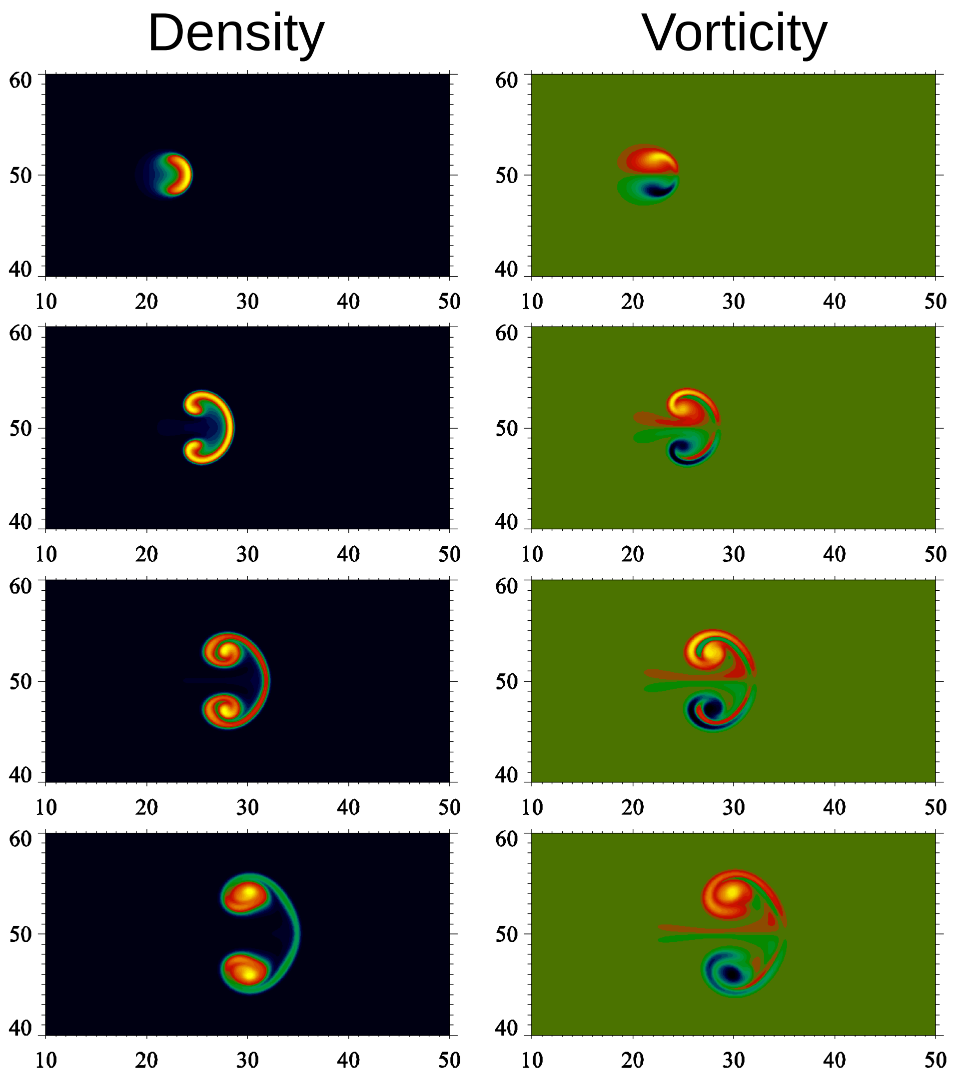
Blobs are filaments stretched long the magnetic field lines



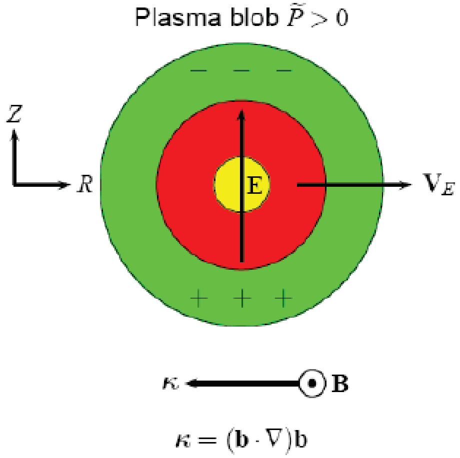
Grulke *et al* Phys. Plasma **13**, 012306 (2006).
Alcator C-Mod

Quasi 2D dynamics

Blob propagation – simple interchange model



Initially: density perturbation; flow arises by vertical charge polarization – Curvature drift.



Isolated blob/filament accelerates and propagates radially.
Eventually the blob decelerates and disperses

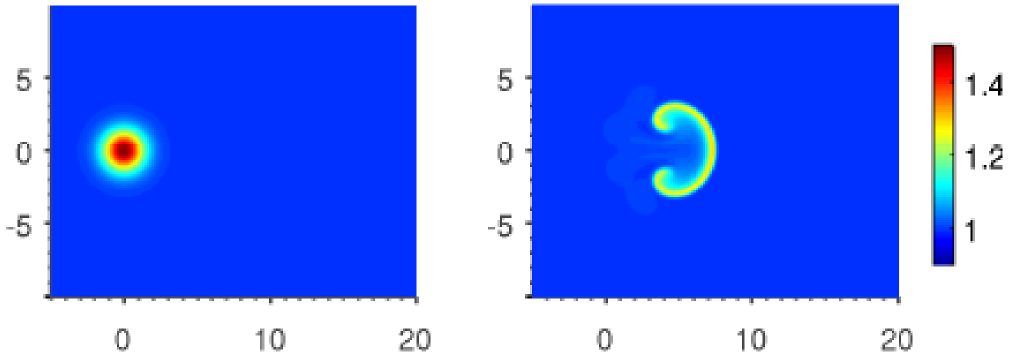
Garcia *et al.* Phys. Plasmas **12,** 090701 (2005); **13**, 082309 (2006)

Tokamak confinement!

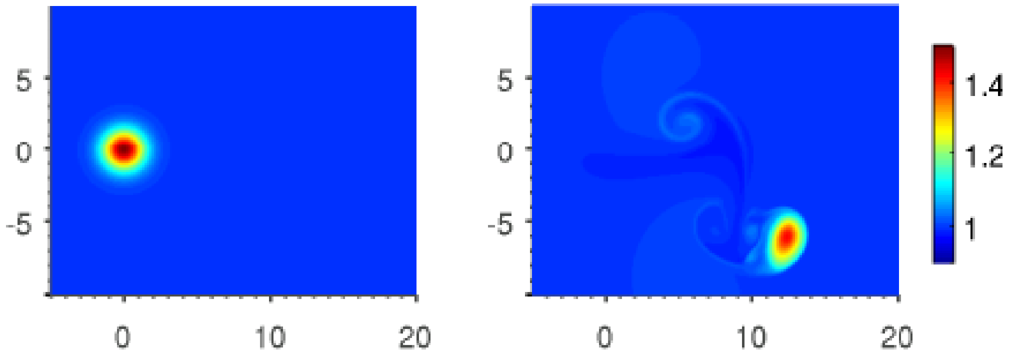
Finite ion temperature blobs

Gyro-fluid simulation of blob propagation – FLR effects

$T_i/T_e = 0$



$T_i/T_e = 3$



Propagation of density blob with finite ion temperature effects – compact density blob – like experiments. Further propagation...

Madsen *et al.* Phys. Plasma **18**, 112504 (2011)

Modelling of blobs in turbulence – ESEL

A self-consistent description of fluctuations and intermittent transport in the edge/SOL by employing the ESEL (Edge SOL Electrostatic) model for interchange dynamics.

2D model perpendicular to magnetic field – dynamics/losses along magnetic field are parameterized

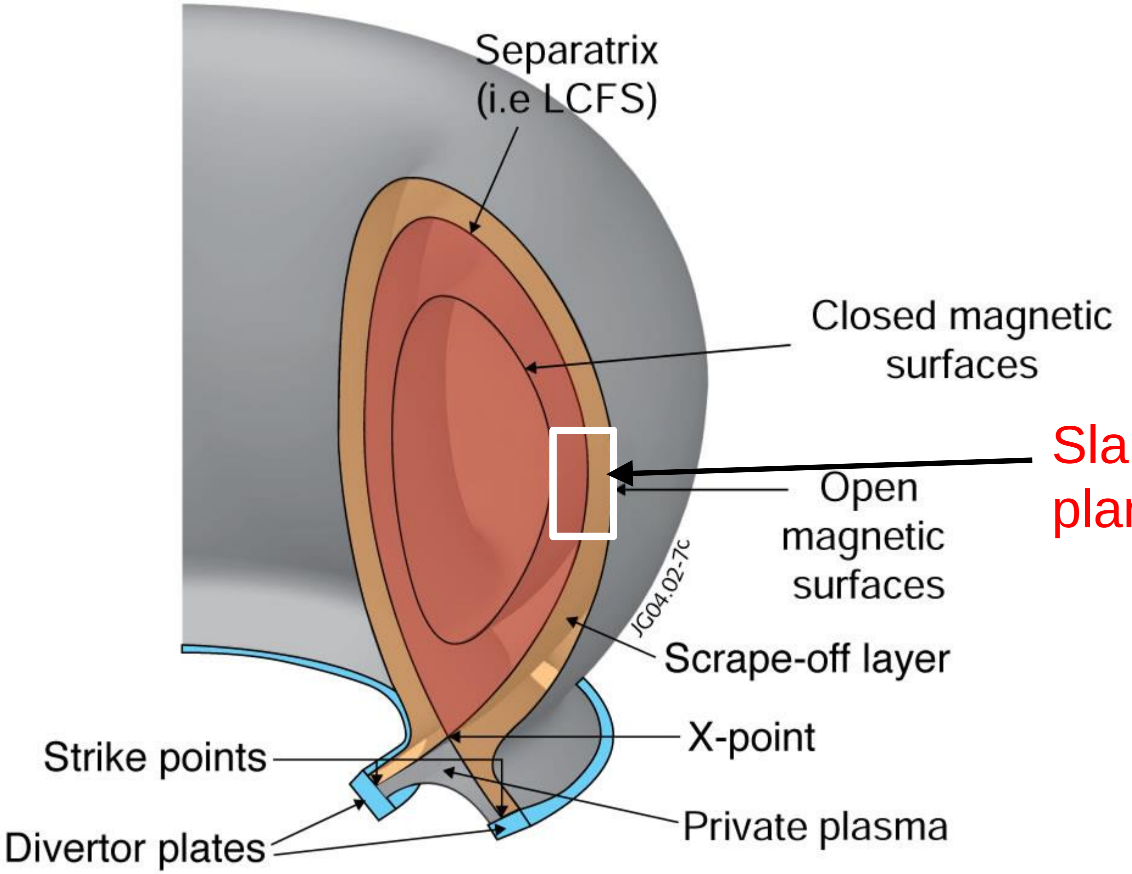
- includes separate plasma production ``edge'' and loss region ``SOL'',
- allows self-consistent flows and profile relaxations,
- profiles and fluctuations are **NOT** separated,
- conserves particles and energy in collective dynamics.

Results agree very well with experimental observations!

Being applied at several laboratories.

Garcia, Naulin, Nielsen, Rasmussen, PRL **92** 165003 (2004); Phys. Plasma **12**, 090701 (2005); Physica Scripta**T122**, 89 (2006).

Model domain: ESEL



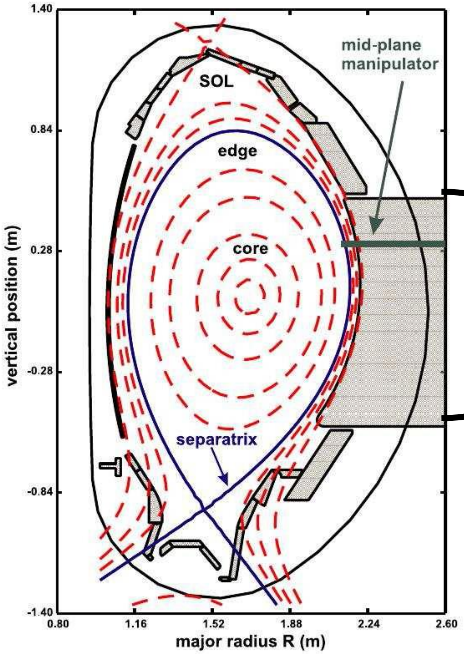
Slab domain at outboard mid-plane

- Local slab 2D geometry, (x,y)
- Including edge and SOL
- Global model with self-consistent profiles

HESEL model (Hot Edge SOL Electrostatic)
Parameterization of the parallel transport

Divertor

Flux tube in SOL

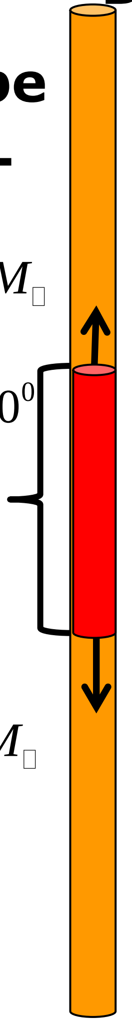


$V_{\parallel} = C_s M_{\parallel}$

Ballooning 60^0

$L_b \approx \frac{2\pi Rq}{6}$

$V_{\parallel} = C_s M_{\parallel}$



Divertor

$$\frac{\partial n}{\partial t} \approx -\frac{2C_s M_{\parallel}}{L_b} n \propto T_e^{1/2} n$$

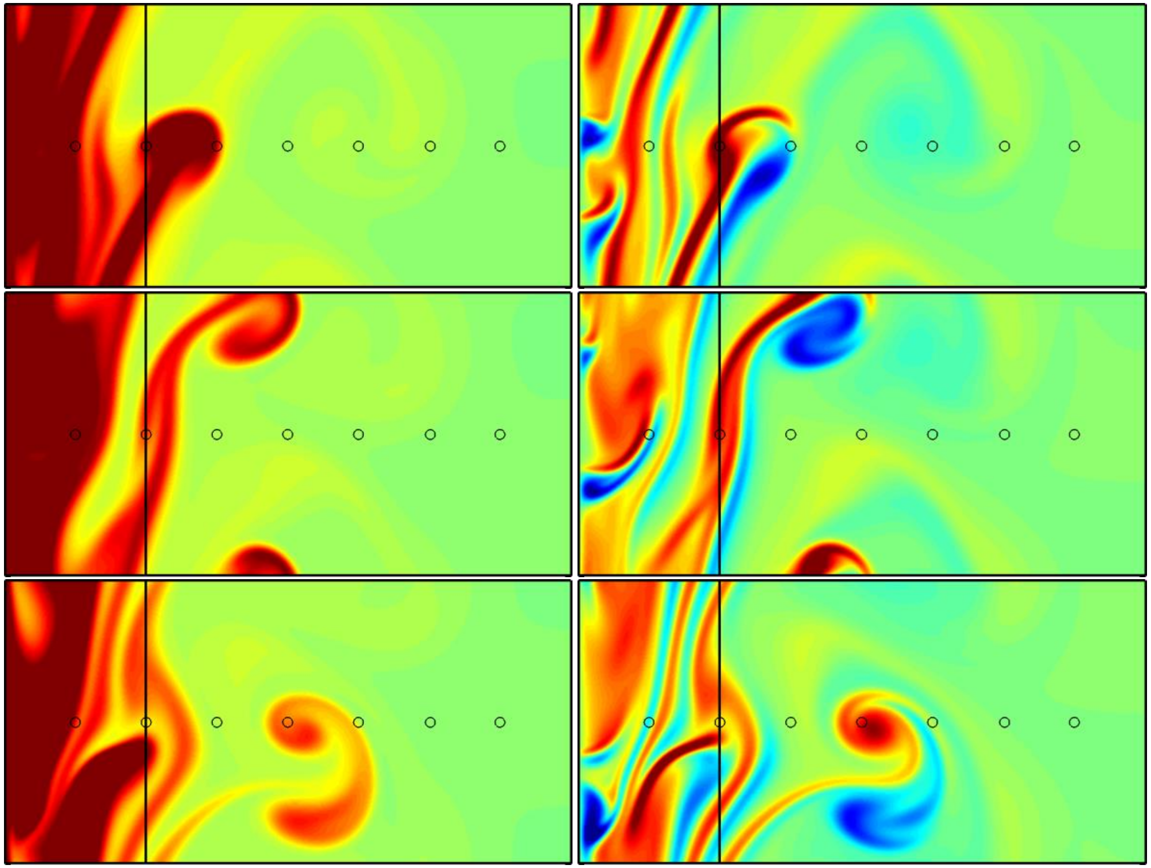
$$\frac{\partial P_i}{\partial t} \approx -\frac{9}{3}\frac{2C_s M_{\parallel}}{L_b} P_i \propto T_e^{1/2} P_i \text{ (adiabatic cooling)}$$

$$\frac{\partial p_e}{\partial t} \approx -\frac{2}{3}\frac{\chi_{\parallel e}^{SH}}{L_p^2} p_e \propto \frac{T_e^{5/3}}{n} p_e \text{ (fast electrons)}$$

$$\frac{\partial \omega^*}{\partial t} \approx -\frac{2C_s M_{\parallel}}{L_b}\omega^* + \frac{2C_s \langle n \rangle}{L_p \omega_{ci}}\left(1 - \exp\left[\frac{\Phi_b - \langle \phi \rangle}{\langle T_e \rangle}\right]\right)$$

$\langle f \rangle$ = time average radial profile of f

Spatial structure during burst - developing blob structure

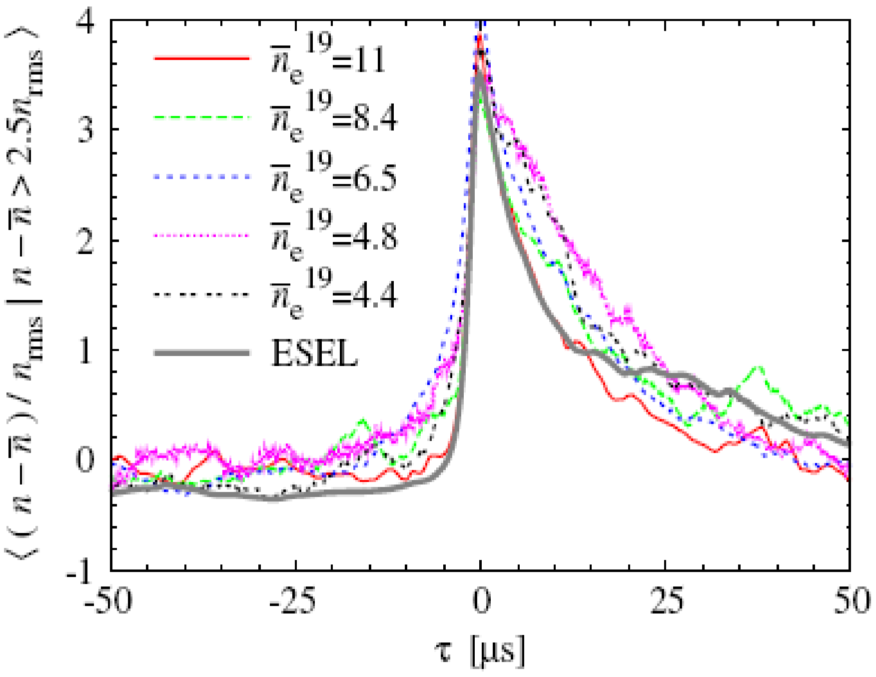


Particle density (left) and vorticity (right) during a burst ($\Delta t = 500$)

Blob like-structure in plasma density and dipole structure in vorticity

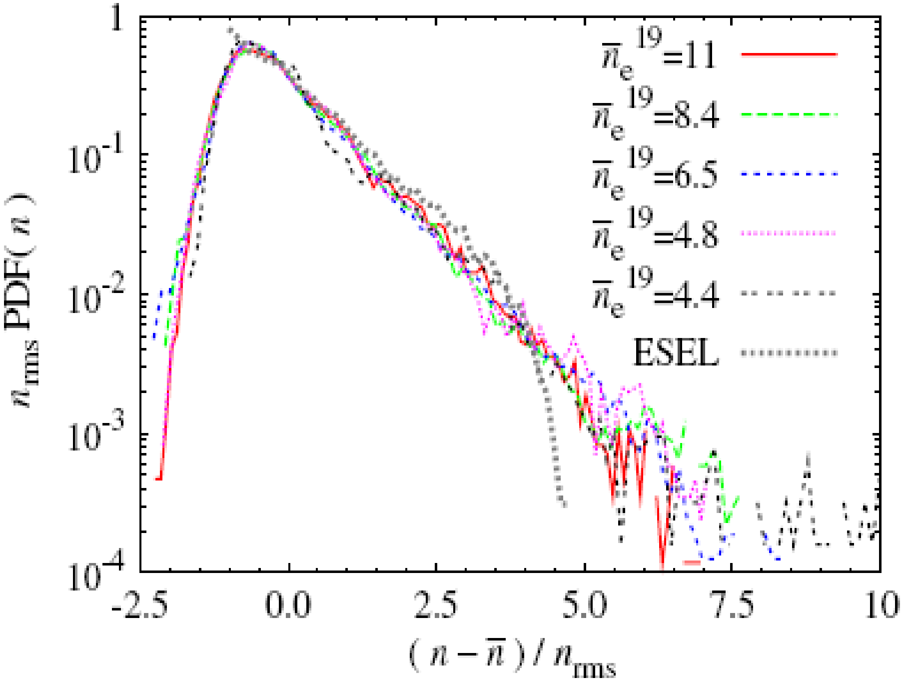
Density fluctuations statistics and wave form

Direct comparison with experimental results from the TCV-Tokamak, EPFL: quantitative agreement



Conditionally averaged density wave form in far SOL

Characteristics of blob propagation



Rescaled PDFs of density fluctuations in far SOL

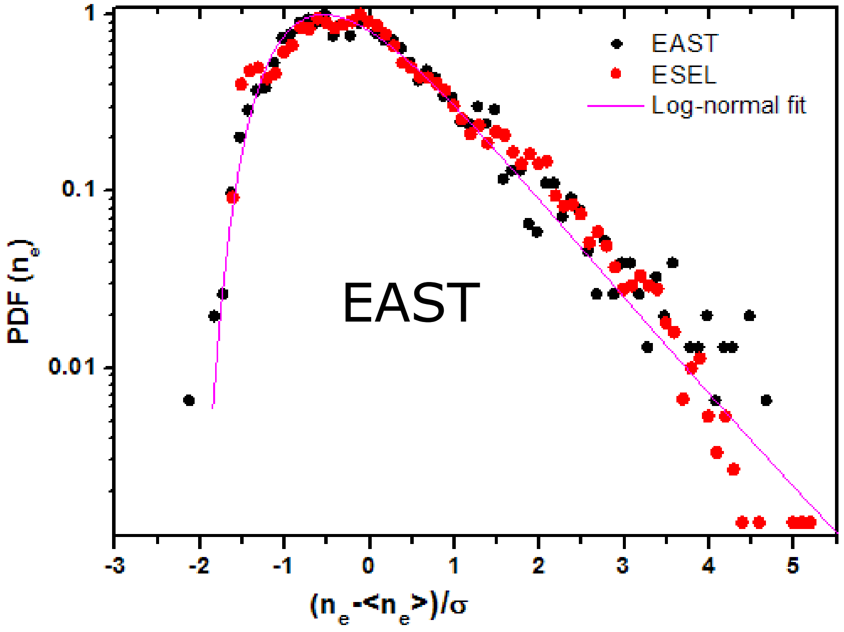
Skewed to the positive side.

Garcia *et al.* PPCF **48**, L1 (2006); Nucl. Fusion **47,** 667 (2007)

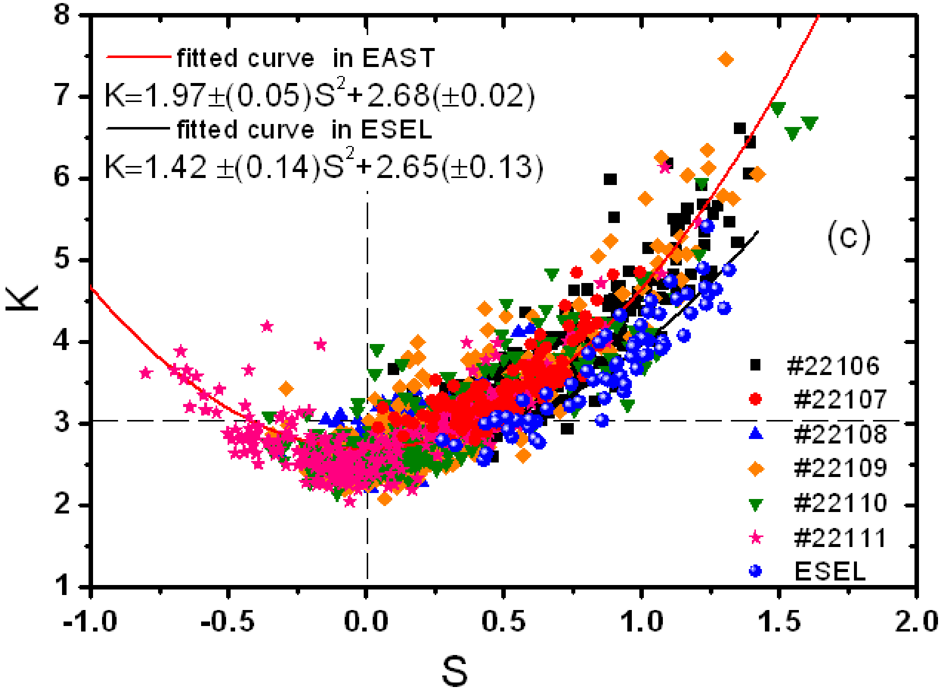
Density fluctuation statistics

Similar statistics for a broad range of devices (mainly Tokamaks)

$$S = \frac{(n-\mu)^3}{\sigma^3}, \quad K = \frac{(n-\mu)^4}{\sigma^4}$$



Yan *et al* PPCF **55**, 115007 (2013)



$K = aS^2 + b$,

S: Skewness, *K:* Kurtosis – signature of a Gamma distribution

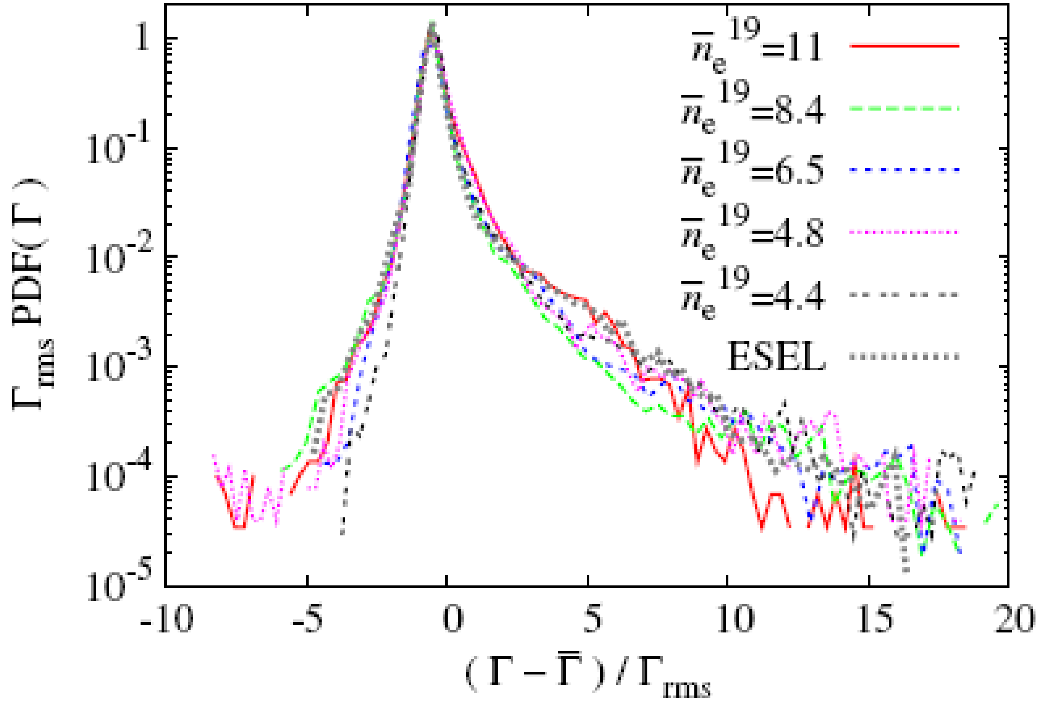
(Gaussian: S=0, K=3)

Found in several cases – different diagnostics, e.g.,

Sattin *et al* PPCF ***51***, 055013 (2009);

Garcia *et al.* PoP **20**, 055901 (2013)

Particle Transport statistics



Particle density flux:

$\Gamma = n\, v_x = n\, v_{ExB}$

Rescaled PDF of particle flux in far SOL at TCV Tokamak. Almost independent of n_e.

Flux dominated by strong bursts and agreement with simulation results.

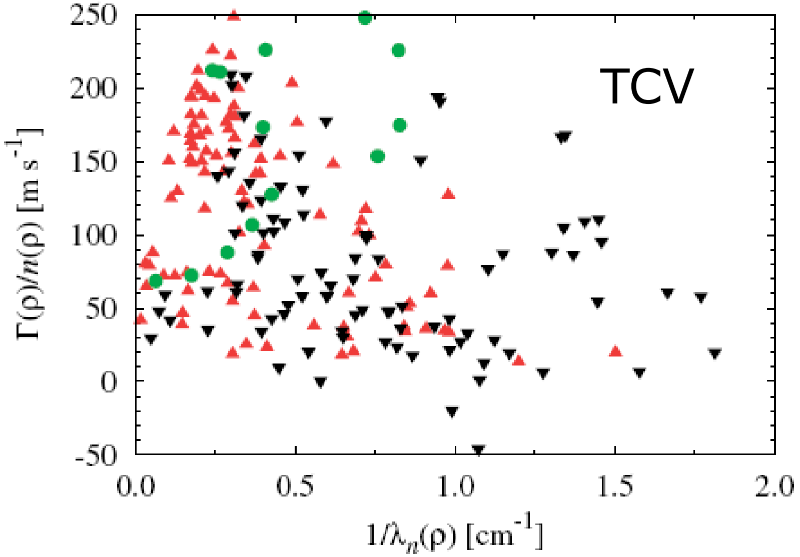
Exponential tail -- mean value only contains very limited information

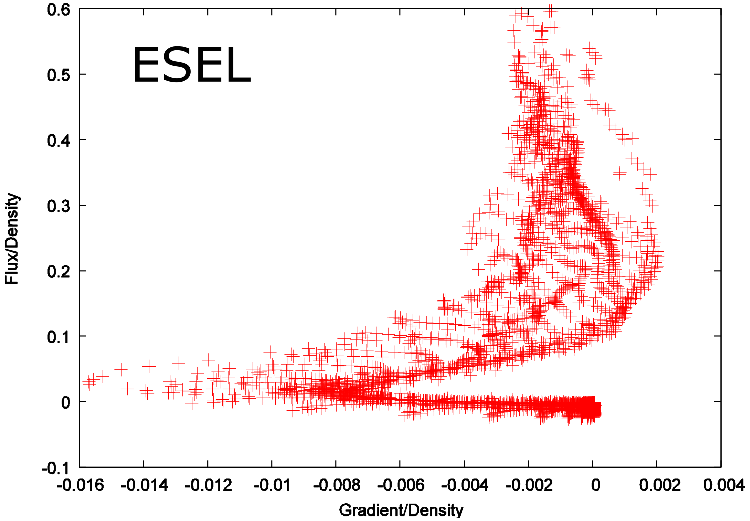
Transport is NOT diffusive! No simple parameterization in terms of an effective diffusivity and a convection velocity

Garcia *et al.*, Nucl. Fusion **47,** 667 (2007)

Parametrization of SOL fluxes?

Scatter plot for the flux-gradient relation.





Garcia *et al.*, J. Nucl. Mater. 263-265, 575 (2007)

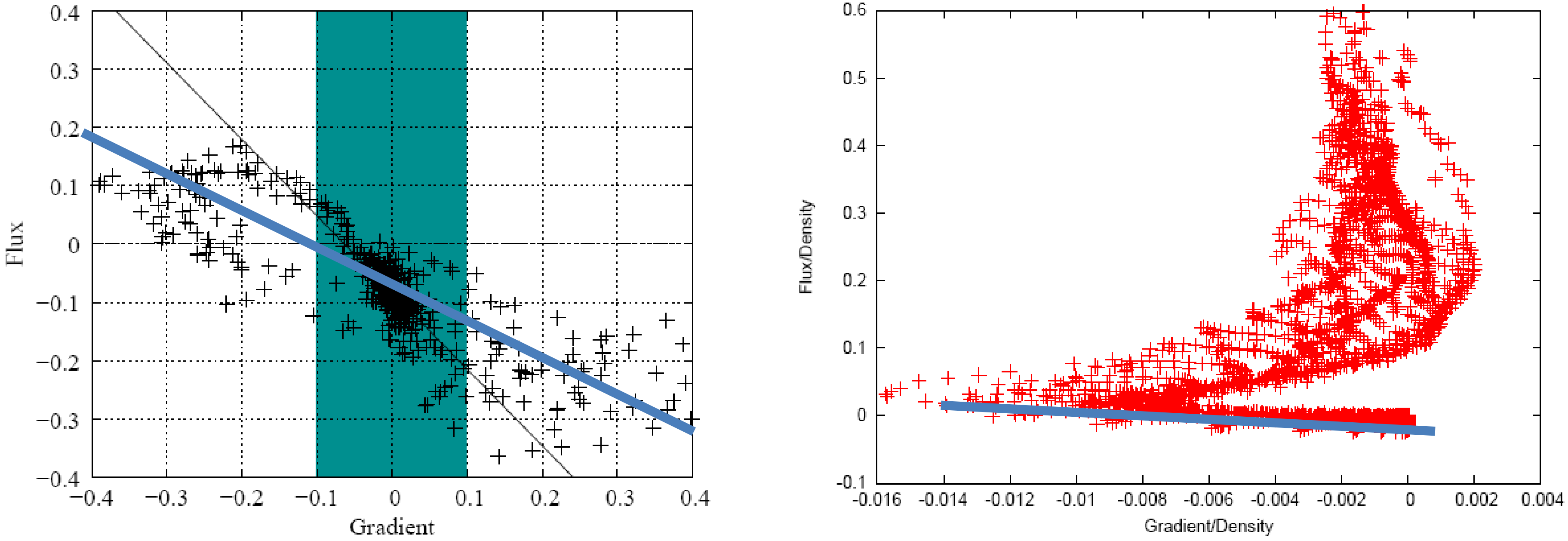
Naulin, J. Nucl. Mater. 263-265, 24 (2007)

Transport modelling: linear combination of convection and diffusion:

$$\Gamma = nV_{\text{eff}} - D_{\text{eff}}\frac{\partial n}{\partial r} \quad \Rightarrow \quad \frac{\Gamma}{n} = V_{\text{eff}} - D_{\text{eff}}\frac{1}{n}\frac{\partial n}{\partial r}.$$

Transport **cannot** be parameterized by an effective diffusivity and a convection velocity: It is **non-local** and **non-diffusive**

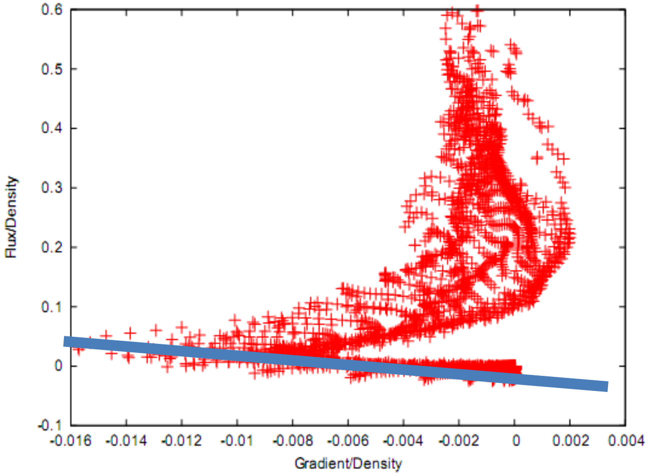
SOL Transport is not diffusive



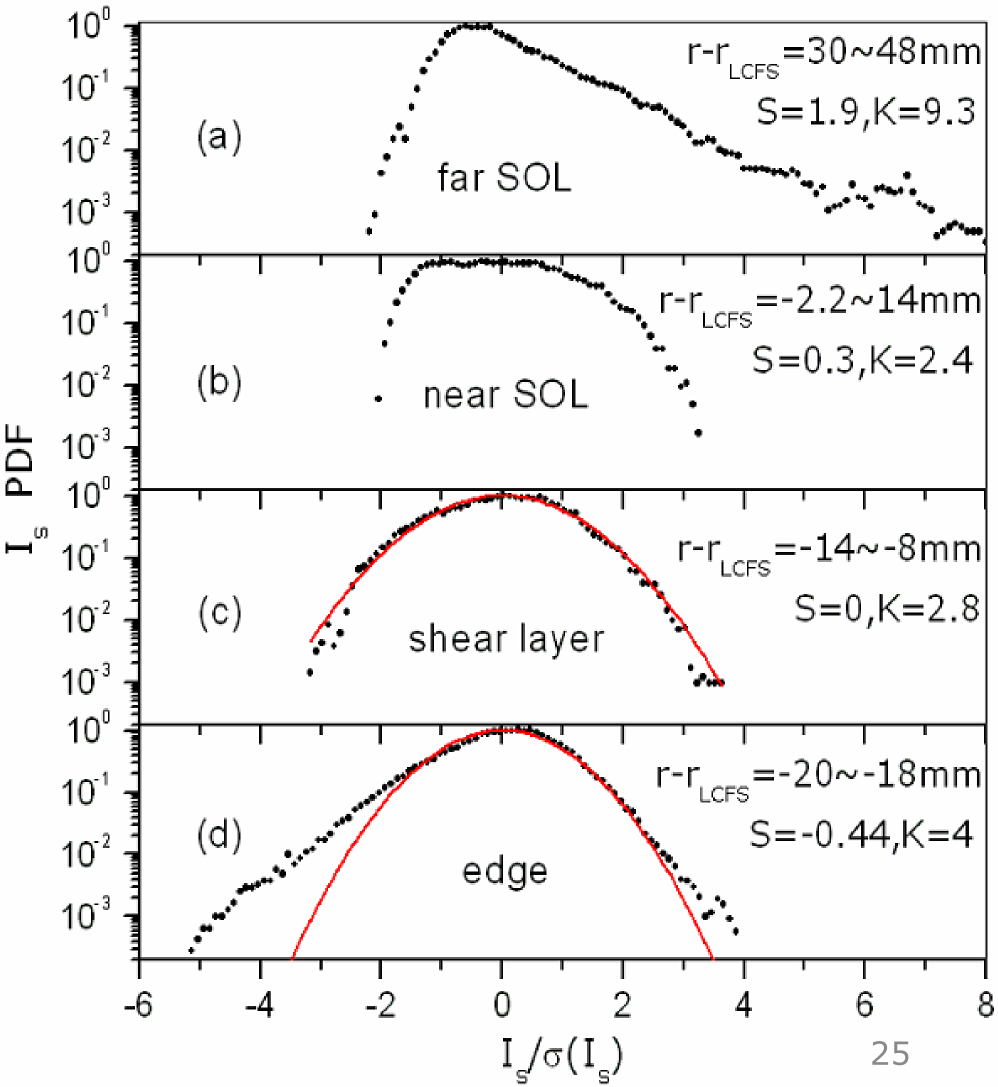
Flux gradient plots from fluctuation based turbulence model (TYR, left) and from global model of the edge/SOL interaction (ESEL, right), showing large transport events at small gradient (blobs) [Naulin, JNM, 2007 , Plasma Surface Interaction, Hefei, 2006].

Flux is not related to how steep the slope is. WHY??? **Non-locality**

Transport in the SOL: Nonlocal, non Fickian, universal



Xu et al. 2009, JET



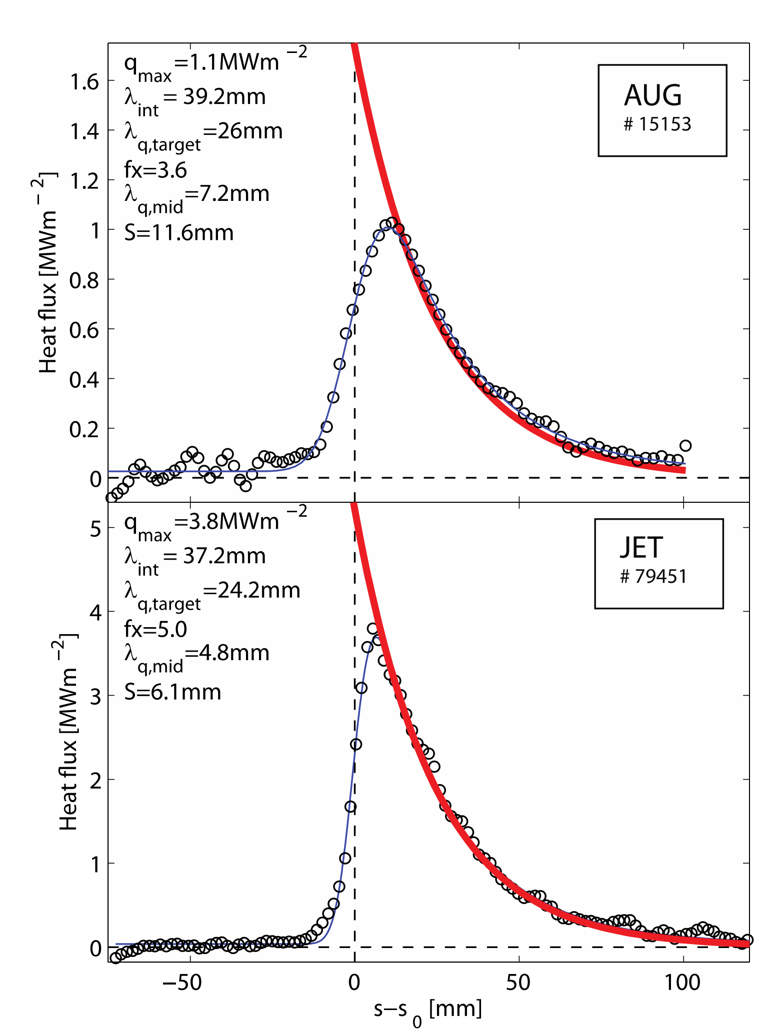
- Flux in SOL does not depend on local slope
- Ficks law does not apply $\Gamma = -D\nabla\theta + V\theta$
- **Structures/turbulence generated at shear layer**

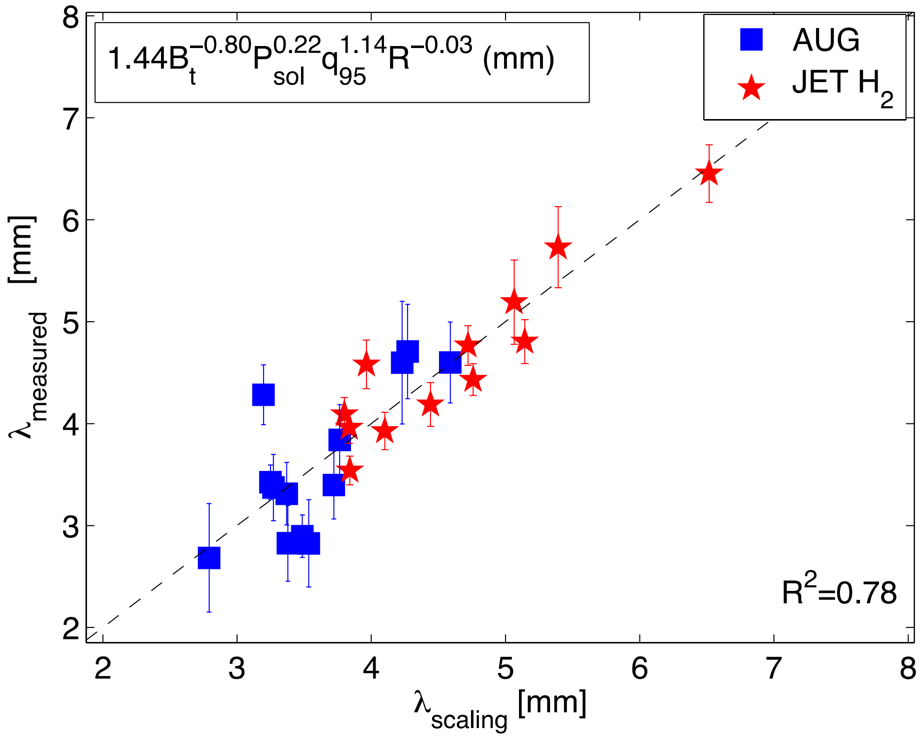
What do we mean by.....

- Non-local
  - Transport at location R is **not** a function of gradients, temperature, density etc. **AT** location R
  - Water flow downstream does not depend on local conditions....
- Non-diffusive
  - Relation gradient-flux is broken
  - Non-locality ONE possible reason

Scale SOL width for L-Mode plasmas

1. L-Mode scaling similar to H-Mode with larger constant
2. L-Mode λ_q for ITER 3.7mm when using P_{sol} = 50MW



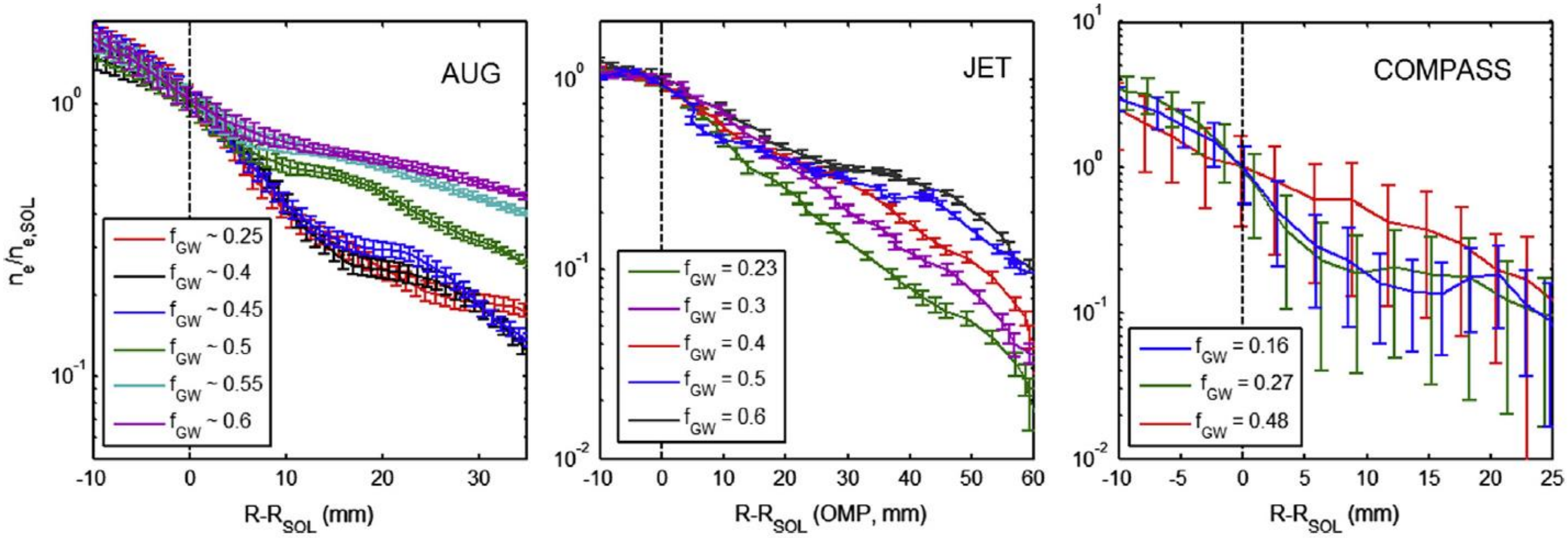


$$\lambda_q = 0.72 \times B_{tor}^{-0.70} \times P_{SOL}^{0.10} \times q_{95}^{1.01} \times R_{geo}^{0.06}$$

H-Mode scaling from JET/D3D/AUG

Density profile AUG, JET, Compass

Carralero *et al.* JNM **463**, 123 (2015)



$$f_{GW} = n_c/n_{GW} \qquad n_{GW} \sim I_p/\pi a^2$$

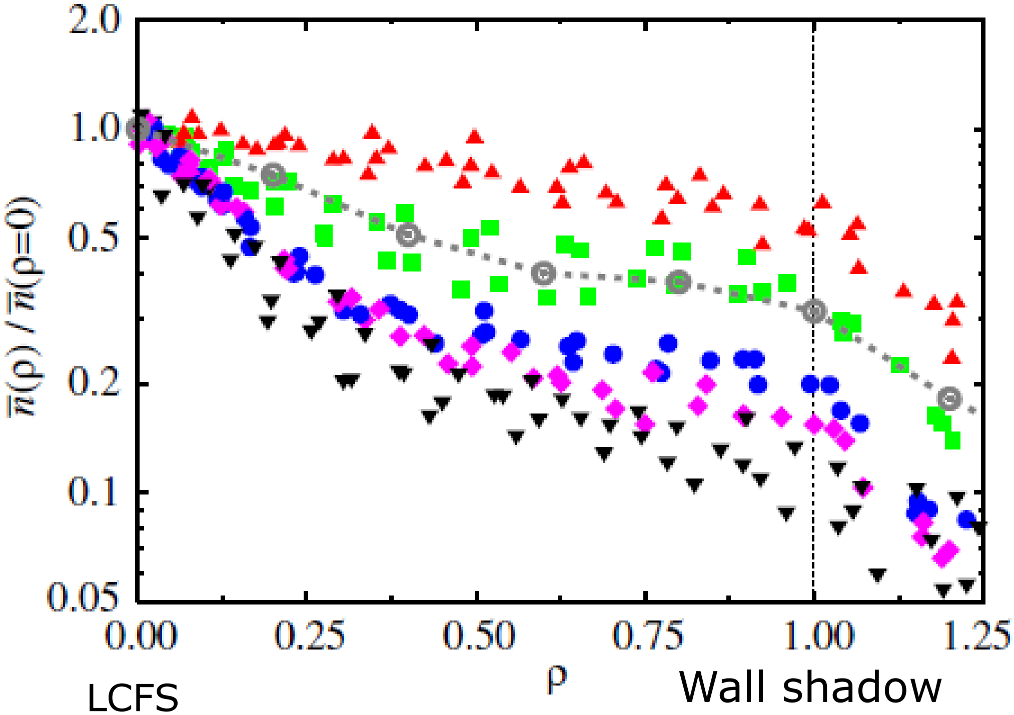
$$\Lambda = \frac{L_{\parallel}/c_s}{1/\nu_{ei}} \frac{\Omega_i}{\Omega_e} \simeq \frac{\tau_{\parallel}}{\tau_{ie}}$$

Myra *et al.* PoP **13** 112502 (2006)

$\Lambda < 1$ Sheath limited regime – blobs decay

$\Lambda > 1$ Inertial regime – detached conditions blobs penetrate to the wall – **broad deposition profile** on the divertor target

Density profile vs line averaged density -



LCFS

Wall shadow

TCV

$\bar{n}_e$ (10^{19} m^{-3})	Symbol	$f_{GW} = \bar{n}/n_{GW}$
11	▲	0,6
8.4	■	0.49
6.5	●	0.38
4.8	◆	0.28
4.4	▼	0.25
—	○	

ESEL simulations

Garcia *et al.* Nucl. Fus. **47**, 667 (2007)

Profile broadens with increasing plasma density (length scale and extent)

Flat profile - “shoulder” - at high density : strong plasma-wall interactions

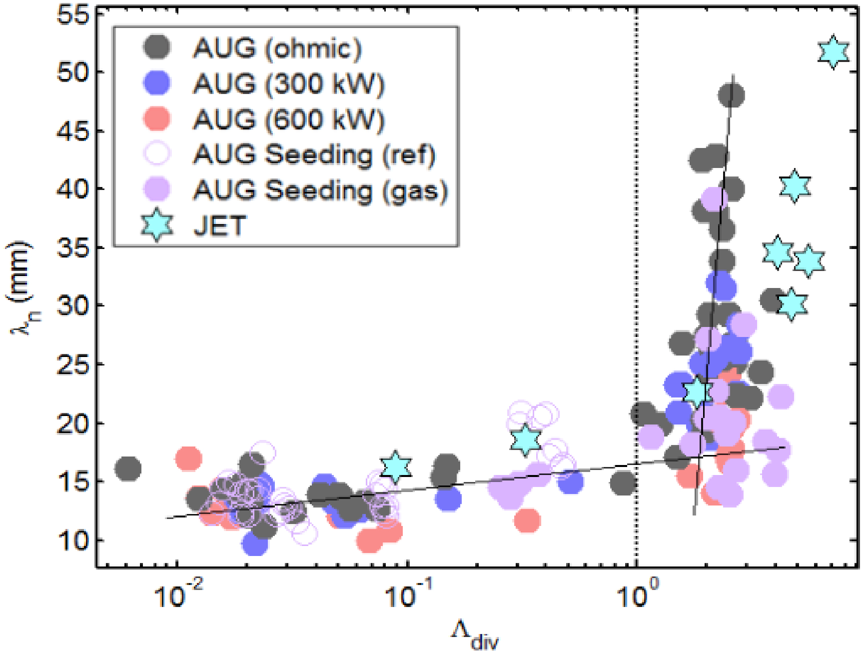
Simulations in quantitative agreement with high density case

Generic feature – Alcator C-mod LaBombard et al. PoP 8, 2107 (2001)

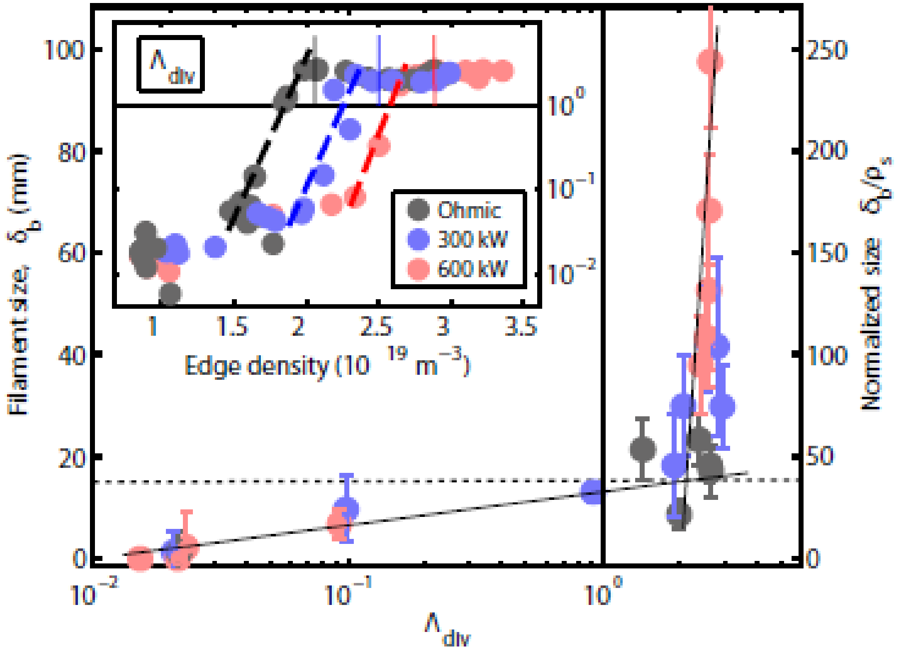
DIII-D Rudakov et al Nucl. Fus. 45, 1589 (2005)

Details from AUG and JET – L-mode

Carallero *et al*. PRL **115,** 215002 (2015)



Density scale length



Blob size

$$\Lambda = \frac{L_{\|}/c_s}{1/\nu_{ei}}\frac{\Omega_i}{\Omega_e} \simeq \frac{\tau_{\|}}{\tau_{ei}} \quad \sim n\, T_e^{-2}$$

Λ_{div} determined from divertor parameters

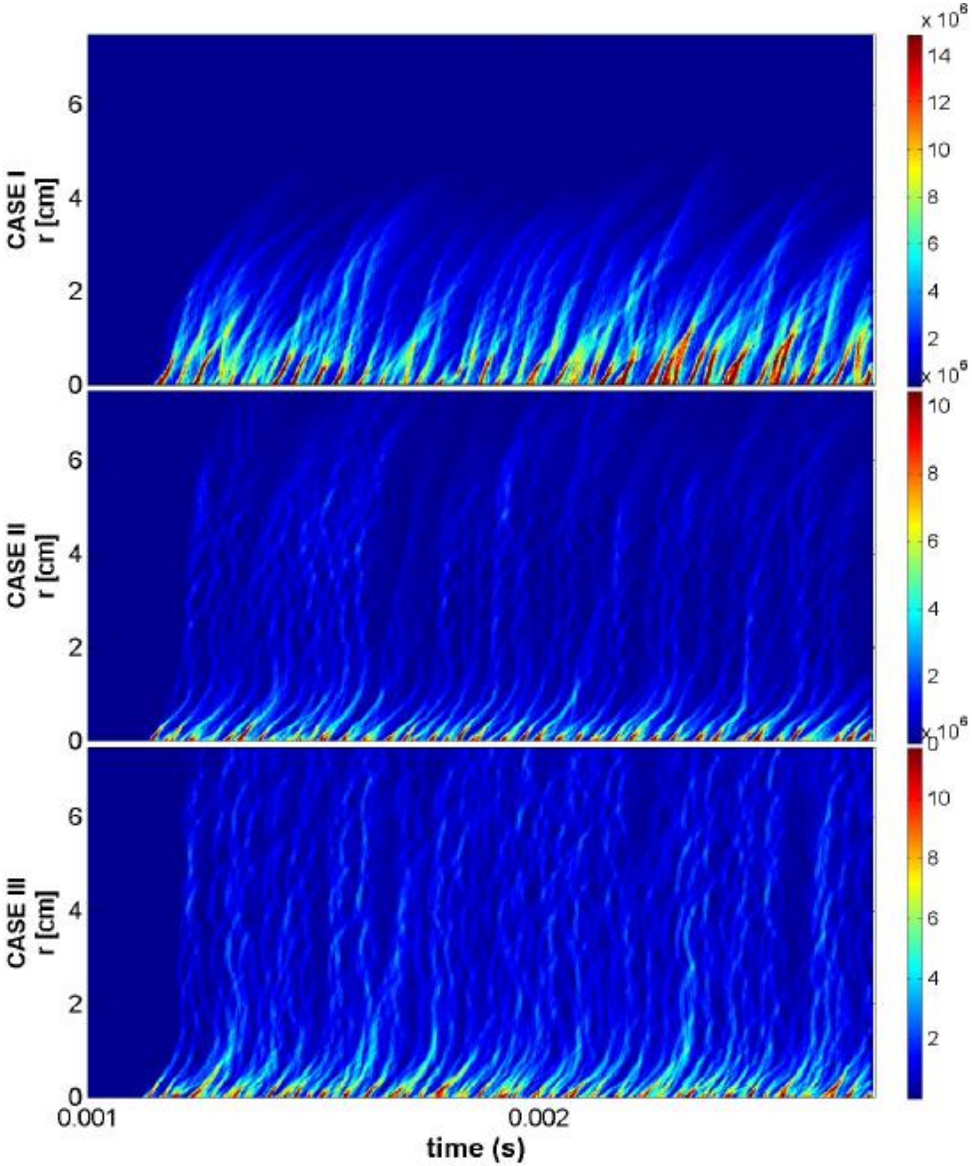
Changed by changing heating power---

The shoulder formation appears to be related to detachment - but

detachment seems not to be a necessary condition but a sufficient condition?

Power deposition at the limiter

Projected power deposition to the limiter from the mid-plane profile – simulations HESEL model (hot ions)



"Detached"

Broader power deposition profiles at higher density

Well documented for L-mode plasma – Low confinement mode

- **Good news for the divertor – larger wetted area**
- **Bad news for the first wall and the PFC – increased wall load and wall recycling**

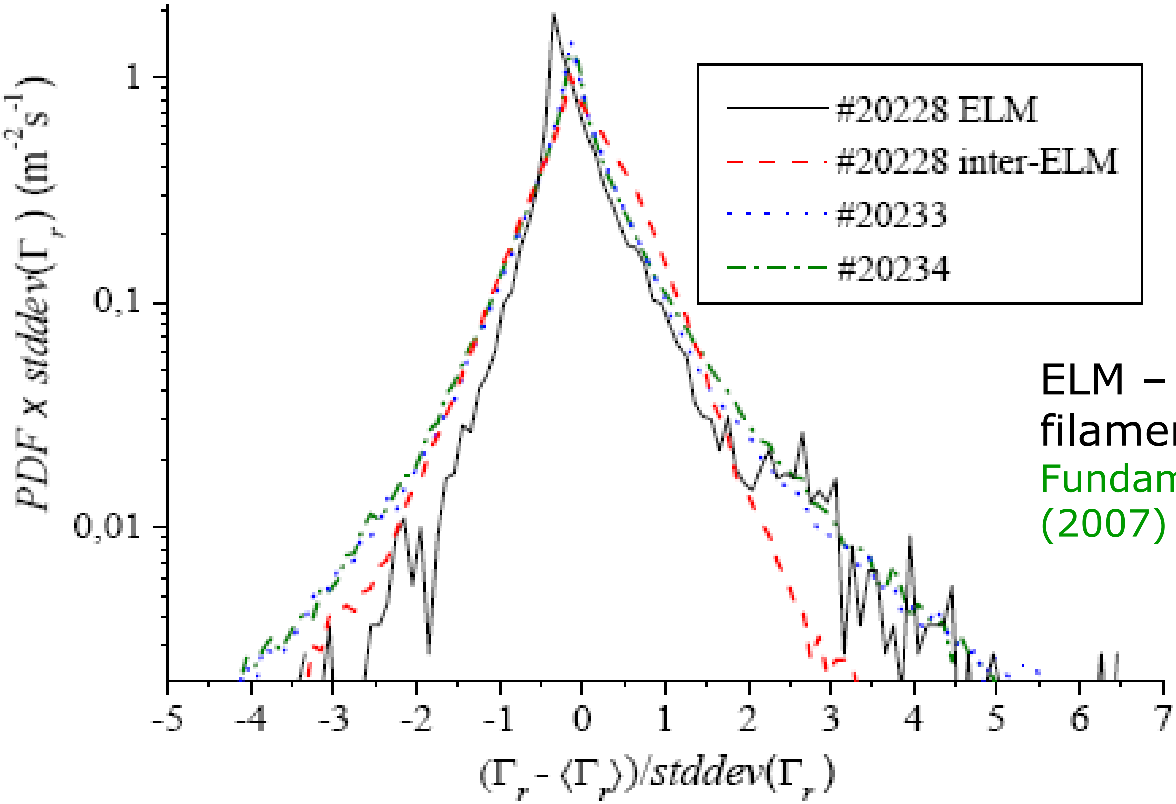
But what happens in the H-mode – High confinement region?

H-mode is the operation regime for ITER to reach the goals of power output with Q = 10.

Similar investigations are in progress under the EUROfusion programme for the H-mode in
ASDEX Upgrade and TCV!

Similar behaviour may be expected – similar fluctuation characteristics

Particle density flux, Γ, in H- and L-mode - AUG



ELM – Edge localized mode with filamentary structures

Fundamenski et al PPCF 49, R43 (2007)

Renormalized PDF of Γ in far SOL, for H-mode, during ELM activities, in between ELM activities and in two L-mode cases.

Similar statistics: during ELMs, in between ELMs and in L-mode (blobs)

Ionita *et al.* Nucl. Fus. **53** 043021 (2013)

Summary

- The plasma conditions in the edge/SOL determines overall plasma performance.
- Transport of particles and energy in the SOL is dominated by large-amplitude, radially propagating blob-like structures of enhanced pressure.
- Blob structures give rise to localized power loads on plasma facing components.
- The pressure profile in the SOL widens with increasing density.
- Strong demands on the materials
- sets engineering limits to power plant operation.
- For ITER, events with power loads of several tens of MW/m^2 are expected and control will be essential.

How is Plasma created???

Plasma is a bird in a magnetic cage

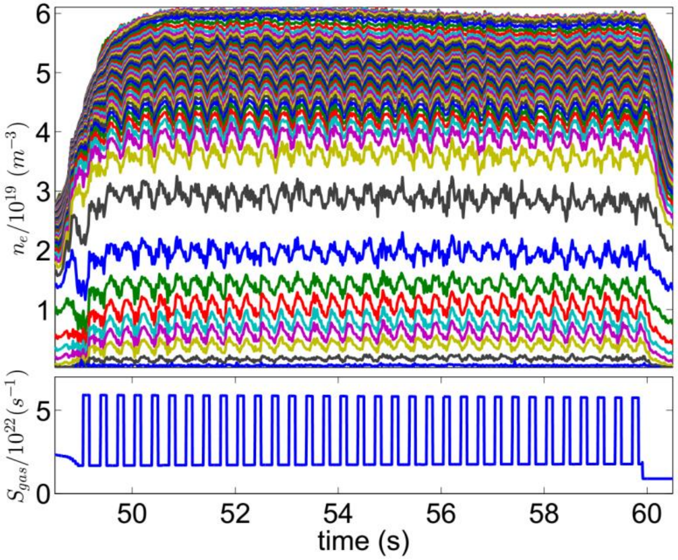
Birds cannot enter the cage

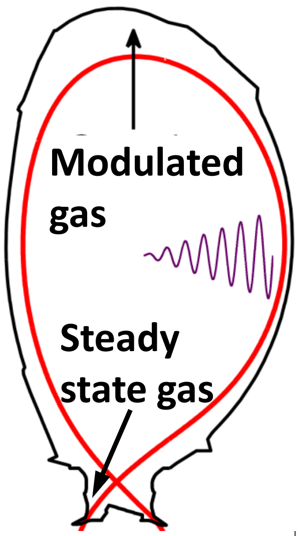
Ionisation needs to be inside the cage

For ITER parameters more and more gas is ionised already in the SOL, outside the cage

How do we fuel ITER?????

JET experiments with gas modulation





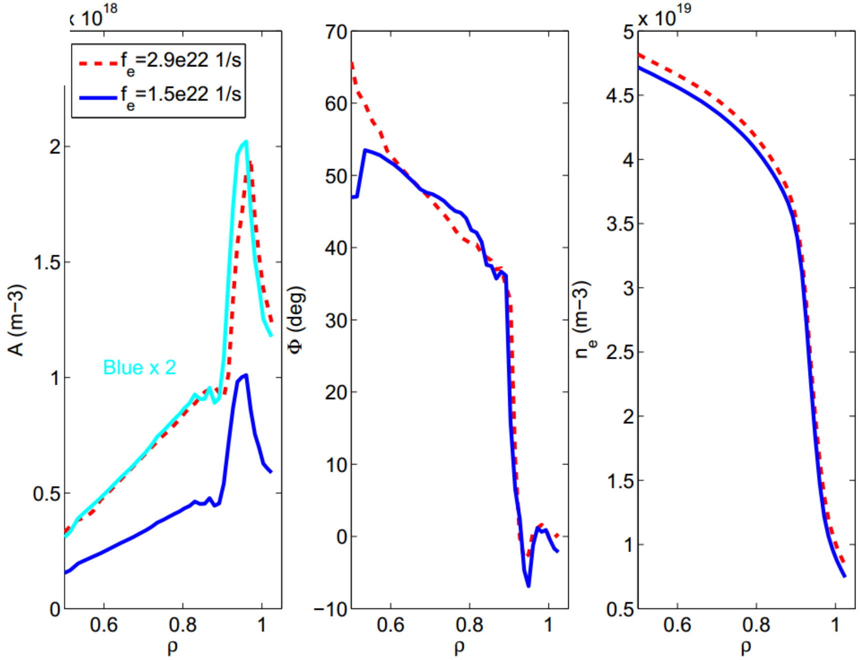
Modulated gas

Steady state gas

- 3 Hz gas modulation from top of the machine
- Study the inward propagation of the electron density wave

- Measured density modulation is doubled with doubled gas injection while the propagation speed is unaffected

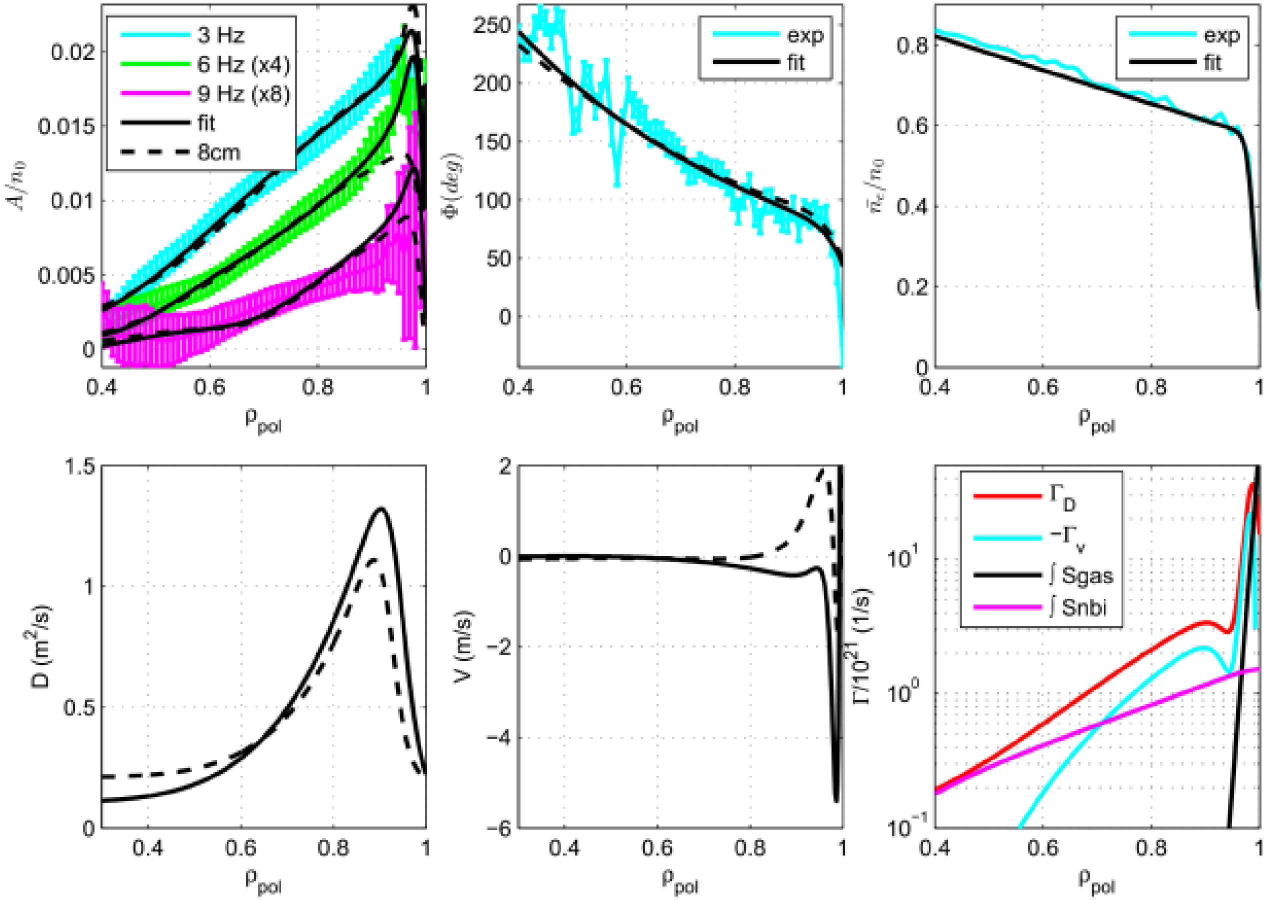
➔ Linear response verified



Experimental D and V from optimisation

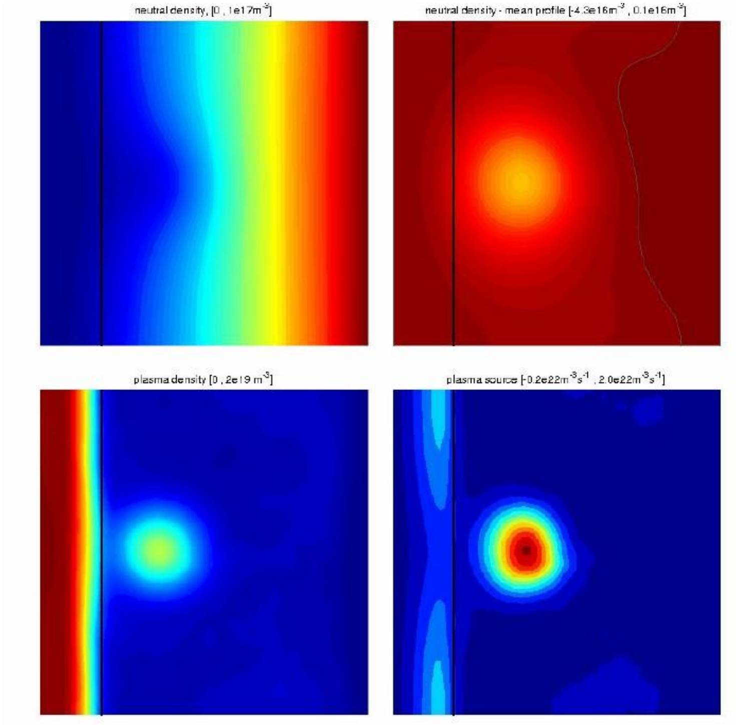
- Reflectometer used for amplitude profiles and Thompson Scattering for phase profile
  - Unfortunately only one shot with sufficient HRTS statistics

- Optimisation prefers narrow cold neutral source profile with inward pinch
  - Fixed source width (8cm) leads to poor fit in especially the 6 Hz amplitude near the edge
- Small core transport means that density peaking is mainly due to NBI fuelling
  - Caveat: one shot



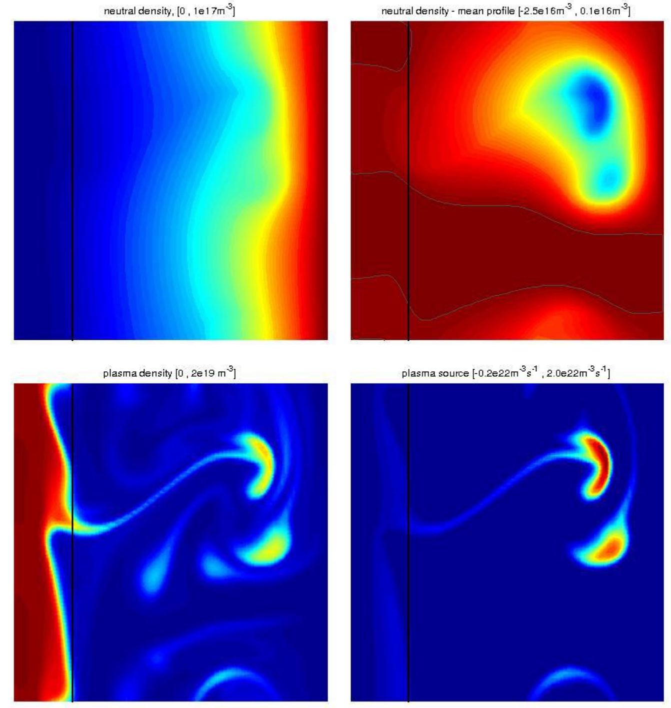
Blobs interacting with neutrals

Neutral gas - background



Plasma Plasma source

Neutral gas - background



Plasma Plasma source

Impact ionization and charge exchange

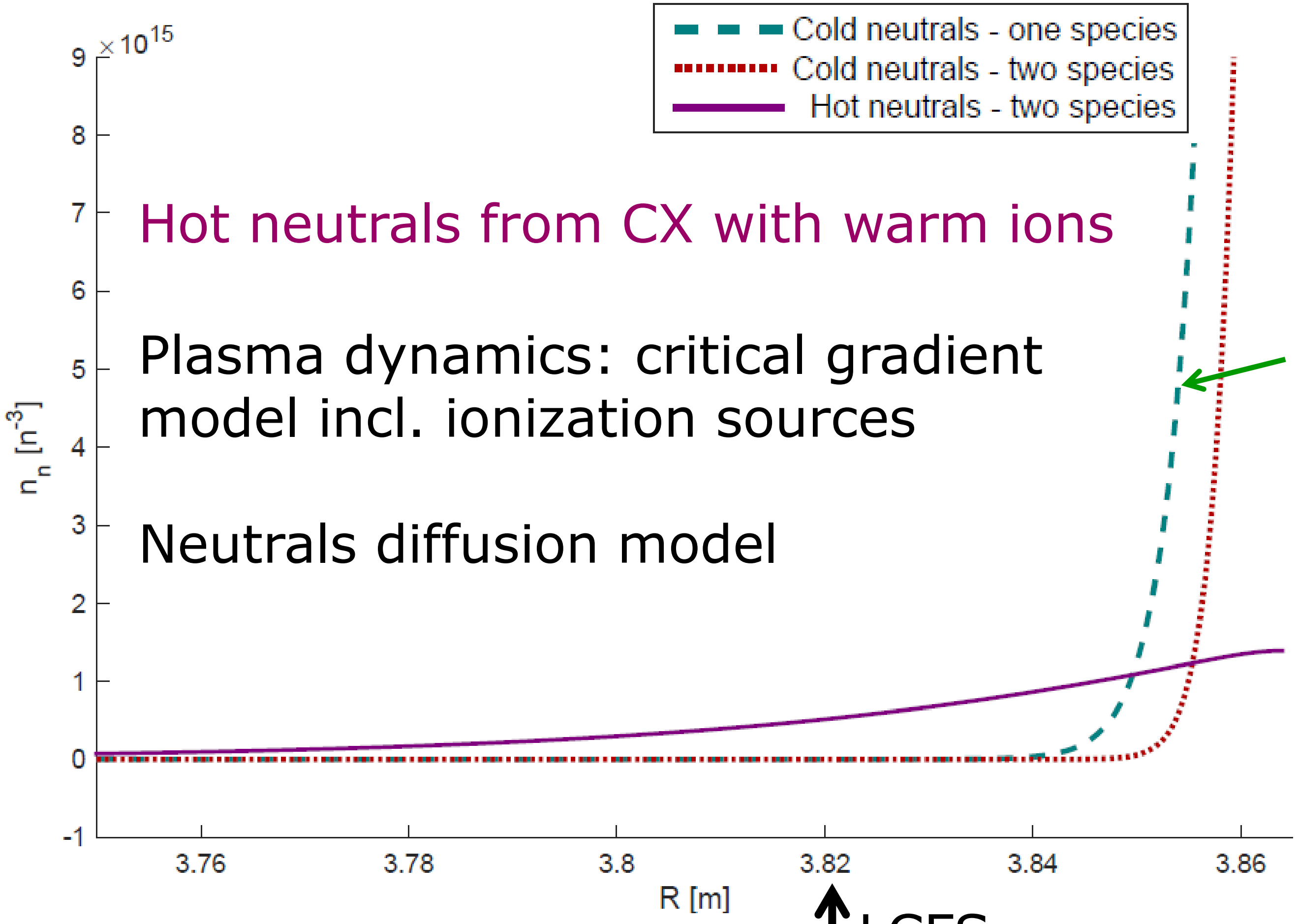
Blob evolution: HESEL model coupled with neutrals

Neutral gas dynamics: diffusion-convection equation

Significant ionization by transient blobs

Plasma gas puff fuelling

Initial results



Hot neutrals from CX with warm ions

Plasma dynamics: critical gradient model incl. ionization sources

Neutrals diffusion model

Impact ionization

↑LCFS

Hot neutrals enhance fuelling

A.S. Christensen *et al.* EPS 2015 P1.167

L-H transition

Modelling:

- **Based on "predator-prey" paradigm** á la Kim & Diamond PRL 2003, PoP 2003
  - **0D:** *Malkov and Diamond PoP 2009, Dam et al. PoP 2013 …*
  - **1D:** *Miki et al. PoP 2012, Wu et al. NF 2015, Malkov et al. PoP 2015…* – heuristic models, qualitative descriptions
- **Fluid simulations:** *Drake et al. PRL 1998; Xu et al. PoP 2000; Thyagaraya et al. PoP 2010; Chone et al. PoP 2014 …* demonstrate L-H transition in particularly the formation of the edge transport barrier – no detailed scaling and comparisons with experiments.

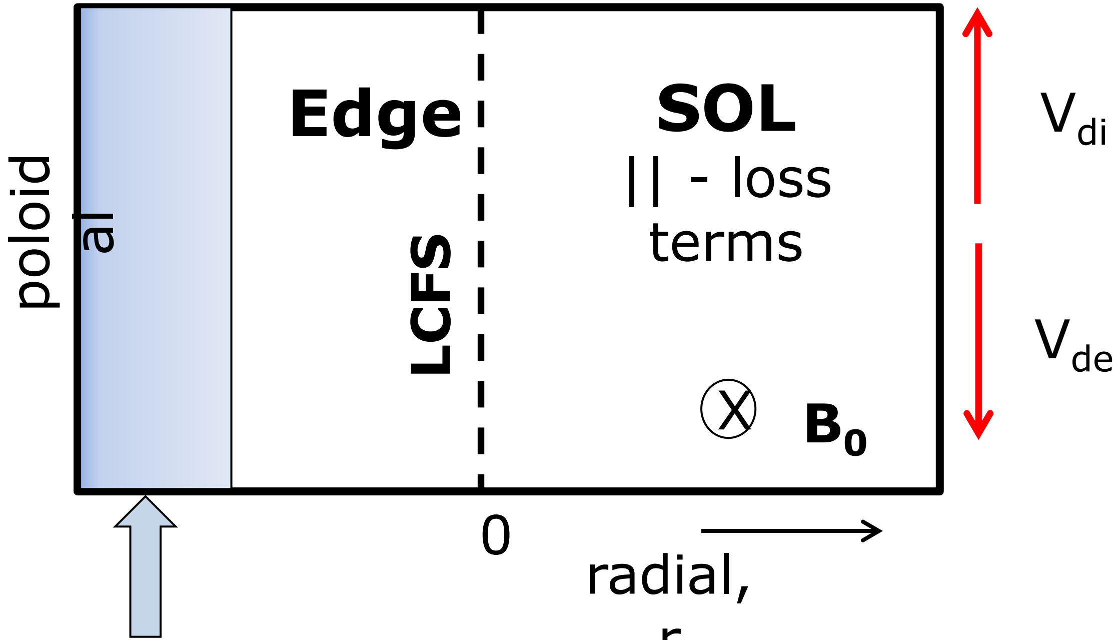
Experiments:

- **Recently experimental progress** – advanced diagnostics: e.g., *Xu et al. PRL 2011, NF 2014; Schmitz et al. PRL 2012; Cheng et al. PRL 2013; Kobayashi et al. PRL 2013; Cziegler et al. PPCF 2014; Ryter et al. NF 2014; Estrada et al. NF 2015 ….*

Reference list far from complete – just few typical references --

Set-up and parameters

- Slab geometry at outboard mid-plane
- Flux driven - interchange turbulence



Parameters:

Typical conditions
EAST (#41362):
$n_0 = 1.5\ 10^{19}\ m^{-3}$ @LCFS
$T_{e0} = 20$ eV @LCFS
$T_{i0} = 20$ eV @LCFS
$B_0 = 2.0$ T ; $q_{95} = 4.0$
$R = 2.0$ m ; $a = 0.5$ m
$\Delta_{SOL} = 2.4$ cm

Wide parameter regime

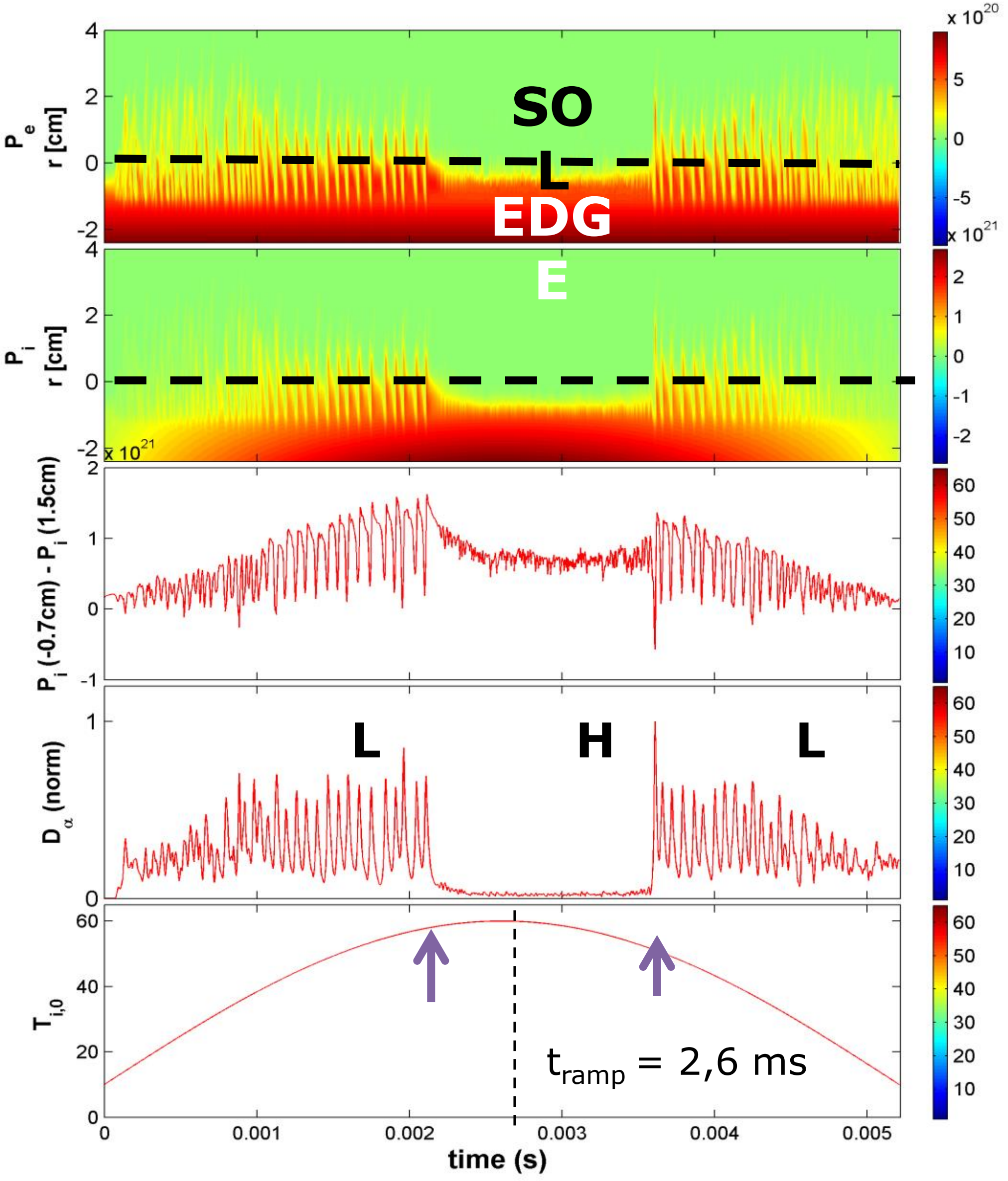
Neo-classical transport and parallel damping rate coefficients calculated from plasma parameters @LCFS

Prescribed profiles – driving the fluxes

Ramp up of T_i profile part to increase the fluxes

Parameters updated consistently

L-H-L transition



Electron pressure profile

Ion pressure profile

Ion pressure difference across LCFS

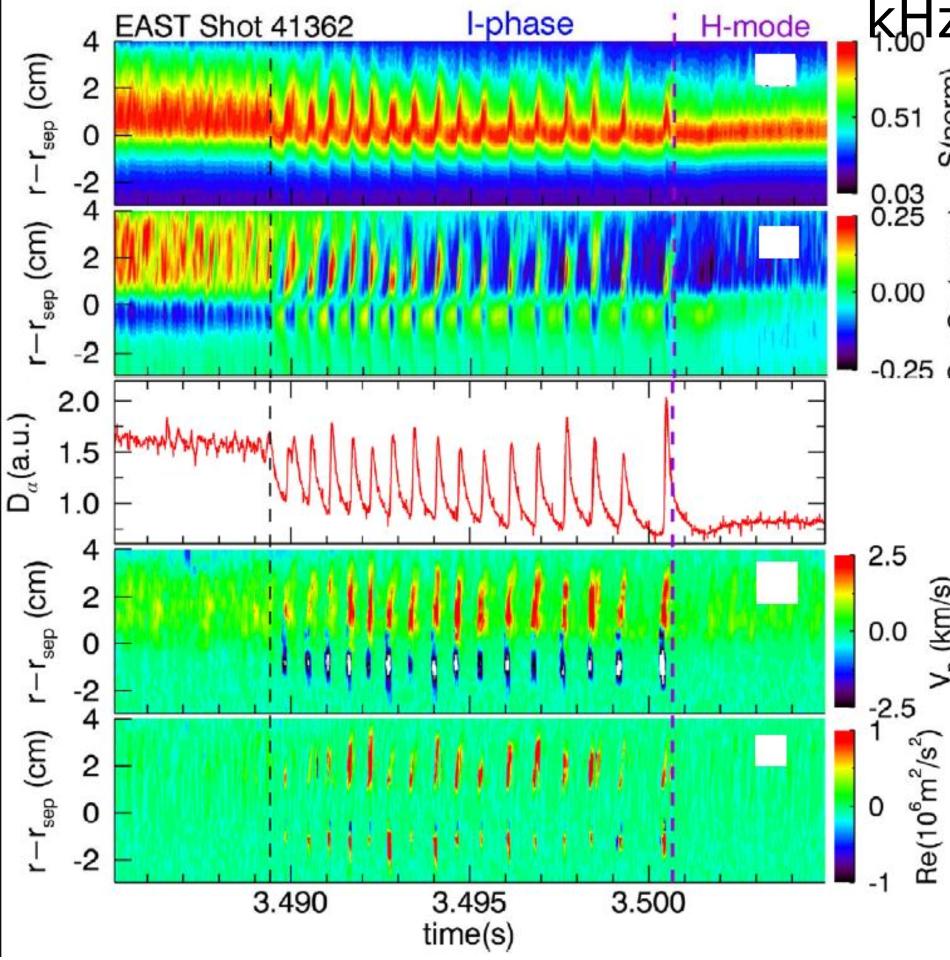
Integrated || energy flux @ outboard mid-plane – proxy for D_α

Power input: ion temperature ramp-up - increase of ion heat flux

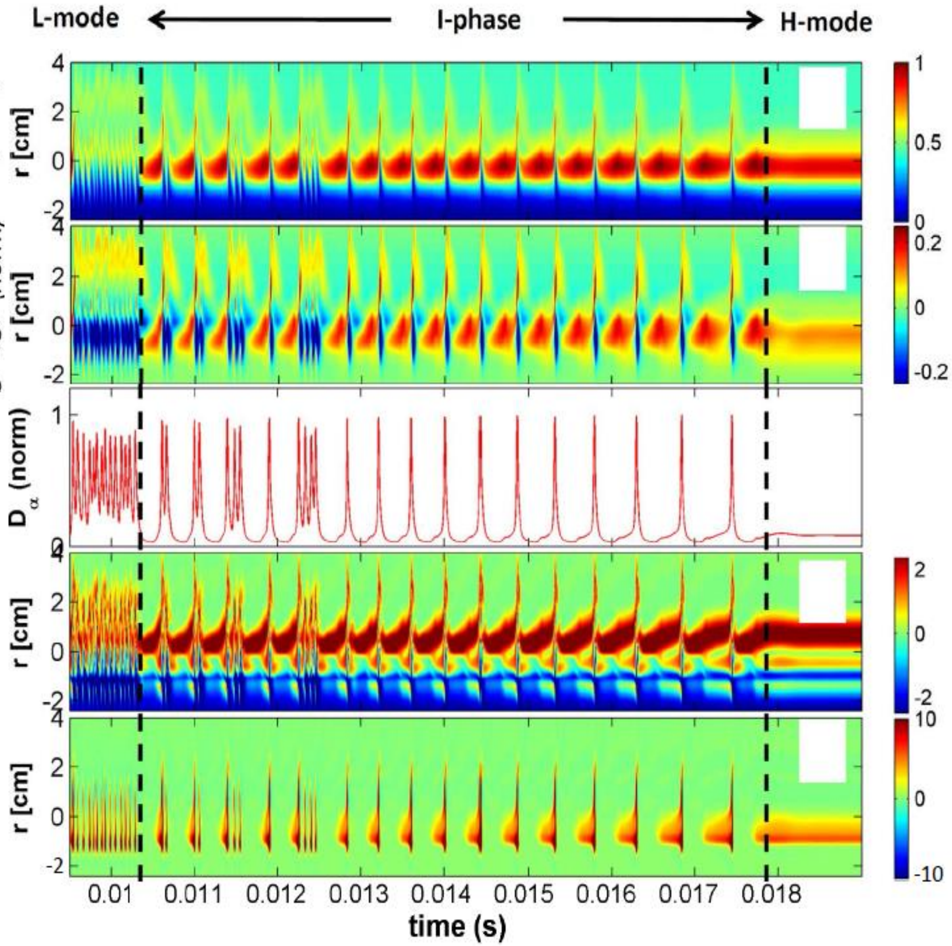
L–I–H at EAST and in HESEL

EAST

f_{osc}~1.5 kHz



HESEL



Gas puff imaging GPI – HeI line

Synthetic GPI in HESEL provides S

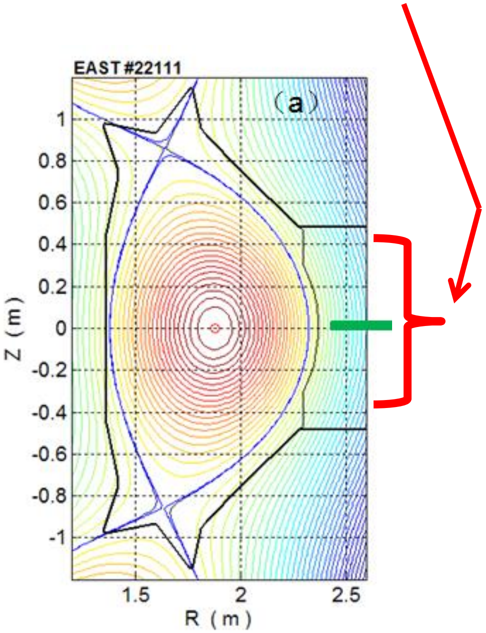
Xu et al. NF 2014; Nielsen et al. arXiv:1409.3186

S is emission intensity, HeI line

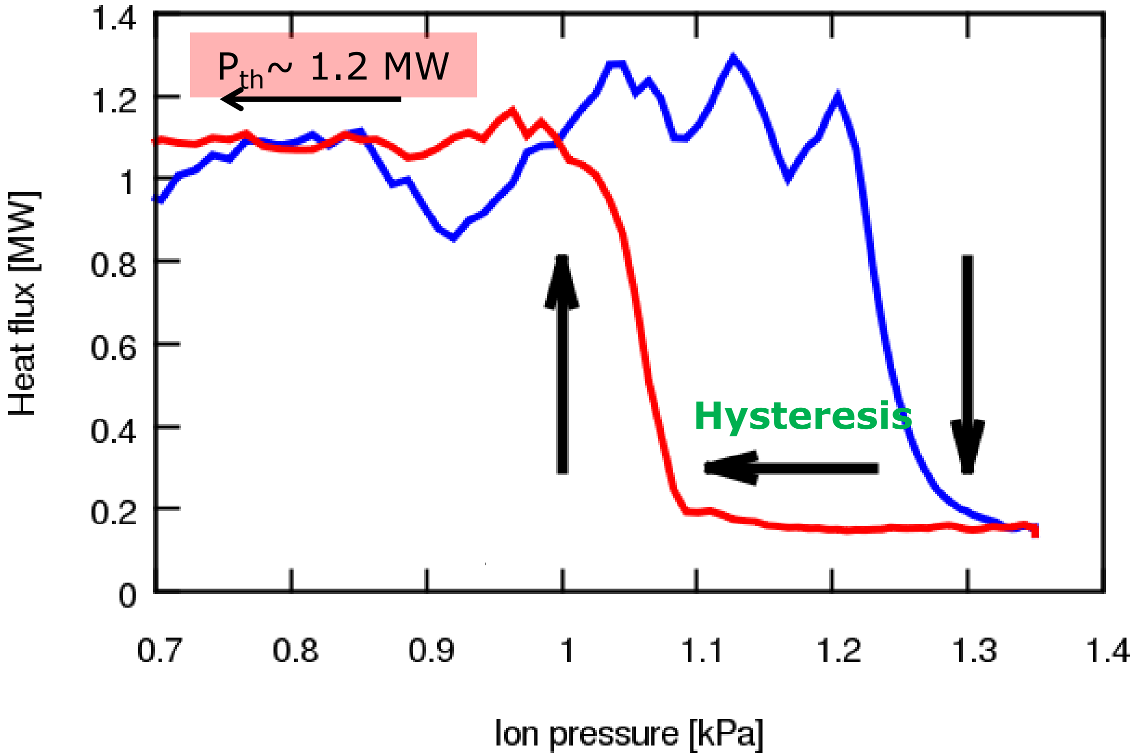
Heat flux across LCFS for L-H-L phase

Integrated heat flux over LCFS

Assumptions:
Flux is concentrated at LFS : +/-30°



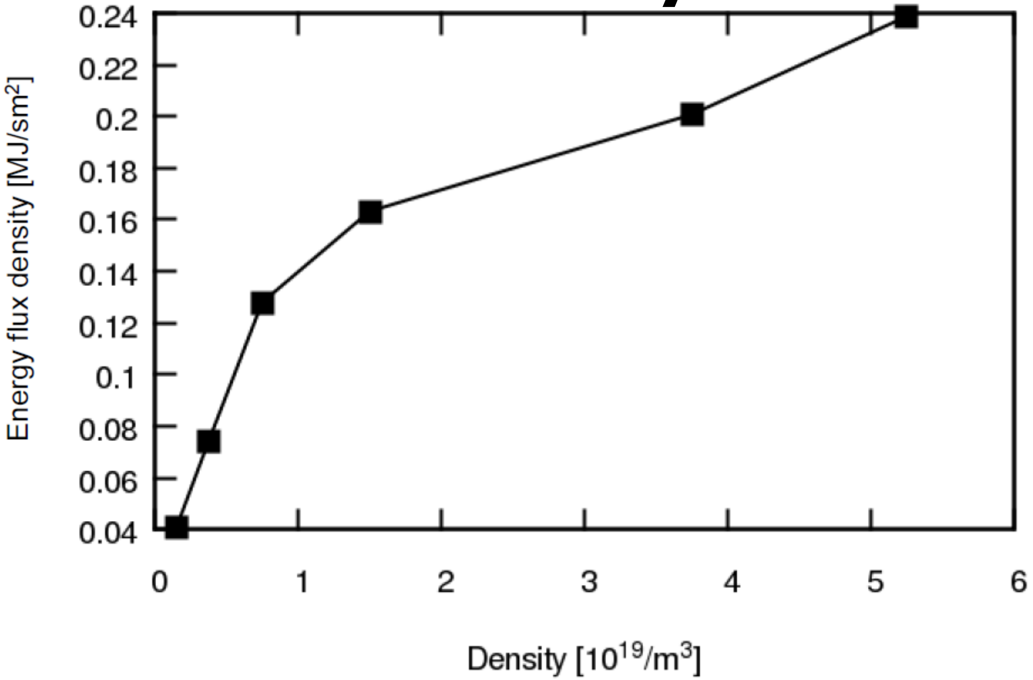
Gunn et al. JNM 2007



Threshold power P_{th} ~ 1.2 MW – close to observed P_{th} @ EAST for the same parameters.

*Xu et al. PRL **107**, 125001 (2011); Nucl. Fus. **54**, 013007 (2014)*

Threshold power: linear scaling at high density

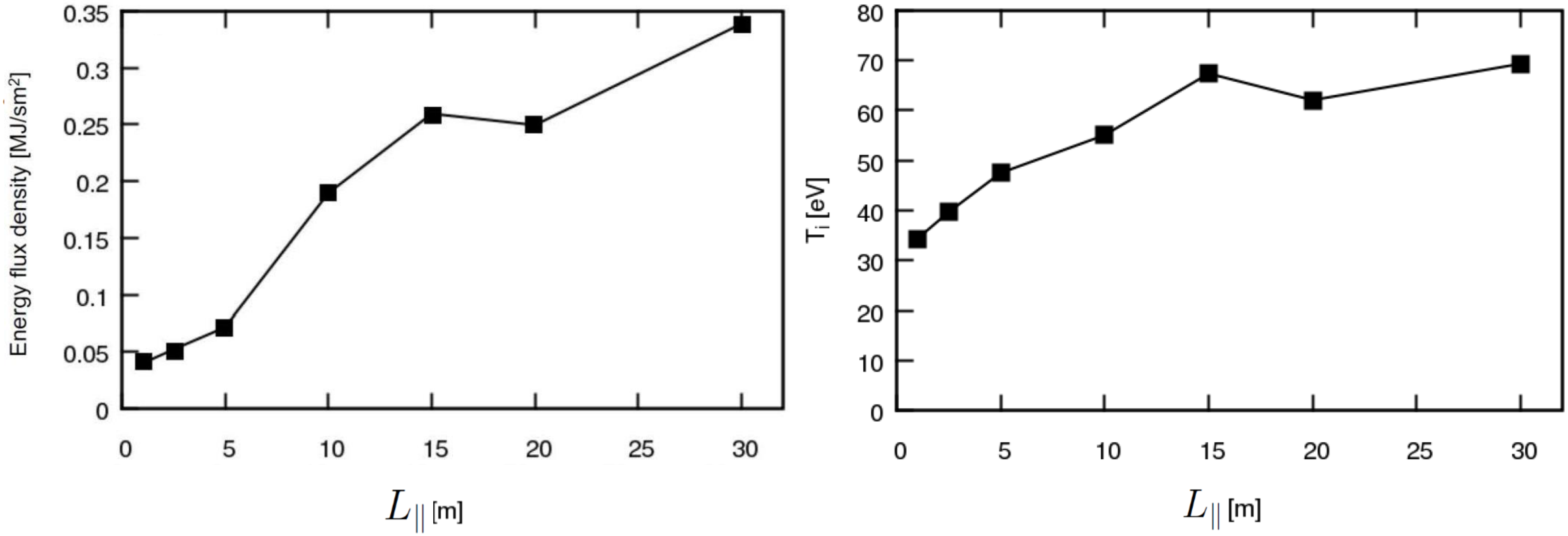


Nielsen et al.
arXiv:1409.3186

- Increase in energy input is to ions mainly
- the ion channel is dominating the transition dynamics
- hence no increase of P_{th} at low density is expected
- no rollover, no power minimum!

Ryter et al. Nucl. Fusion ***54****, 083003 (2014); Malkov et al. PoP* ***22****, 032506 (2015)*

Threshold power: scaling with connection length



Energy flux density across LCFS @ transition

Ion temperature @LCFS @ transition

Parallel losses prop to $1/L_\parallel$

➡ **Double Null lower L-H threshold power than Single Null**

↙

Liu et al. Nucl. Fusion ***54****, 073041 (2013) ; Martin et al. Nucl. Fusion* ***54****, 114006 (2013)*

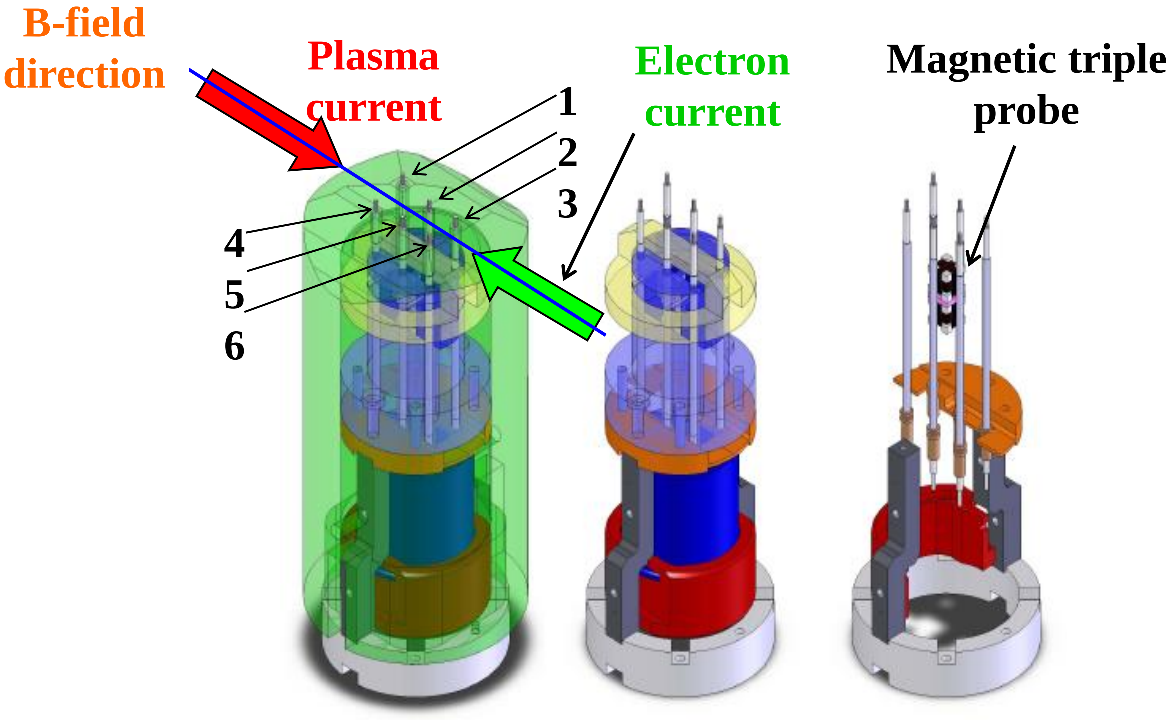
Thanks for your attention!

Extra

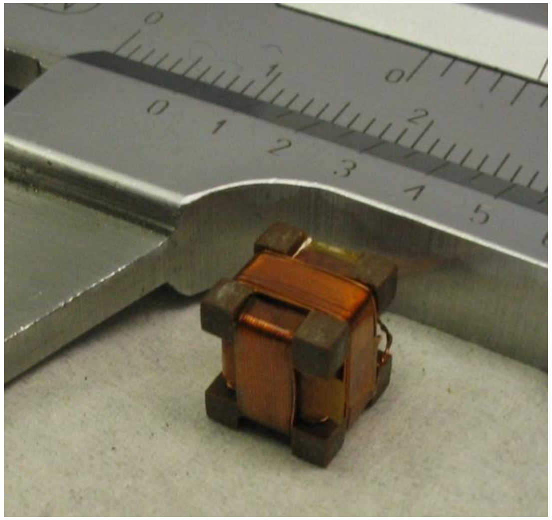
Measurements: Probe Head in AUG

Simultaneous measurements of electric and magnetic perturbations

Schrittwieser *et al.* Contrib. Plasma Phys 50, 860 (2010)



(a) Full assembly (b) Hidden shield (c) Hidden parts

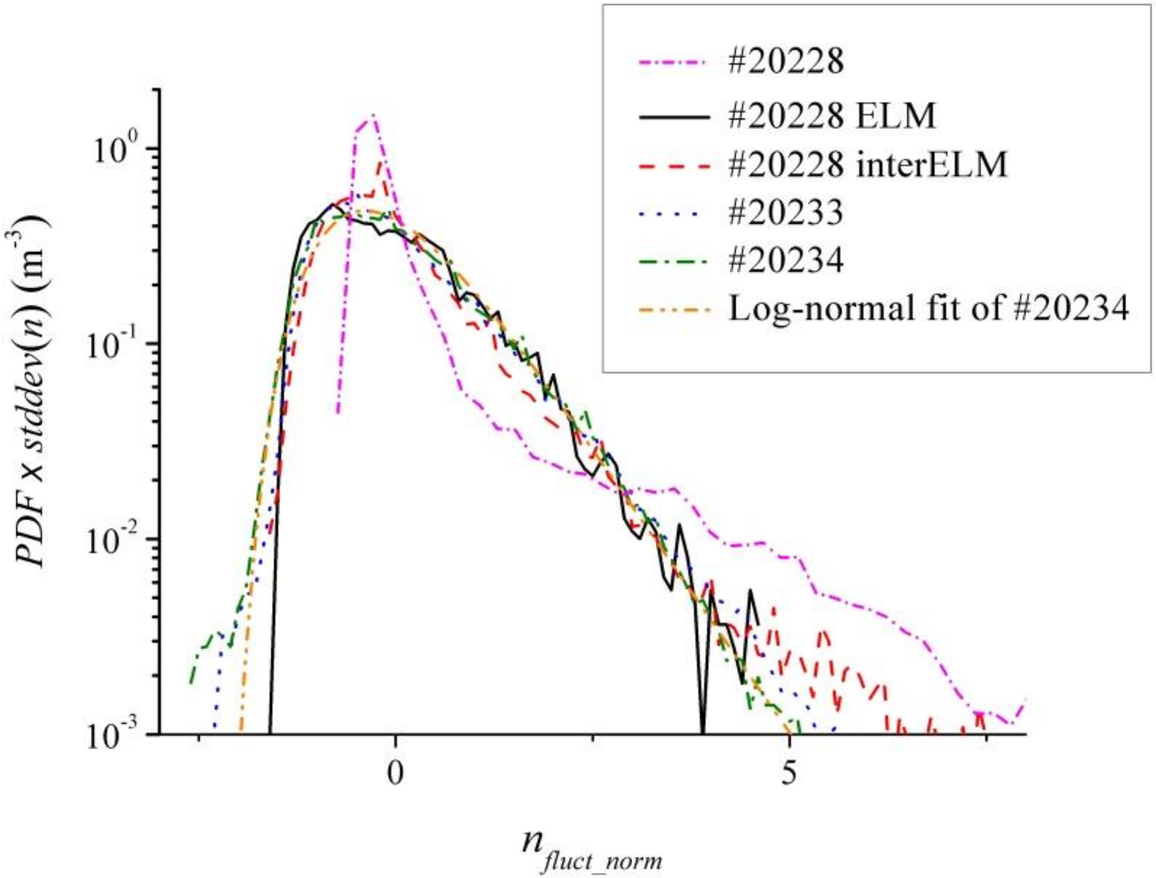


Three coils, dimension: $7 \times 7 \times 8$ mm^3. Measuring three components of magnetic field fluctuations: b_r, b_ϕ and b_θ.

The electric probe: determine poloidal and radial electric field ~ potential difference the density, the electron temperature

Cold probes – floating potential $V_f = V_p - T_e$

Density fluctuations in H- and L-mode - AUG

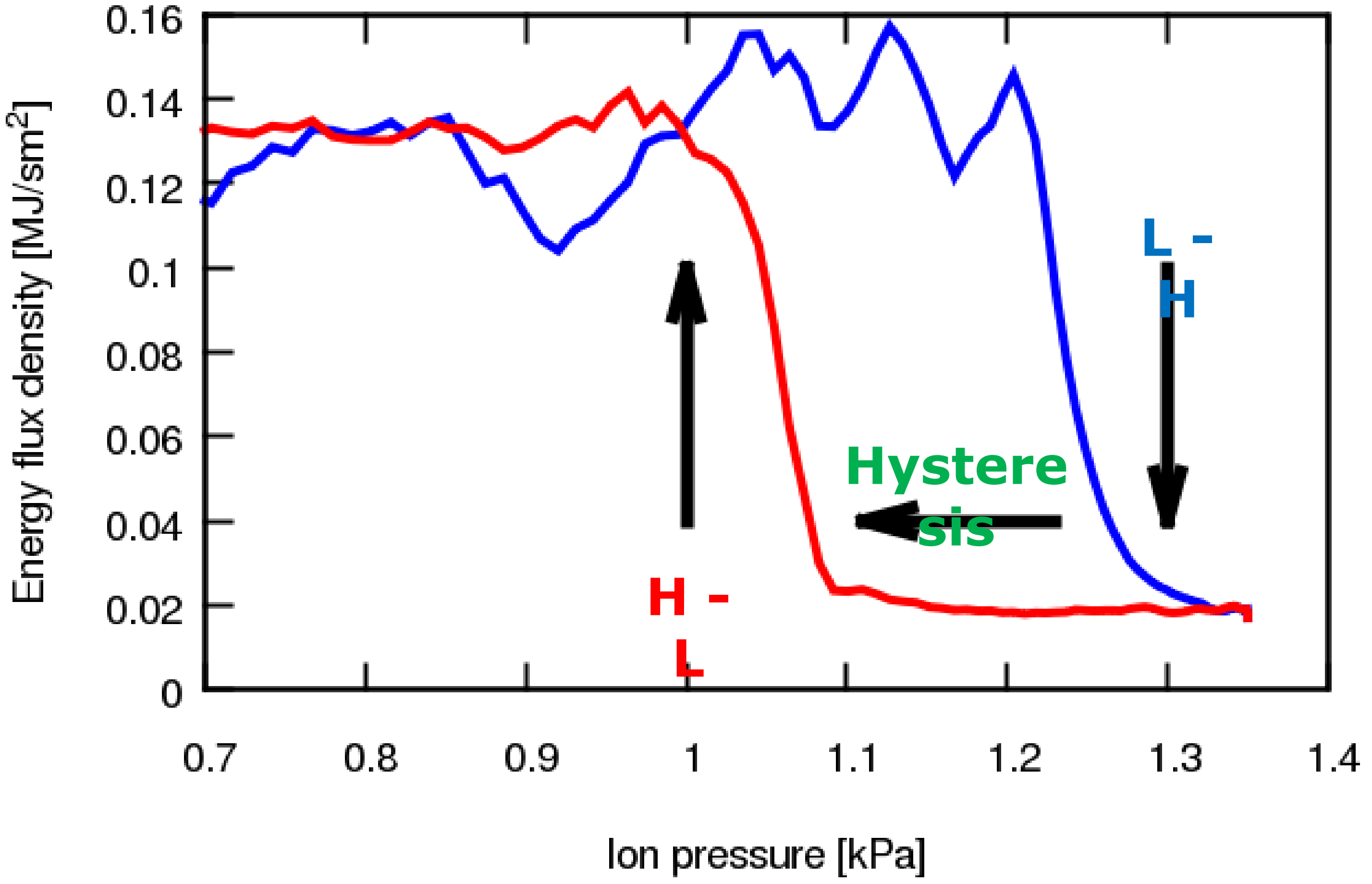


Renormalized PDF of density fluctuations in H-mode during ELM activities, in between ELM activities and in two L-mode cases.

Similar statistics: during ELMs, in between ELMs and in L-mode (blobs)

Ionita *et al.* Nucl. Fus. **53** 043021 *(*2013)

Energy flux density at LCFS for L-H-L phase



H-mode significantly decreased energy flux – improved confinement by changing ion temperature - energy flux adjust consistently

TCV15 -2.2-3 experiments

Sofar

$$\Lambda = \frac{L_{\|}/c_s}{1/\nu_{ei}} \frac{\Omega_i}{\Omega_e} \simeq \frac{\tau_{\|}}{\tau_{ei}} \quad \sim L_{||}\, n\, T_e^{-2}$$

has been changed by scanning density and temperature at the divertor regime by density scans and impurity seedings

In TCV we can scan $L_{||}$ without touching other terms.

$$\Lambda = 2.27\ 10^{-19} \frac{L_{\|}}{T^2} \frac{n\, \lambda^c}{\sqrt{(1+\tau)}}$$

$$\lambda^c \cong 8\ - 12$$

Coulomb logaritm – weak dependence on n and T

Note: this expression is calculated for D-plasma

For ions of mass m_i and charge Z we get:

$$\boxed{\Lambda_i = \Lambda_D \sqrt{\frac{m_D}{m_i}} Z^3}$$

$L_{||}$ may be changed by changing I_p for fixed parameters

$$L_{\|} = C^b I_p{}^{-b}\ ; \quad n_{GW} = \frac{I_p}{\pi a^2} = \frac{1}{C\pi a^2 L_{\|}{}^{1/b}}$$

i.e., n_{GW} decreases, for $L_{\|}$ increasing