Turbulence in and around fusion plasmas

(Turbulencia a fúziós plazmában és körülöttük)

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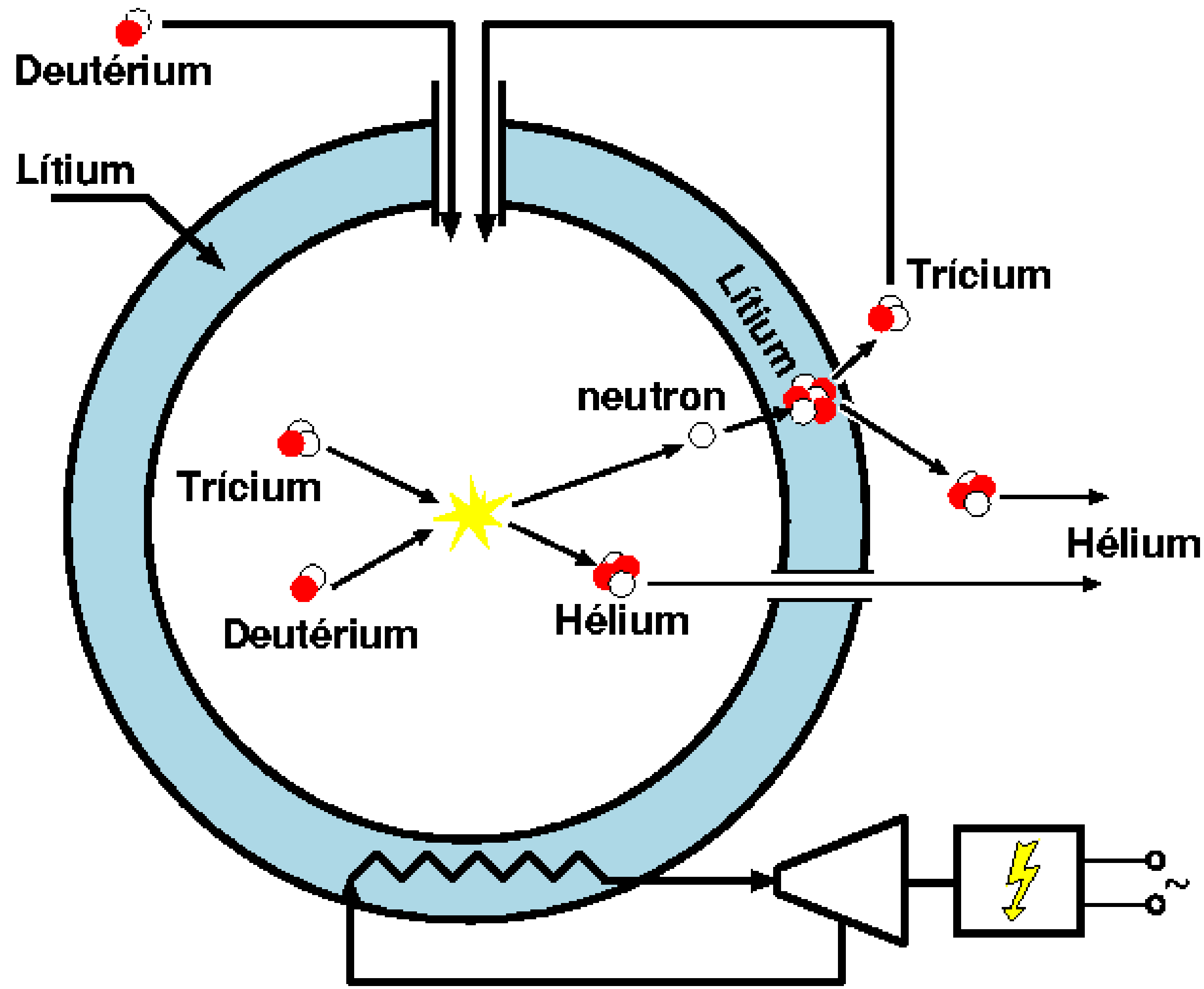
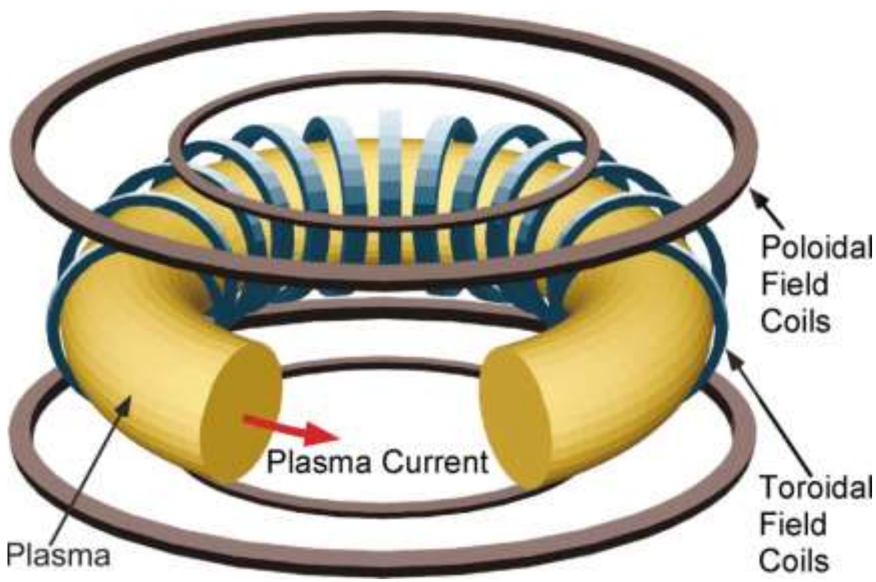
Aim is to build a fusion reactor

- 100 mio C DT plasma
- T production in blanket
- Nuclear energy without long-term radiation problem
- No possibily to meltdown, runaway

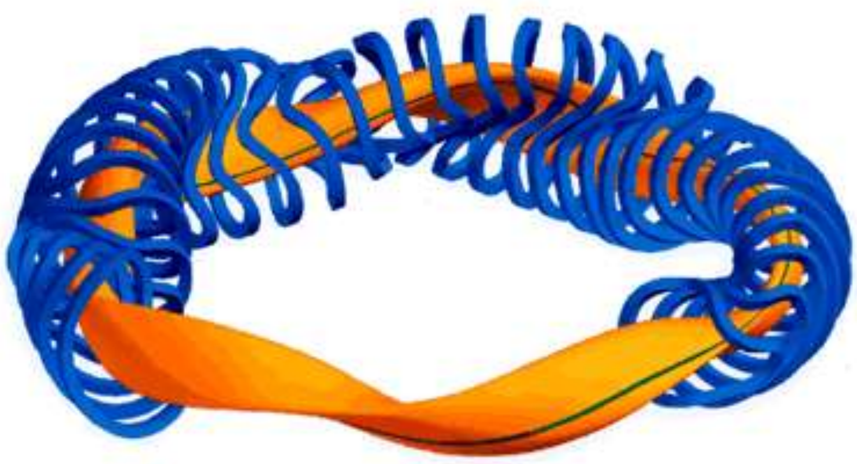


Background



Plasma confinement by magnetic fields:
Closed field lines → toroidal geometry

Tokamak:
Strong toroidal field + plasma current
axial symmetric geometry
→ inherently pulsed
→ self regulating system
→ unstable under some conditions



Stellarator:
Only external fields:
→ no axial symmetry
→ no plasma current → no instability
→ inherently steady state

Losses from the plasma determine the possibility of building a fusion reactor.
Rough 0 dimensional analysis under stationary conditions:

$\tau_E = W/ P_{loss}$, $n\tau_E > 10^{20} \rightarrow P_{loss,} < nW/10^{20}$, $W=nTV \rightarrow P_{loss,} < n^2TV/10^{20}$

(W: plasma energy, n: plasma density, T: plasma temperature, V: plasma volume)

That is, losses must be limited.

There are two types of losses:

· Volume losses (Bremsstrahlung, recombination, line radiation, cyclotron radiation,···)

· Surface (transport) losses: transport across the magnetic field, (neutral particle losses)

The limit for volume losses is independent of machine size:

→ must have the right plasma parameters.

(Moreover $P_{rad} \sim VZ^2n^2\sqrt{T} \rightarrow Z^2 < \sqrt{T}/10^{20}$, that is the plasma must be pure.)

For surface losses $P_{loss} = P_S F$ (F: plasma surface)

$$P_S < Rn^2T/10^{20}$$

R: machine size

This means if the plasma is pure enough a reactor is just a question of machine size.

In the 1970's tokamaks showed a tendency which would have allowed the construction of a reactor at a reasonable size, but it was known that the plasma must be heated by some additional way than just the plasma current (Ohmic heating)

→ Additional heating

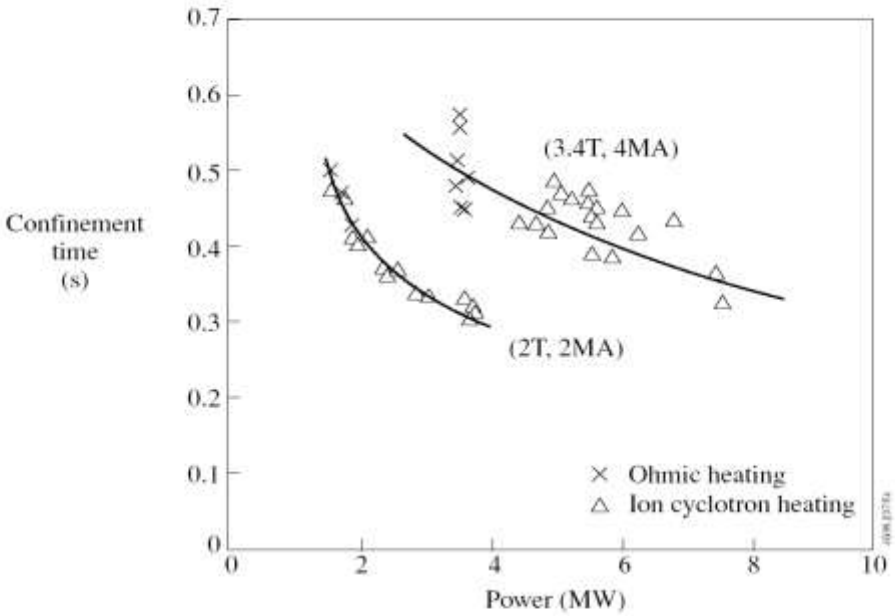
Additional heating experiments in various devices quickly revealed that losses increase with additional heating independent of what technique is used:

$$\tau_E \sim 1/P_{add}$$

This is called power degradation. This phenomenon is against physics, but a general tendency in fusion.

Power degradation meant that no fusion ractor can be built at a reasonable size.

→ It practically inhibits building a reactor



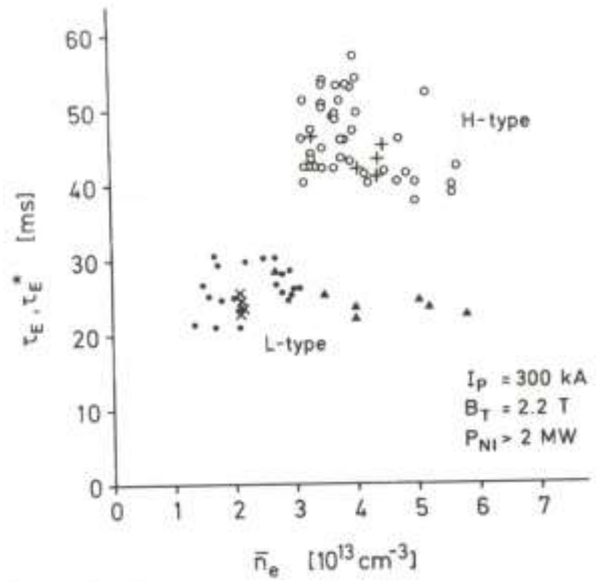
In 1982 an unexpected phenomenon was found on ASDEX (now HL–2A, China), the first divertor tokamak:

Discharges spontaneously grouped into two categories:

- L–mode : Low confinement
- H–mode: High confinement

Figure from the original publication by Wagner at al.

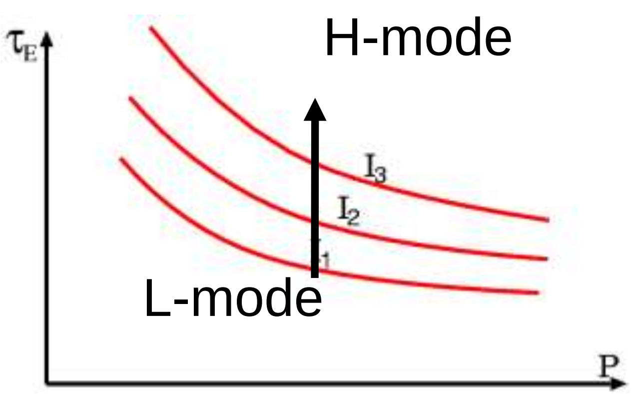
(F. Wagner is presently the president of the European Physical Society)



The plasma underwent a *spontaneous* transition in the divertor tokamak above a certain heating power.

H–mode restores the confinement degradation due to power degradation.

However, it does not remove power degradation, just shifts curves upwards in τ_E.



The H–mode allows construction of fusion reactors.

Usually the H–mode transition occurs above a certain heating power.

(H–mode power threshold)

The signature of the H–mode transition is a drop in the edge D_{α} radiation.

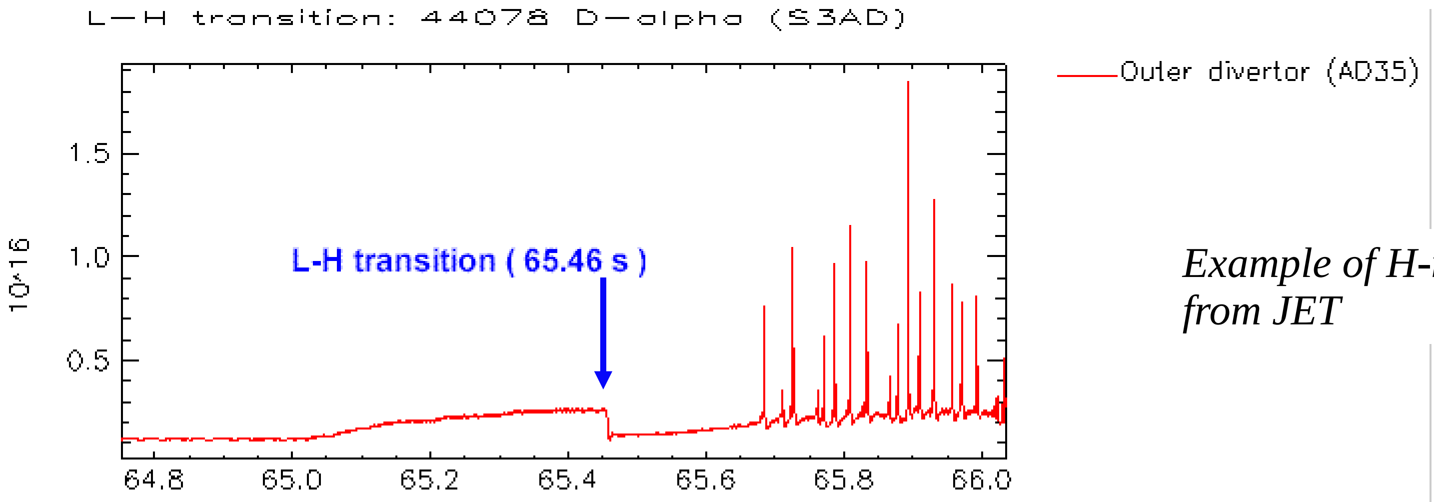
The number of photons radiated by *one* Hydrogen atom:

$$\Phi = n\langle v_e\sigma_{exc}\rangle\tau_{ion} = n\langle v_e\sigma_{exc}\rangle / n\langle v_e\sigma_{ion}\rangle = \langle v_e\sigma_{exc}\rangle / \langle v_e\sigma_{ion}\rangle$$

→ The D_{α} radiation is roughly proportional to the flux of D atoms into the plasma.

The number of atoms is proportional to the flux of D ions falling onto the wall (divertor)

→ The $D\alpha$ radiation is an indication of the strength of the wall(divertor) interaction



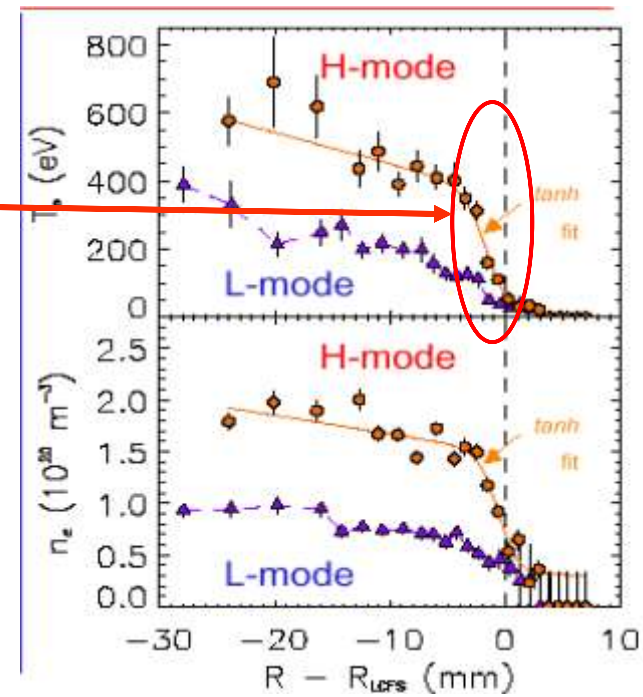
Example of H-mode transition from JET

The transition is fast, in the ms range. → has its own dynamics

Sometimes a series of LHLH··· transitions are seen: dithering

What is the H-mode?

It was soon *(well, after a decade :-)* realized that the H-mode confinement is a result of the drop in plasma transport losses in a narrow layer at the plasma edge: a “transport barrier” forms at the edge.



L and H mode profiles at the plasma edge in ASDEX Upgrade

Inside the barrier transport is as before, but the profiles are raised to a “pedestal”.

The pedestal height becomes a crucial parameter:
Plasma performance is largely determined by this narrow (cm) layer.

There might be different transport barriers:

- Tempature barrier: heat conduction improves
- Density barrier: particle diffusion improves

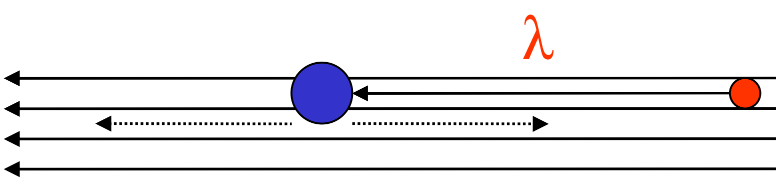
As the electron and ion temperature is only loosely coupled temperature barriers might be different for different species in the plasma:
electron barrier, ion barrier.

How can this transport improvement happen?
→ We have to look at the mechanism of cross-field transport in a fusion device.

Classical transport across the magnetic field

Transport from single particle motions
Classical transport: single particle motion+collisions

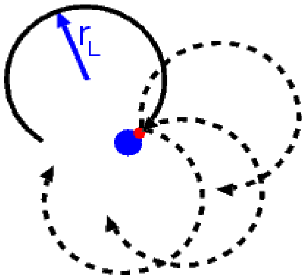
Transport both along and across field lines is diffusive ($r_L << a$) but with different diffusion coefficients.



$$D_{\|} = \tfrac{1}{2}\lambda^2\nu$$

$$\lambda > 10^3 r_L$$

$$\boxed{D_{\|} > 10^6 D_{\perp}}$$

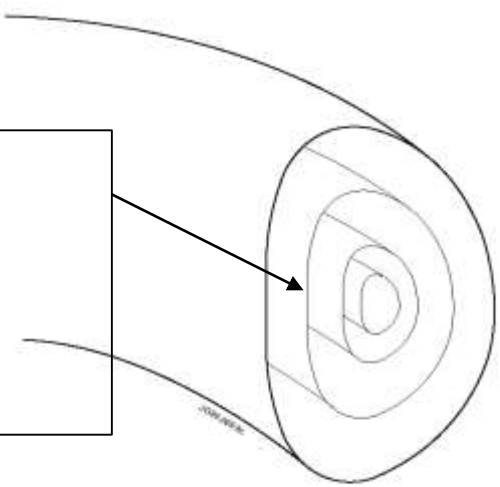


$$D_{\perp} = \tfrac{1}{2} r_L^2\nu$$

Fast transport along field lines equilibrates everything on flux surfaces
→ Transport is essentially one-dimensional

Flux surfaces
(covered by same topology field lines)

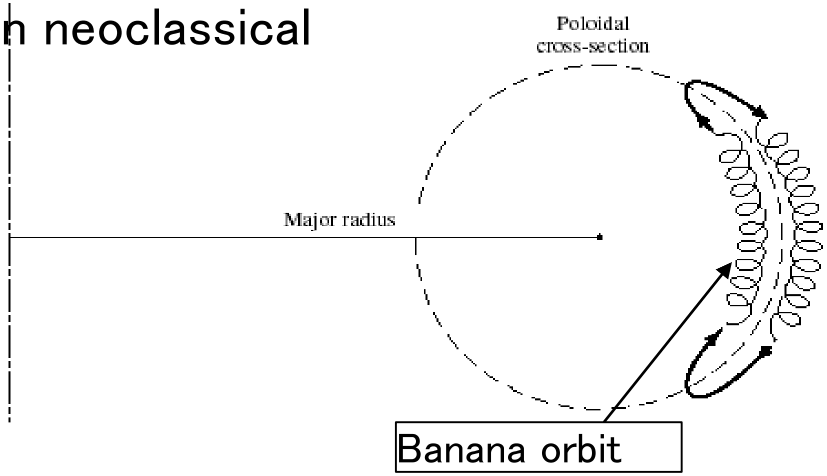
Density, temperature, … is constant



Neoclassical transport:

classical transport
+ drift motion of single particles in actual field geometry

Most important element are trapped particles in "banana orbits"
If banana orbit width is small compared to gradients then neoclassical transport is also *local and effectively 1D*.



Neoclassical transport can be calculated in given magnetic configuration

→ Effective (1D) neoclassical transport coefficients

Electrons and ions cannot diffuse independently
Electric field will adjust until net charge transport is zero.
→ ambipolar electric field

Transport is affected by electric field → neoclassical electric field is part of solution

S. Zoletnik Balaton Summer School Turbulence and transport in fusion plasmas Page 10.

Measured $B_{\perp}$ transport coefficients are usually higher than neoclassical prediction:
->Anomalous transport

Anomalous transport has been experienced since 50 years both in linear and toroidal devices

Best known empirical scaling: Bohm diffusion

$D \sim T/B$ Classical transport would be $1/(T^{1/2}B^2)$

Bohm diffusion is much worse for fusion than (neo)classical diffusion

Anomalous transport

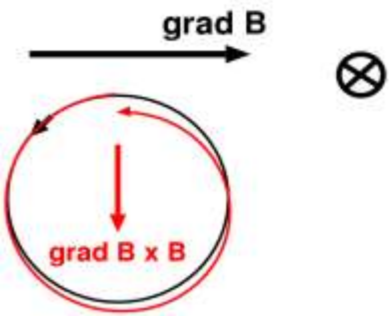
- Should be a collective effect
- Temporal and spatial scale should be smaller than macroscopic scales (ms, cm)

It is generally believed that micro-turbulence causes anomalous transport

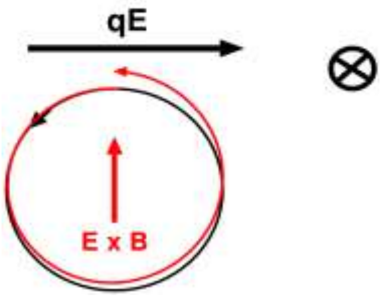
Analogy in fluids:

Stirring a cup of tea is more effective to distribute sugar than simply diffusion.

Grad B and ExB drifts have basic role in plasmas:



grad B drift: charge dependent

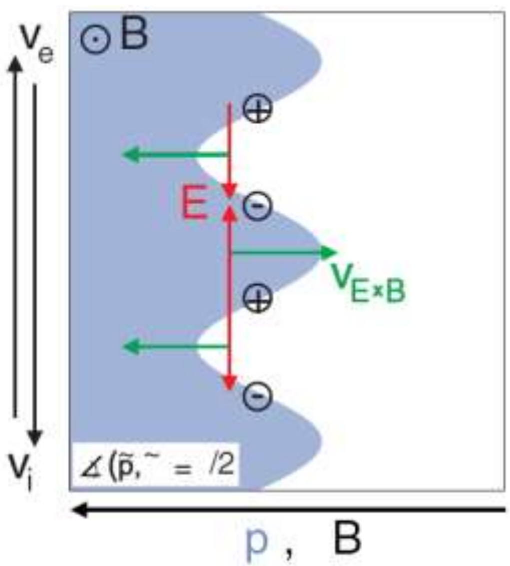


ExB drift: charge and mass Independent: moves whole plasma

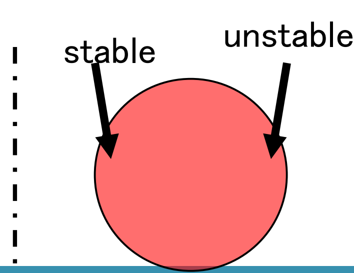
There are two basic mechanisms which are considered to be responsible for plasma turbulence

Interchange:

Always unstable if grad−p and grad−B is parallel: outer edge of plasma

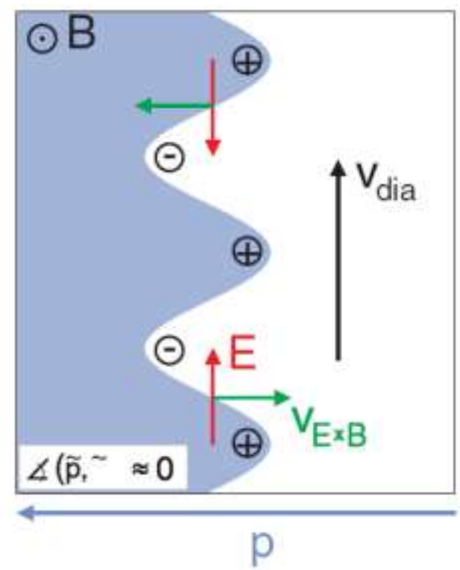


In helical geometry along helical field lines there are alternately stabilizing and destabilizing regions



Drift wave:

Stable waves with finite wavelength along B exists if there is a Density gradient in the plasma

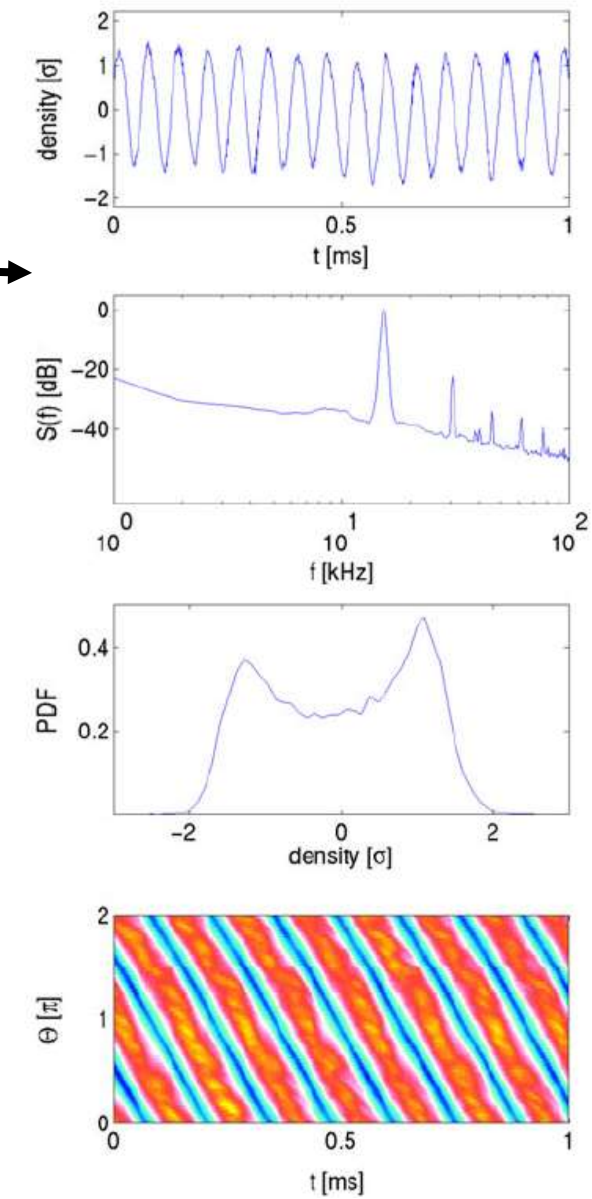


Waves can be destabilized by any effect which breaks the phase relationship between density and potential: Te, Ti gradient, trapped electrons. Several different modes with different scales.

Do we see the unstable waves?

If waves are driven unstable one would expect to see them in experiments:
→should see well defined frequencies, wavenumbers

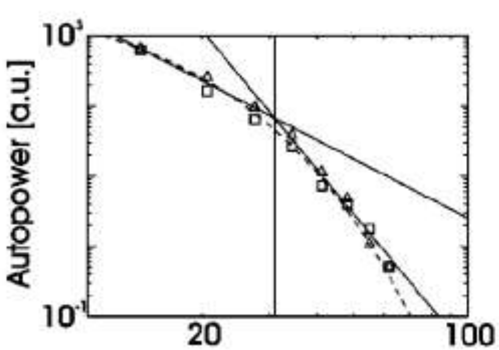
Indeed they can be seen under well defined circumstances:
E.g. drift waves can be driven unstable by externally controlled rotation in linear device.

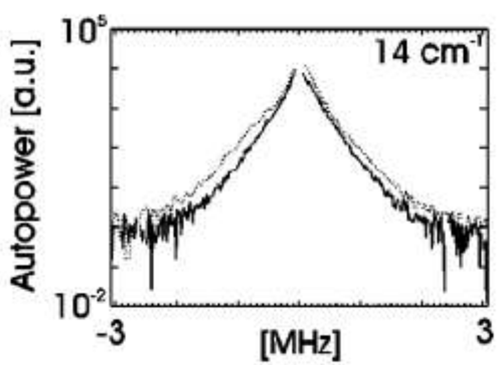


However, in a fusion experiment no distinct wavenumbers and frequencies are seen
but
The range of frequencies and wavenumbers is right.

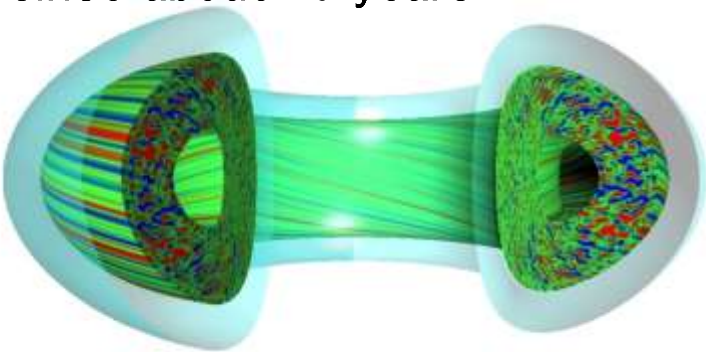
→ Fusion plasmas are in strongly turbulent state

- A range of waves are unstable and interact nonlinearly
- Energy is transported between scales



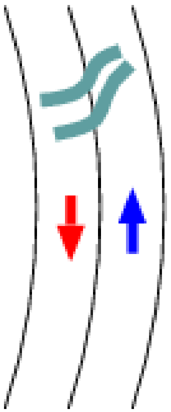


- 3D reduced kinetic simulations (gyro-kinetic) are available since about 10 years
- They are run on most powerful computers in the world
- Turbulence is strongly developed, nonlinear interactions are important



Results show that multiple scales are involved:

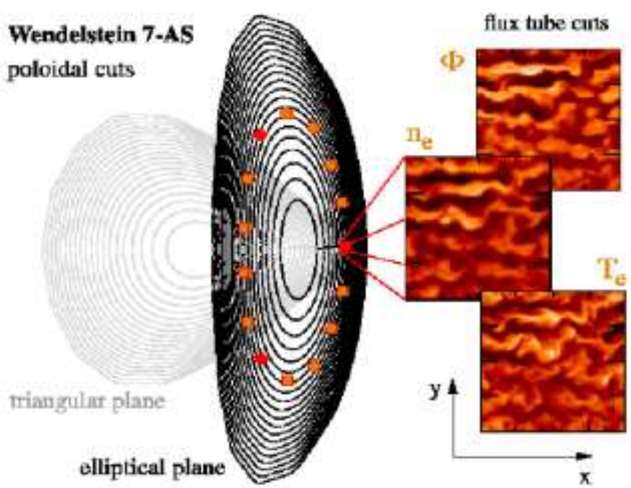
- Primary unstable waves interact and build mesoscale structures:
  - Zonal flow: toroidally and poloidallly symmetric structure

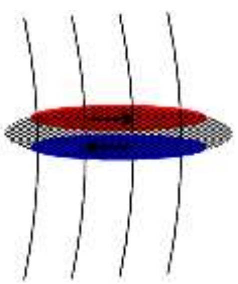


Can affect turbulence by shearing the waves.

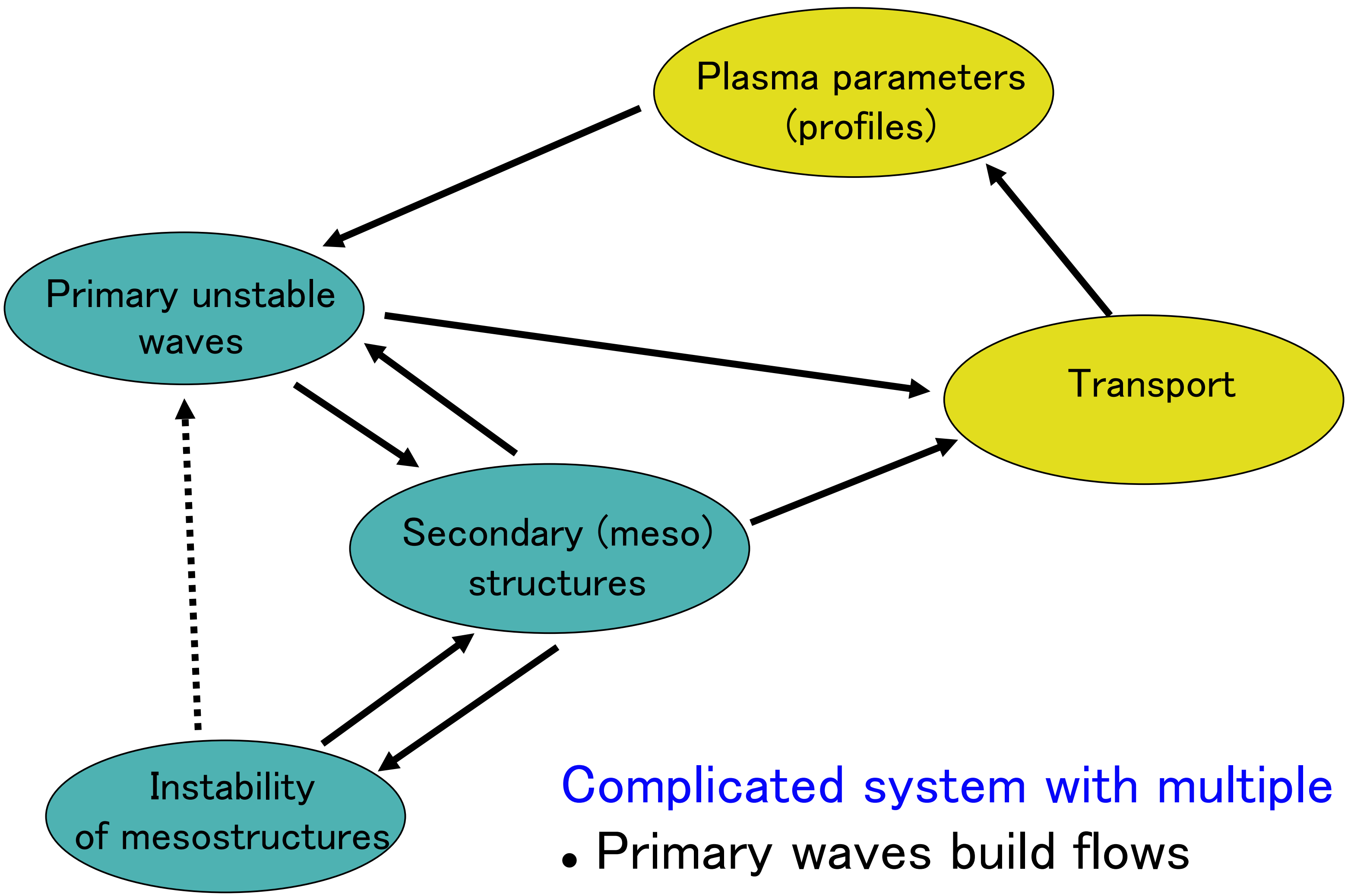
  - Streamer: localised radially elongated structure

Increased transport due to long “conveyor belt”.





→ *Show itg.avi*



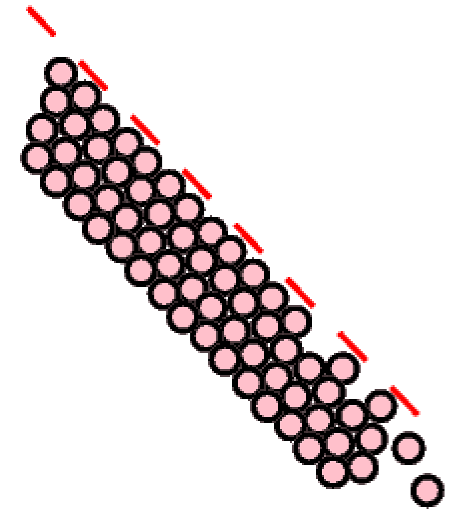
Complicated system with multiple feedback loops

- Primary waves build flows
- Flows regulate primary waves
- Transport changes profiles
- Profiles change instabilities

Self–organization

Plasmas are self–organized systems:

- Plasma parameter gradients grow to the point where instabilities start
- Instabilities keep gradients around critical

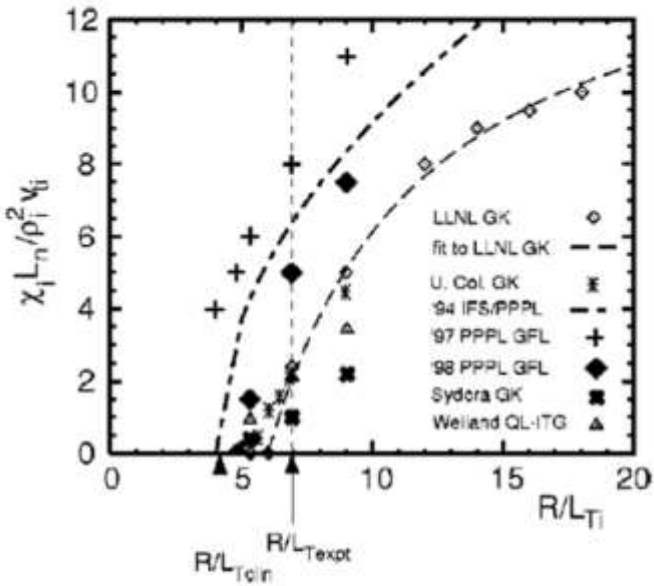


Similar behaviour is known from other physical systems:
Self–Organized Criticality (SOC)

Sandpile model:

- Slope of sandpile is always close to the critical gradient
- Avalanches transport sand

Indeed profiles in tokamaks are usually "stiff":
They grow to a critical gradient and do not move any further.



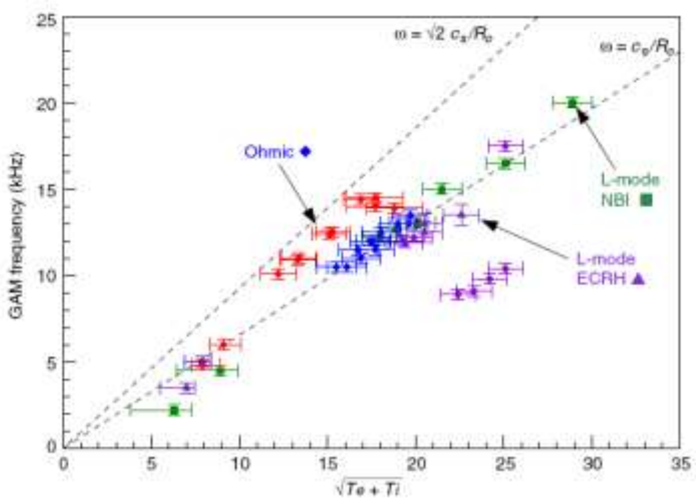
Ion thermal transport as a function of ion temperature gradient in various simulations. The dashed vertical line is the experimental gradient.

The great achievement of the last 5 years is that zonal flows and their interaction with turbulence has been seen experimentally.

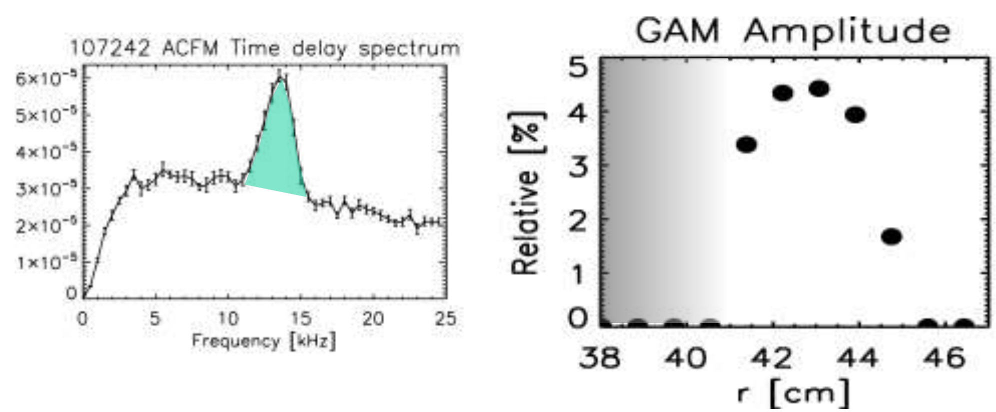
→ *Illustration*

Oscillatory branch: Geodesic Acoustic Mode (GAM)

- The basic mechanism was predicted in 1968 *(Winsor et al, Phys. Plasmas **11** 2448)*
  - An m=0,n=0 electric potential perturbation on a flux surface creates ExB flow along the surface
  - The toroidicity of the geometry creates compressioin on the top or bottom of the plasma
  - The density change creates a diamagnetic current which removes the potential



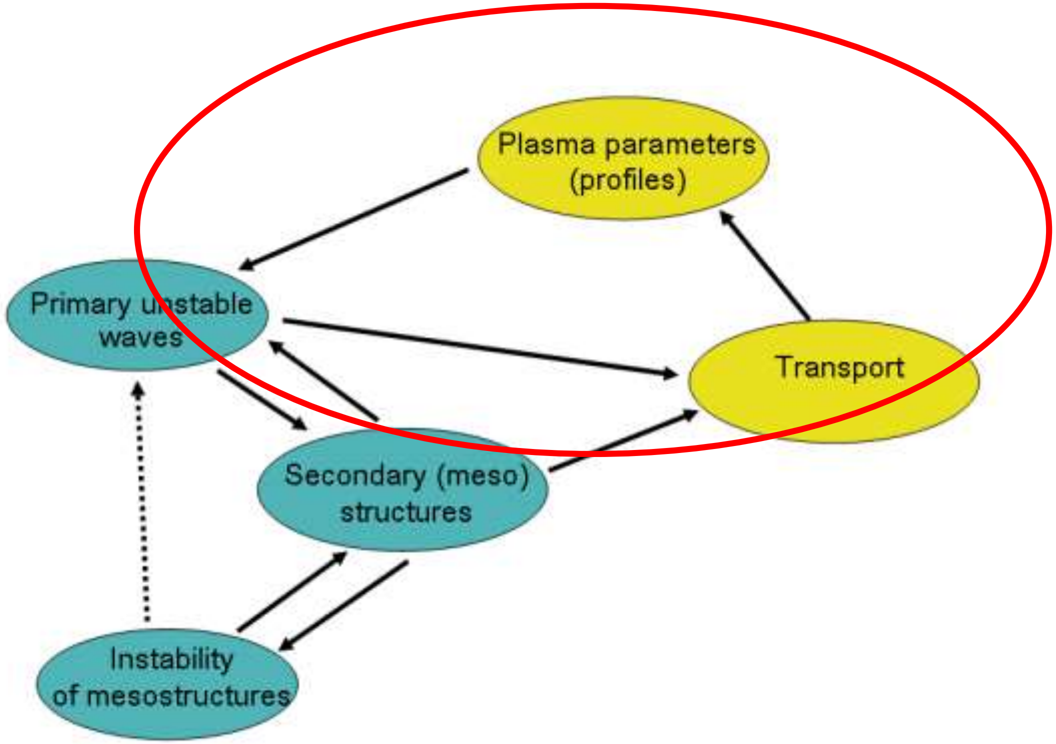
Scaling of GAM frequency in ASDEX
G.D. Conway et al,
PPCF 47 1165 (2005)



GAM related velocity modulation spectrum in TEXTOR and the GAM amplitude distribution at the plasma edge.
S. Zoletniki et al, EPS 2009

Summary of turbulence

- The basic instabilities, flows and their interactions have been identified
- Quantitative agreement with simulations
- Details are not clear: GAMs are more complex than originally foreseen
- Low frequency zonal flows a bit controversial: periodic/random, nor always seen
- The role of small scale instabilities and their interactions is not clear
- The second interaction loop has not been really studied yet.



The H-mode barrier is believed to be the result of a large sheared poloidal flow at the plasma edge → suppresses turbulence

The flow velocity cannot increase to arbitrary levels:
→ The barrier must have a finite width

There is indeed some evidence:
- Flow velocity increases in H-mode
  (not clear whether before or after the transition)
- Turbulence is suppressed in the pedestal

L-H transition might be a bifurcation in the second feedback loop
(turbulence-transport-profiles)

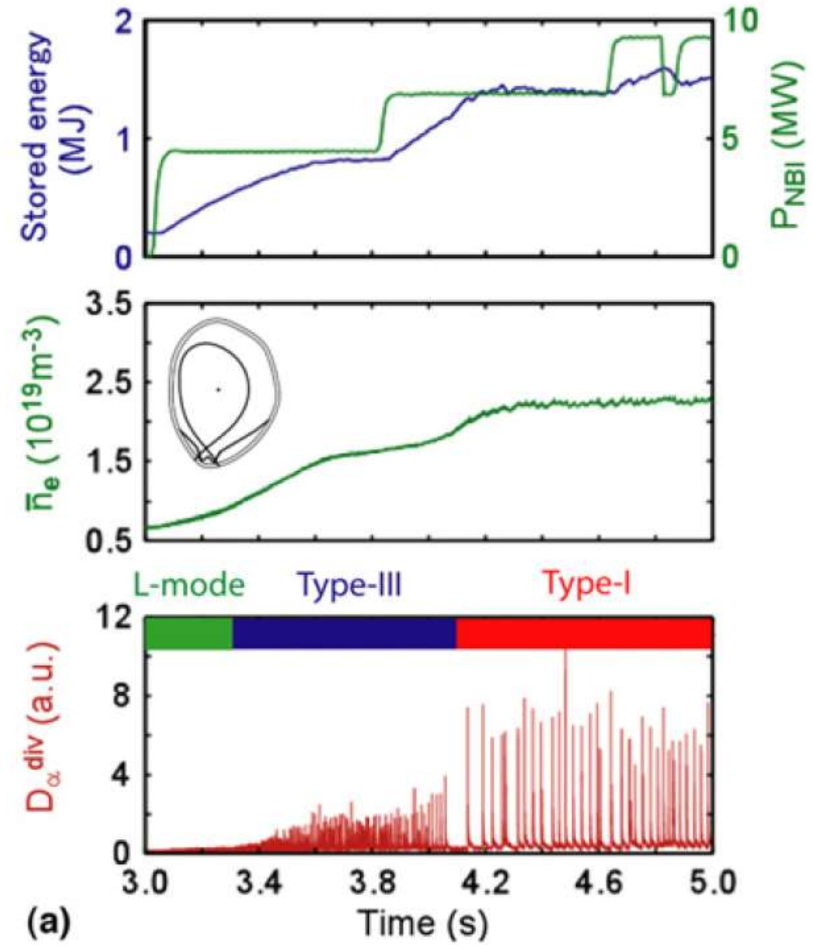
The problem is that none of the turbulence theories can generate an H-mode transition. There are many questions:
- Why do we have the barrier at the edge?
  → We do have sometimes barriers inside the plasma (Internal Transport Barrier, ITB)
- What sets the barrier width and height?
- Why do we need a clean plasma for the H-mode?

The basic mechanism of the H-mode is probably understood
but there is no quantitative understanding.

The spikes after the transition

Normally the H–mode transition is followed by the appearance of Edge Localized Modes (ELMs):

- First type III:
  Frequency decreases with increasing heating
  Small spikes
- Second stage is an ELM–free H–mode:
  Density increases and impurities accumulate
- At higher heating type I ELMs appear:
  Frequency increases with heating
  Large spikes



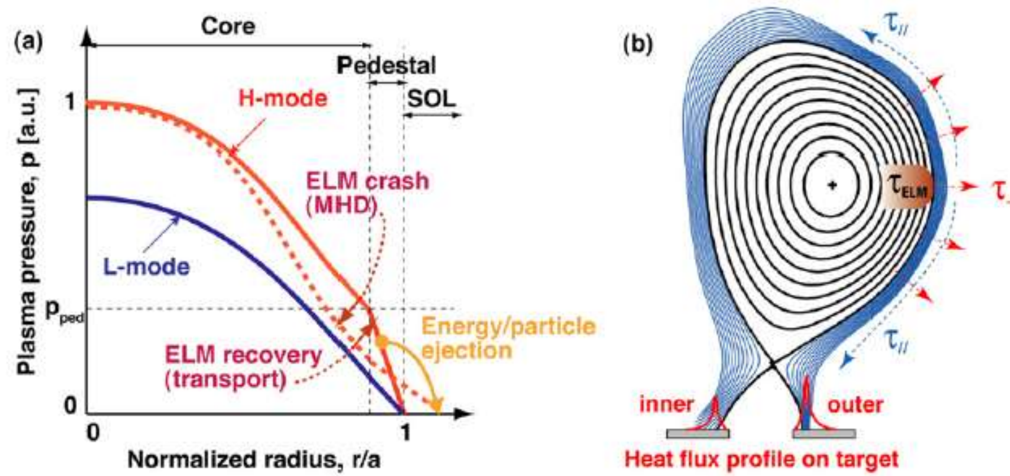
K.Kamiya, Plasma Phys. Control. Fusion 49 S43 (2007)

Phenomenology of ELMs

ELMs are a pulse of energy and particles from the plasma to the wall and divertor

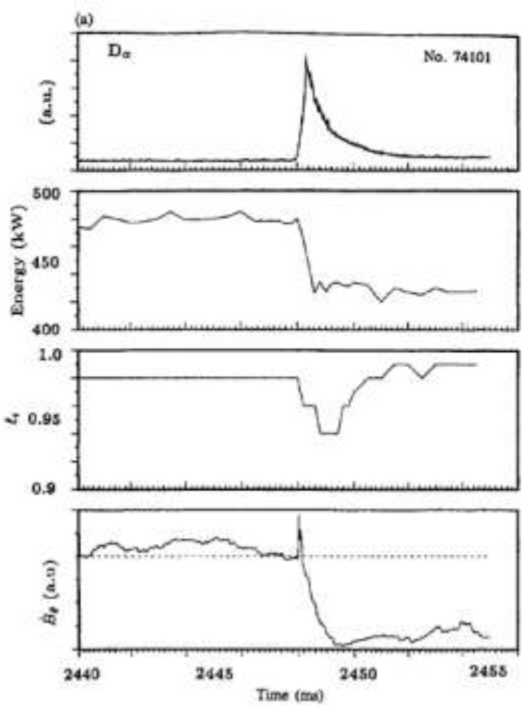
- Some kind of instability of the pedestal
- Heat loss happens within a few hundred microsecond
- Large ELMs can even crash the H-mode for a short period: compound ELMs

Energy loss can be 10% for type I ELMs.

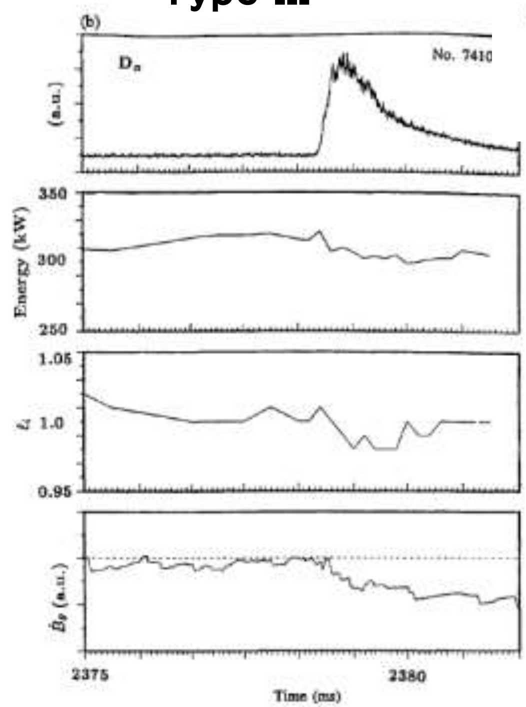


*K.Kamiya, Plasma Phys. Control. Fusion **49** S43 (2007)*

Type I



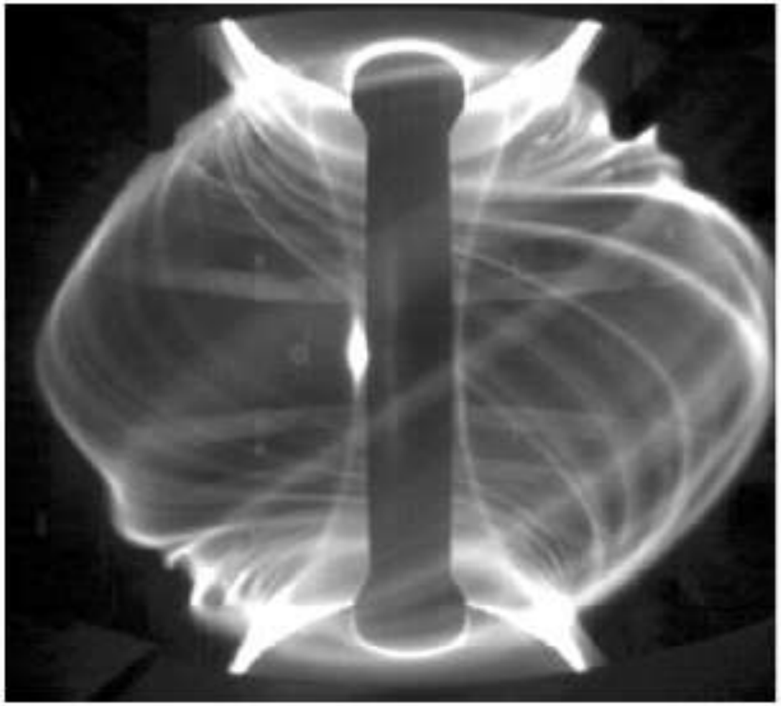
Type III



ELM lossed in type I and type III ELMs

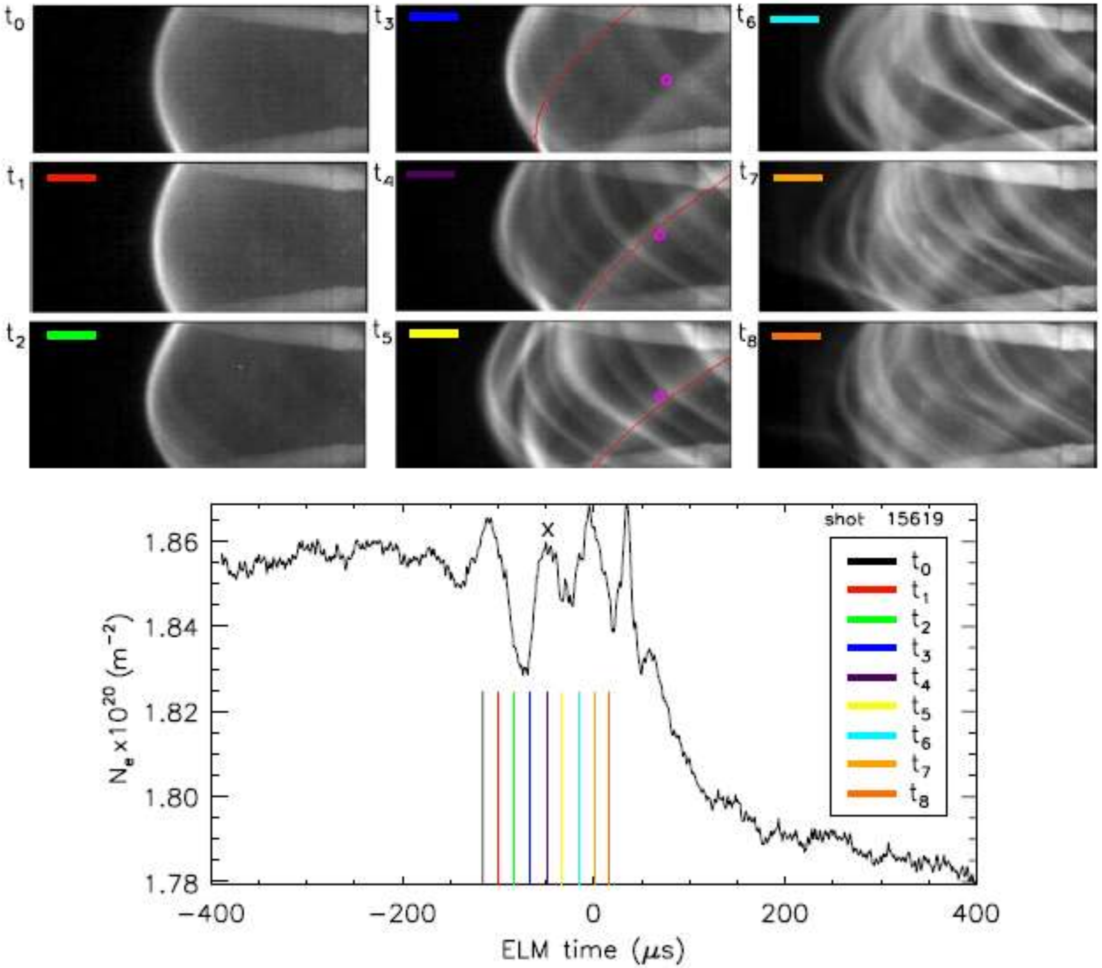
*Zohm, Nuclear Fusion **35** 543*

Plasma filaments appear at the edge during the ELM and they propagate across the Scrape-off Layer. The filaments take part of the energy with themselves, but they might also serve as a heat conduit.



ELM filaments in MAST

Scannell, PPCF 49 1431



Are ELMs good or bad?

In H-mode not only the energy confinement but also the particle confinement improves:

- Impurities are sucked inside the plasma
- Increase of Z_{eff} → increased radiation

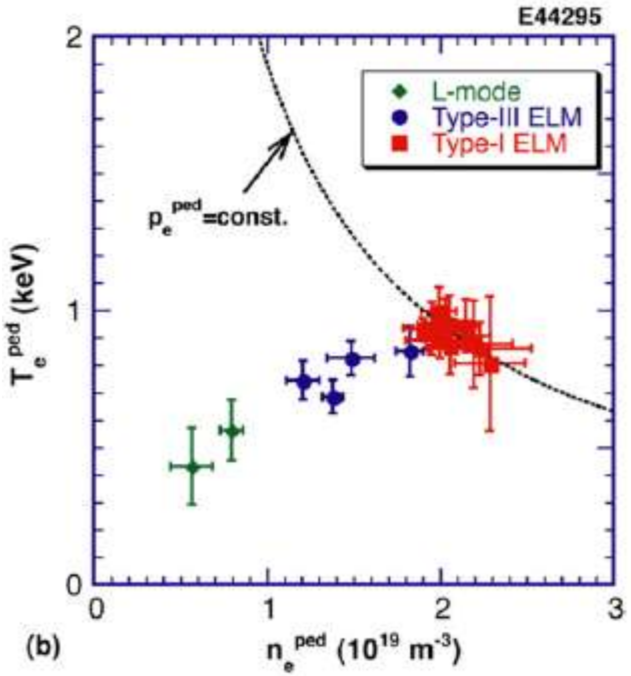
In a fusion reactor He is generated in the plasma from the fusion reactions. In the normal (ELM-free) H-mode these cannot be pumped out.

ELMs are an important consituent of a reactor plasma:

Type I ELMy H-mode is the standard operation regime of ITER, a compromise between good enough energy confinement and bad enough particle confinement.

What are ELMs?

ELMs are considered to be an instability of the pedestal:
Transport drops in the pedestal at the L-H transition
→Pressure gradient increases
→Pedestal becomes unstable
→MHD instability "explodes" and removes steep pedestal pressure



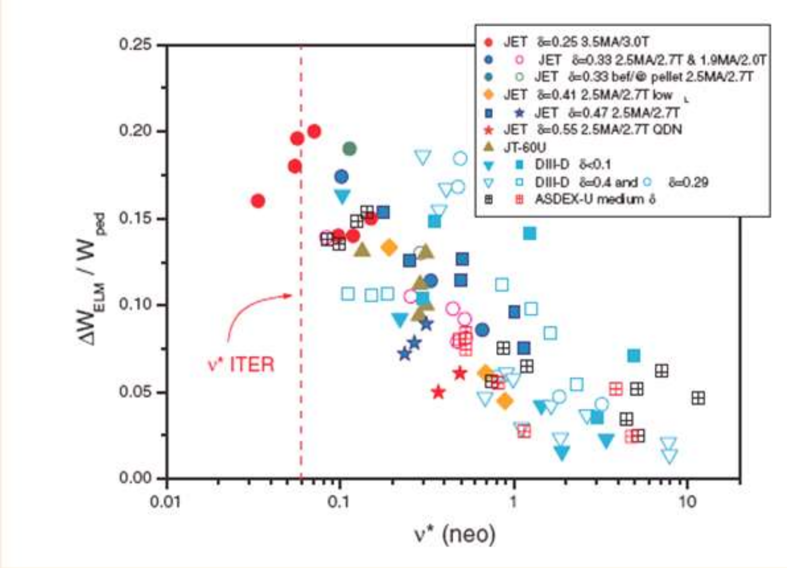
*K.Kamiya, Plasma Phys. Control. Fusion **49** S43 (2007)*

This picture might be right:
· Indeed type I ELMs are at the pedestal stability limit.

But details are not consistent:
·The pressure gradient comes back to the original steepness shortly after the ELM
· The ELM frequency is not set by the pressure build-up
· Type III ELMs are not at the pedestal stability limit

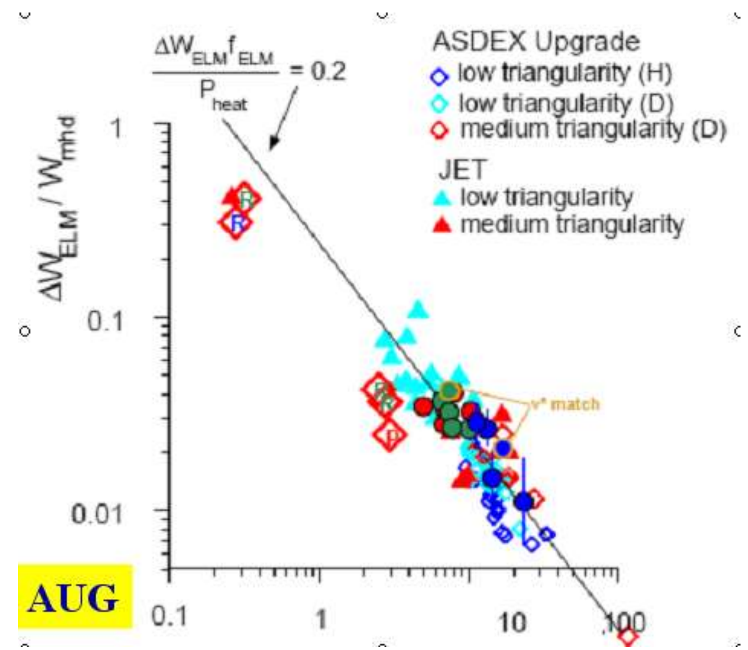
Standard good confinement is associated by type I ELMs:

- ELM loss increases with temperature:
  Although extrapolation is not very clear
  but the ITER divertor might not tolerate
  type I ELMs.



What can be done:

- Increase ELM frequency (ELM pacing, kicks)
  → reduces energy through frequency scaling
- Replace ELMs with a more benign instability:
  MHD mode, current filament, …
- Modify the plasma edge so as to provide the
  necessary transport with external control



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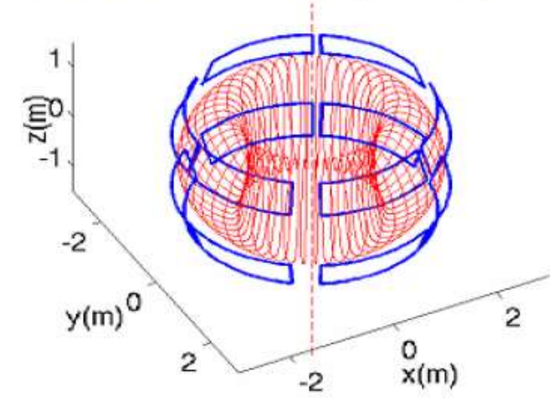
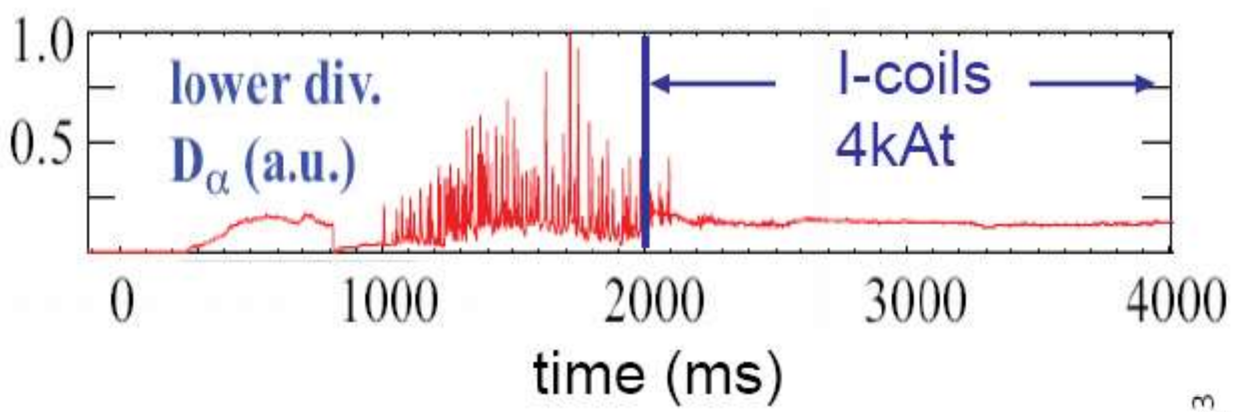
On DIII–D a set of magnetic field correction coils were used to ergodize the magnetic field structure at the edge:

- At a certain edge q overlapping magnetic islands appear
- Idea was that the losses through the islands can be controlled with the coil current and thus the pedestal can be kept withing the stability boundaries.

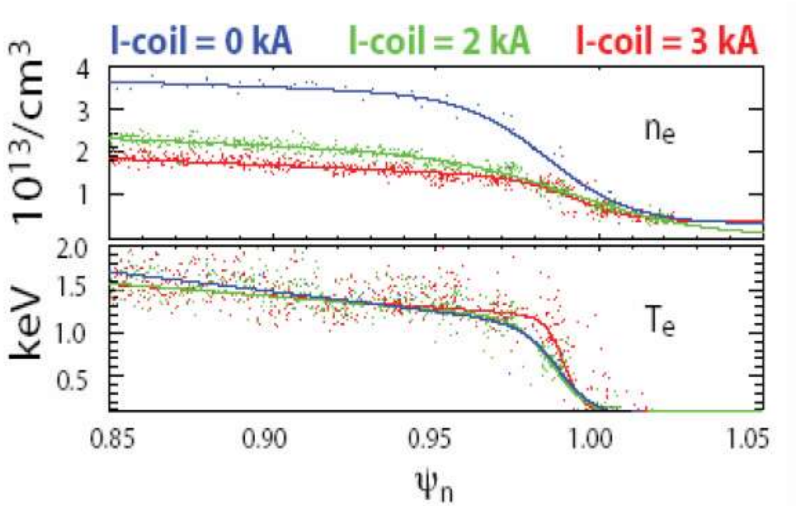
I-coils: 6+6 coils; n=3; ~4kAt





Indeed ELMs disappear, but it is not clear why:

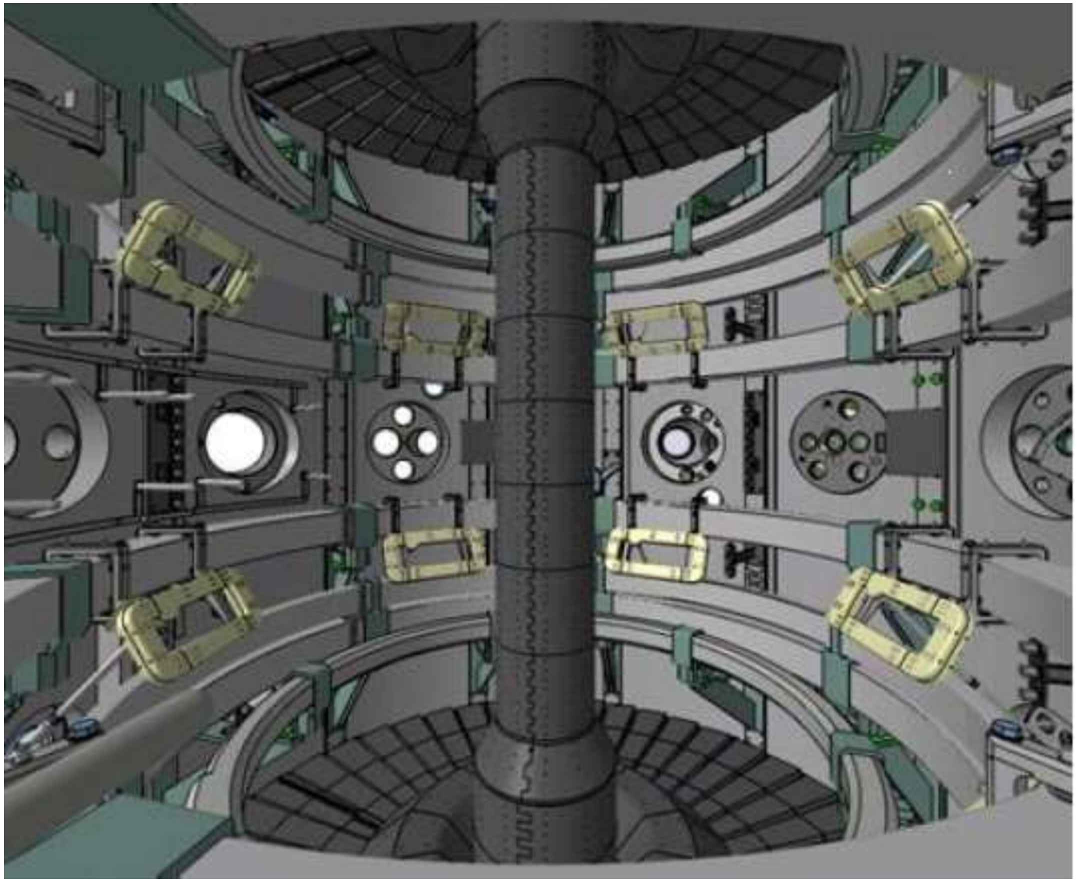
- The edge temperature steepens
- The density gradient becomes lower

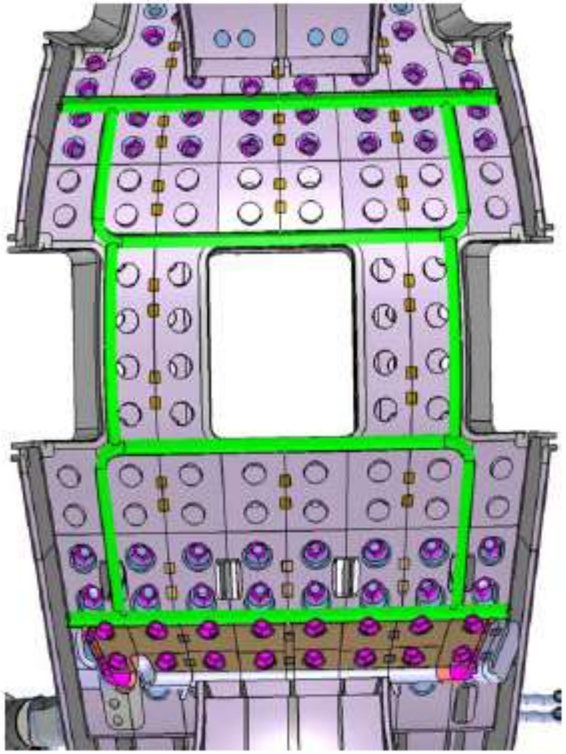


Although the RMP results are not clear several machines started to construct RMP coils: MAST, ASDEX Upgrade, ITER

First results are not clear: e.g. no ELM suppression on MAST

RMPs might be a solution for ITER





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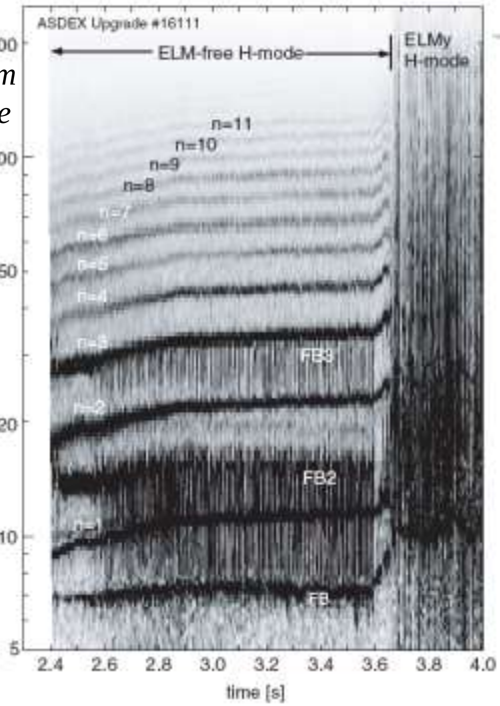
Quiescent H-modes

In soma parameter regimes quiescent H–modes can be found:
ELMs are replaced by some kind of quasi–coherent mode at edge.

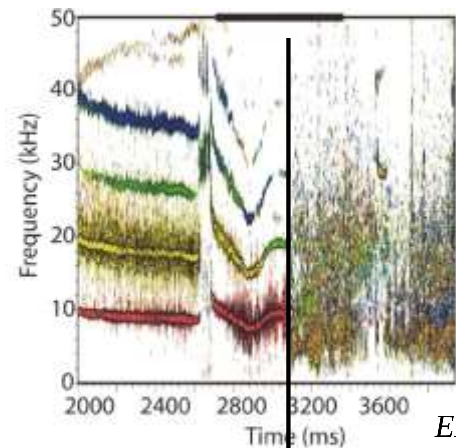
Quiescent Q–mode: DIII–D, AUG, JET, Jt–60U, JFT2–M

- EHO:
  - edge localized
  - series of harmonics like washboard
  - $m/n \sim q_{95}$
- Sometimes broadband turbulence
- Counter injection, large wall gap important
- ELMs return for co–injection or very large wall gap

[Snyder2007] [Oyama2005]



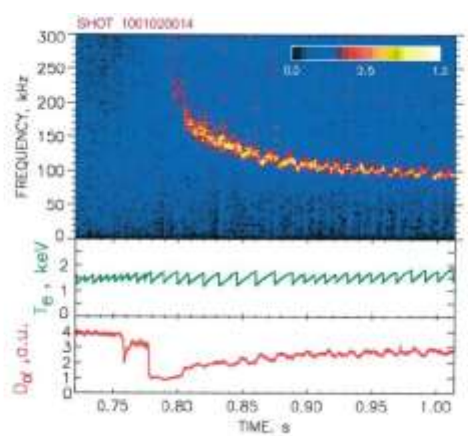
EHO spectrogram on ASDEX Upgarde [Suttrop2003]



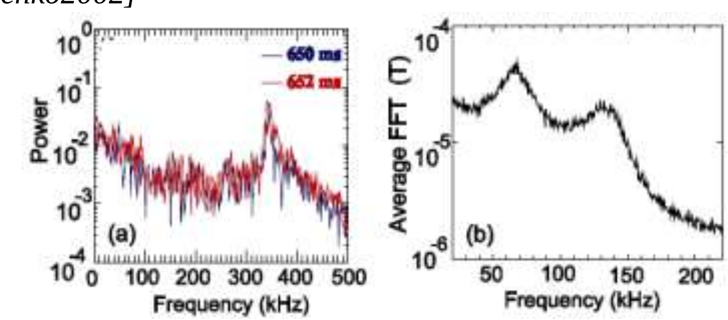
EHO modes are replaced by broadband turbulence [Burrell2005]

Enhanced D–alpha modes, EDA C–MOD

- QC mode causes transport
- At pedestal, spans the separatrix
- $m \sim 100$
- Sometimes double frequency
- May be a resistive X–point mode



QC mode in C-MOD [Mazurenko2002]



HRS: JFT–2M

- QC–like mode at 300–400 kHz
- n=7, m>10

Summary turbulence, H-mode and ELMs

We seem to understand the basic mechanisms involved in plasma turbulence, the H-mode and ELMs but no quantitative calculations can be done.

E.g. H-mode power limit scaling is not clear: ITER might not have enough power to reach H-mode.

There are several empirically developed tools for ELM control and at least one of them Is expected to succeed in ITER.

There is a coordinated action to understand H-mode and ELMs on present day devices

The H-mode is intrinsically linked to the system of turbulence and flows in the plasma, understanding of H-mode requires an understanding of turbulence.

Turbulence around the fusion plasma

Great expectations from 1950–1980

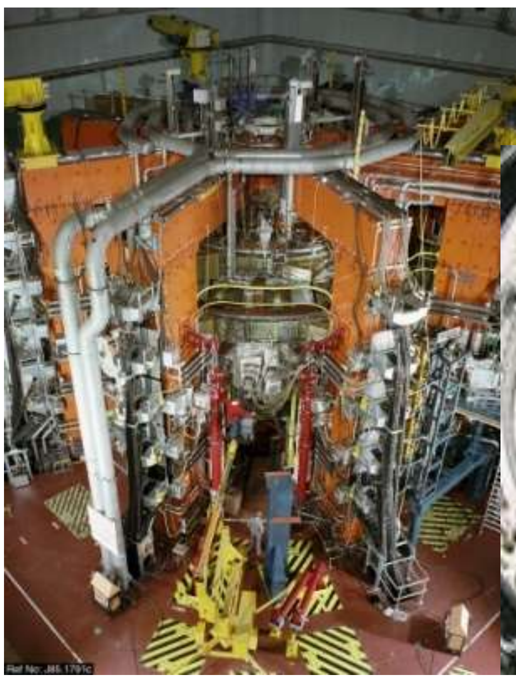
After various magnetic configurations the tokamak emerged as (suprisingly) the best performing device.

Golden age of tokamaks 1970’: >20 tokamaks built worldwide

R=0.4....1.5 m, all operate with pure D (no DT)

Extraplation showed that at about R=3m $P_{DT} \approx P_{heat}$ (Breakeven)

→Rush for the first DT breakeven: TFTR (Princeton), JET (Culham)

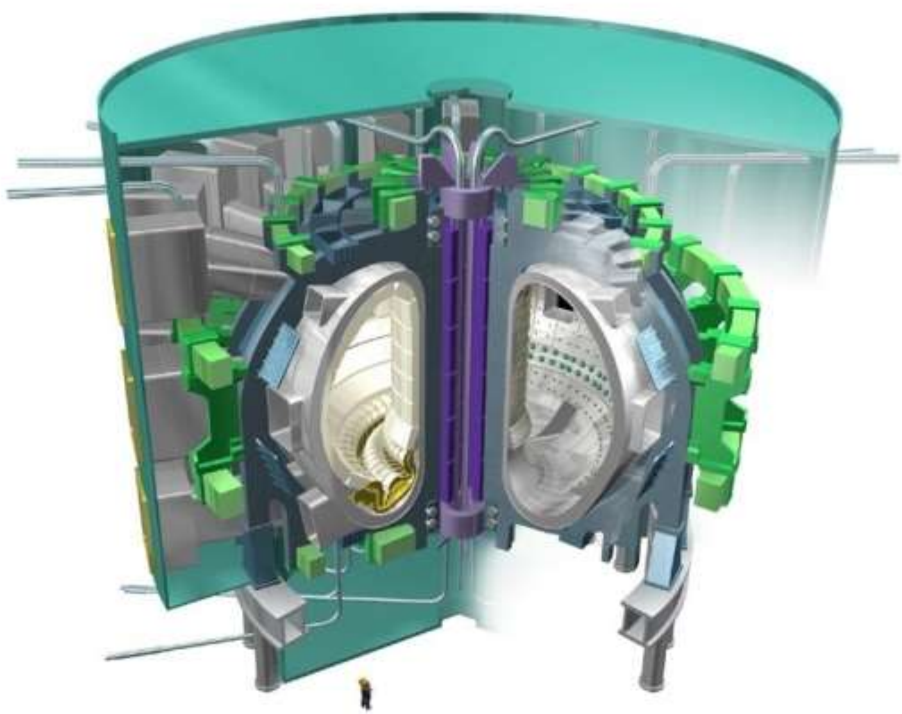


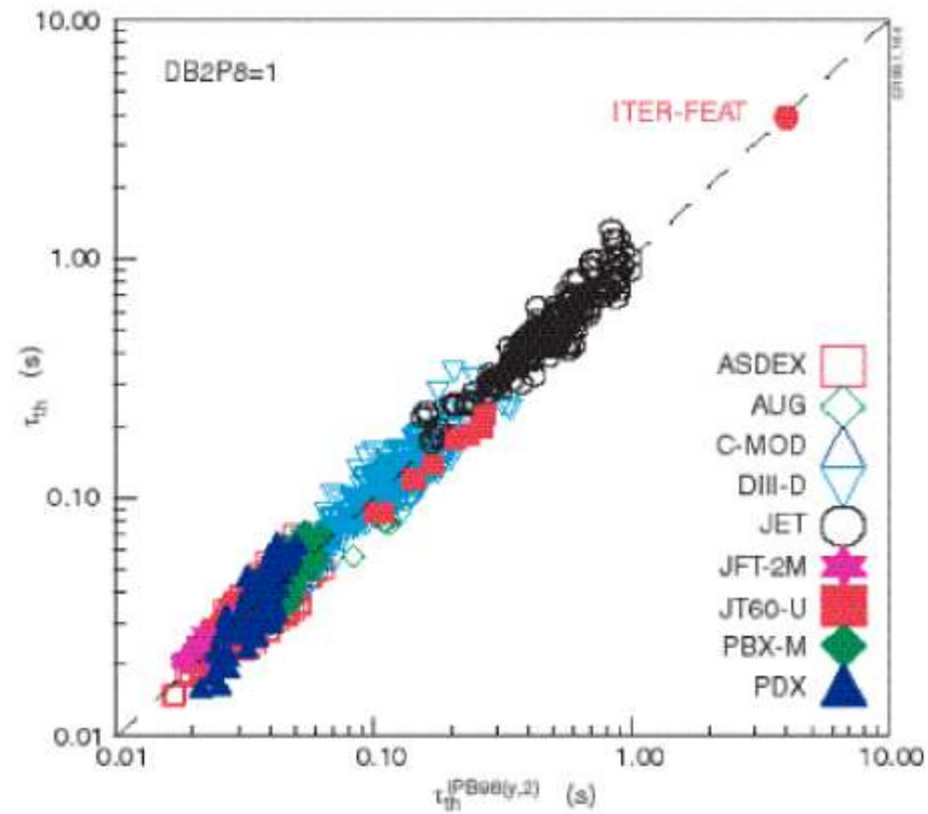
However stronger heating resulted in higher loss

→ power degradation → turbulence is the main actor

Although TFTR and JET did not produce breakeven they set up an empirical scaling at what size this would happen.

$$\tau_{\mathrm{E,th}}^{\mathrm{IPB\,98}(y,2)} = 0.05621 I_{\mathrm{p}}^{0.93} B_{\mathrm{T}}^{0.15} P^{-0.69} n_{\mathrm{e}}^{0.41} M^{0.19} R^{1.97}\ \varepsilon^{0.58} \kappa_{x}^{0.78}$$





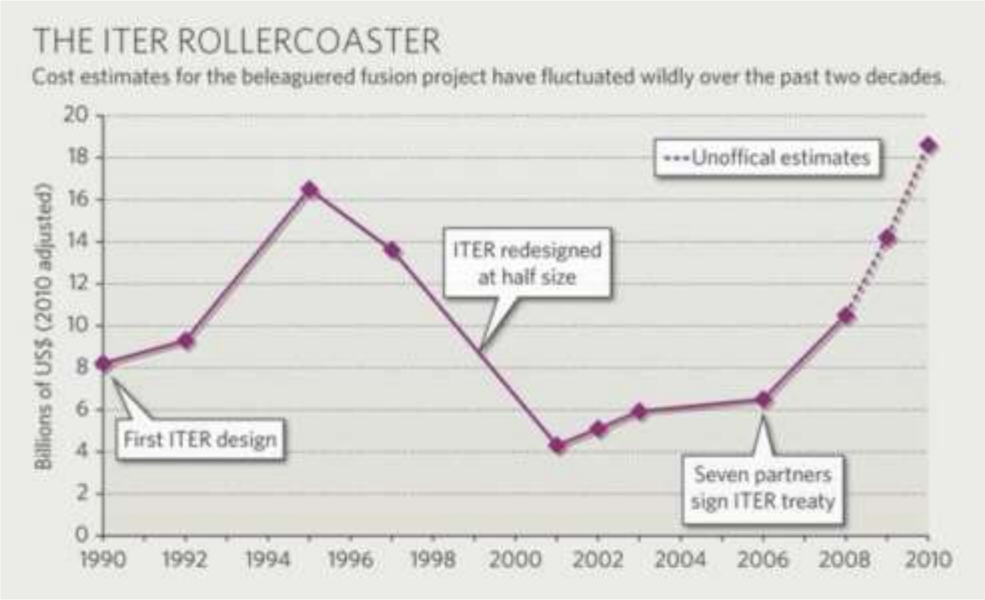
This scaling indicates that a tokamak at about 2x JET size could produce 10 more fusion power than the heating power.

The ITER turbulence

1985: First agreement on developing the concept (EU, USA, Russia, Japan)
1992: Conceptial design: R=6 m
1998: Engineering design: R=8 m 10 Billion USD
→ Political requriremnt: half cost
2001: Little ITER: R=6.2 m, 5 Billon USD (as requested)
2001–2006: Discussion on site
2006: Final ITER agreement (EU, USA, Russia, Japan, S. Korea, China, India)
First plasma 2016

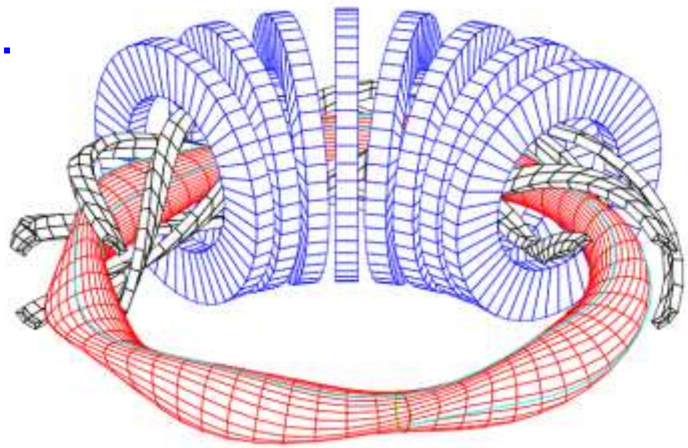
2007: Ratification, preparations
2008–2009: Site preparations
Design review, cost review
~12 Billion EUR
2016: Third ITER director:
works speed up

2025–26: First plasma
2035: First DT plasma



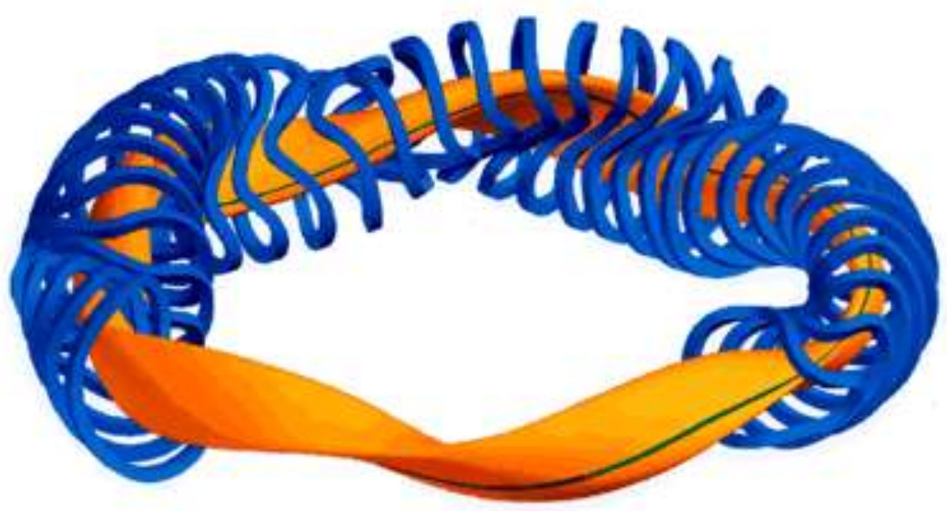
ITER today

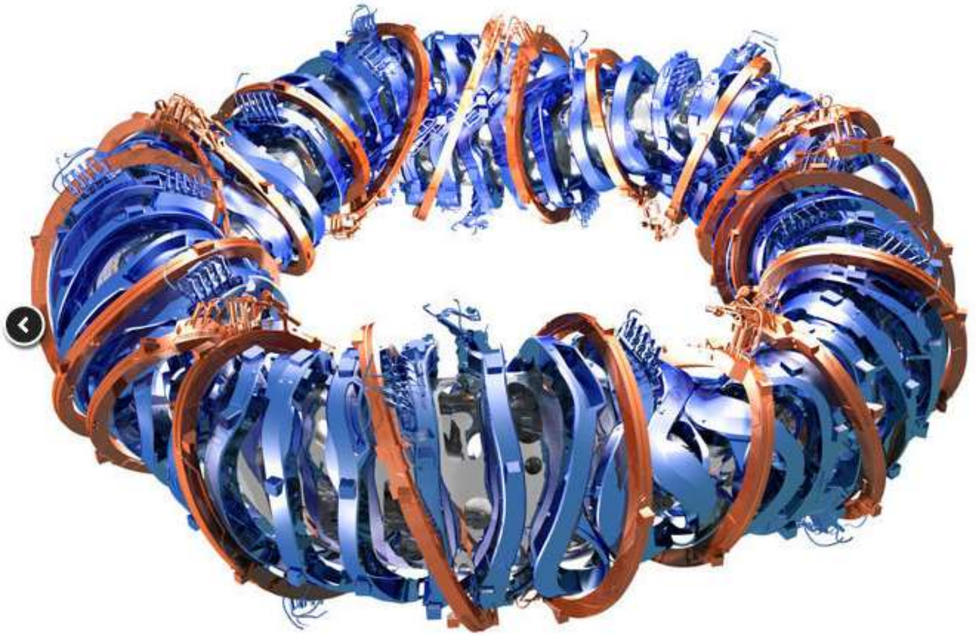
The stellarators in the 1960's did not perform well.
The reason was found in the 1980's:
Missing axial symmetry prevented particles to circulate in the torus



New generation of stellarators:

- Magnetic field configuration optimized to minimize particle transport
- Coil configuration designed to implement field
- Modular design: coils can be manufactured separtely



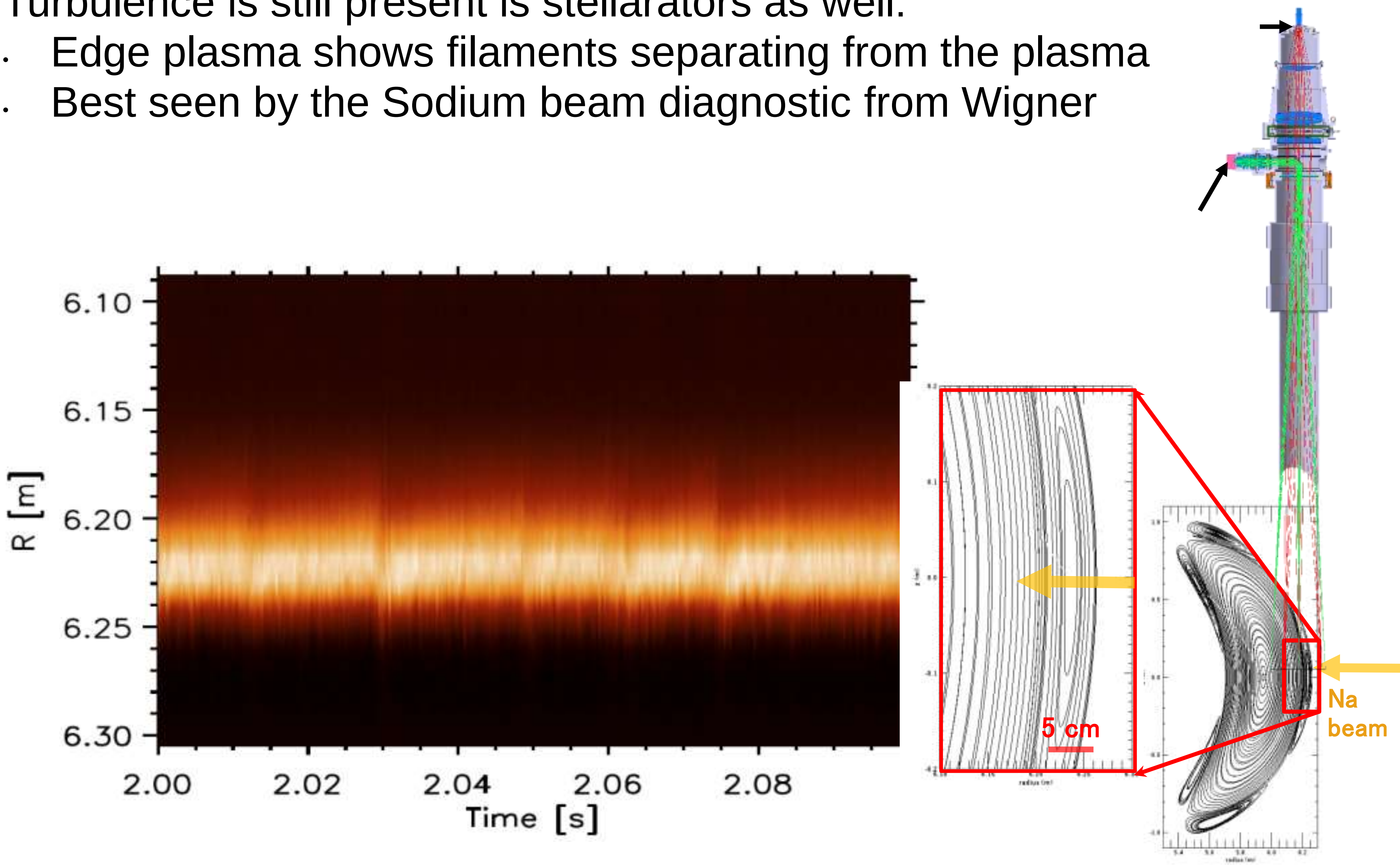


The first large superconducting modular stellarator (Greifswald):
R=5.5 m (ITER: 6.2 m)
5 modules
First two campaigns produced excellent results:

- No plasma current → no instability
- Steady state operation (up to 100s in 2018)

Turbulence is still present is stellarators as well:

- Edge plasma shows filaments separating from the plasma
- Best seen by the Sodium beam diagnostic from Wigner



Plasma turbulence remains a key challenge in fusion research:

- Basic processes are known at least at mm scale
- The full turbulence-profile-flow system cannot be reliably predicted
- Extremely interesting topic for physics theory, diagnostic, engineering, control schemes.

- ITER will hopefully start in 2025
- A demonstration reactor is being designed, to be built after ITER
- Stellarators may be an alternative line, but engineering difficulties are immense.

Hungarian fusion research is on large device around the world: JET(UK), W7-X(D), ASDEX Upgrade(D), COMPASS(CZ), MAST(UK), EAST(CN), KSTAR(KO), JT-60SA(JP)

See you at magfuzio.hu