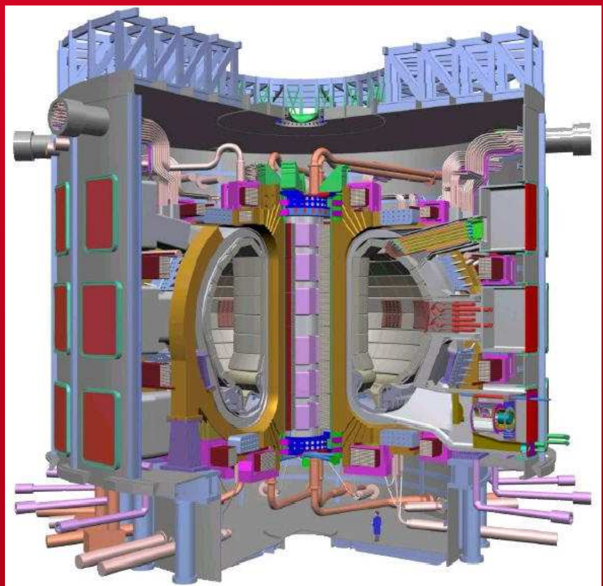
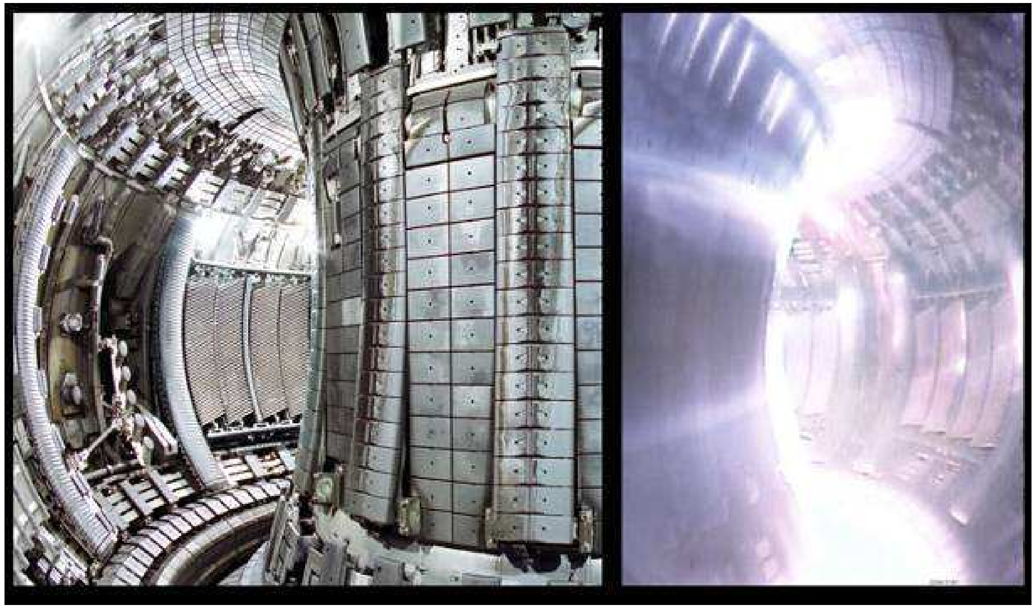
DE LA RECHERCHE À L'INDUSTRIE

Maîtriser les complexités d'ITER





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***Bordeaux**, 13 octobre 2015*

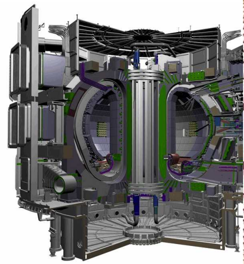
Philippe GHENDRIH

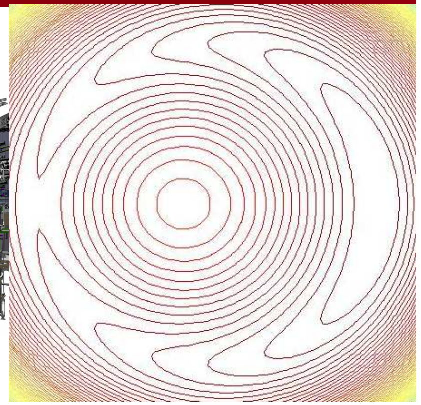
The Fusion Heat Engine

Fusion Energy Source

on the way to burning plasmas

We need maths! (CONTROL)

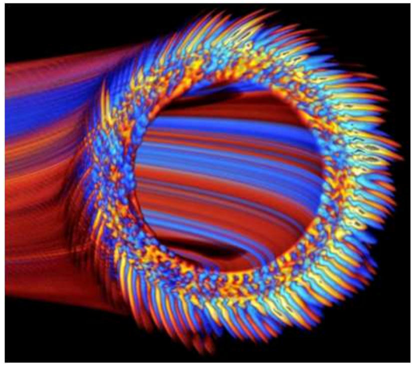




Plasma turbulence

self-organisation (HEAT)

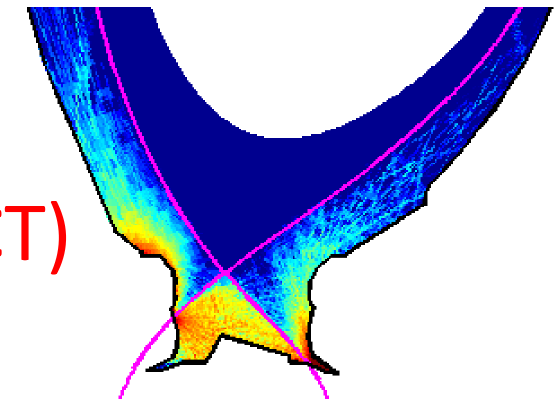
success requires new goals!

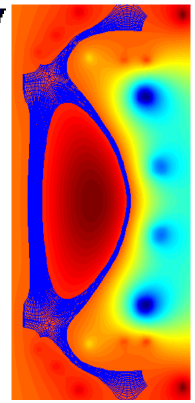


Plasma-wall interaction

divertor nightmare (EXTRACT)

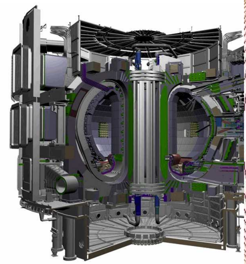
time to face it!

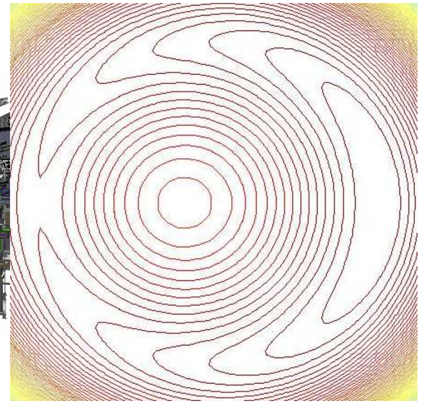




ITER: A long way to go…

Towards burning plasmas





Fusion Energy Source

on the way to burning plasmas

We need maths! (CONTROL)

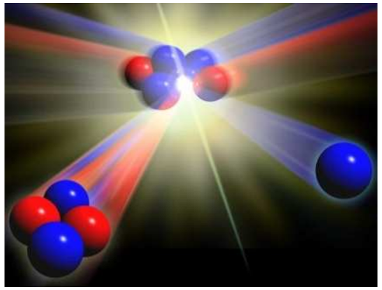
Changing practise

new rules (nuclear safety)

new players (engineers, material science...)

new goals: ITER must succeed

Fusion Engine: confine heat



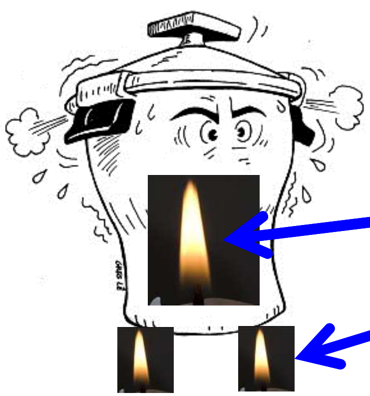
strong collision @10 keV D + T plasma

3.5 MeV helium ash (α particle)

=

plasma energy source

heat losses $\longrightarrow$ plasma energy balance



$$P_\alpha + P_{add} - \frac{W_{internal}}{\tau_E} = \partial_t W_{internal}$$

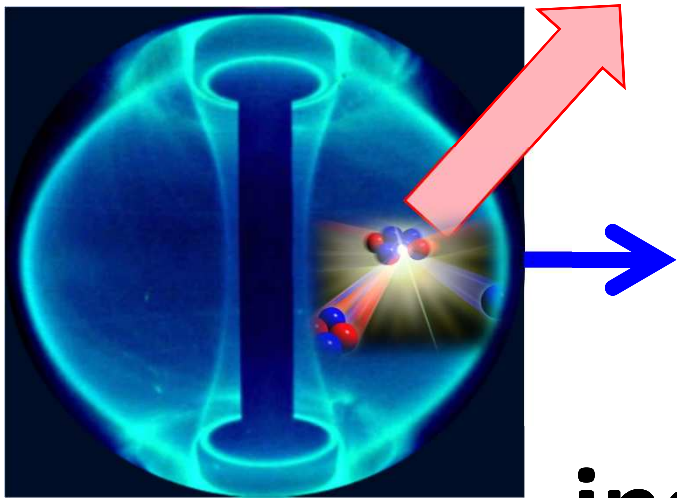
τ_E: heat confinement efficiency

Beat confinement losses

$$\tau_E = \frac{6.2\ 10^{20}\ s\ m^{-3}}{n_e} \frac{Q}{(Q+5)} \qquad Q = \frac{P_{out}}{P_{in}} = \text{Amplification factor}$$

Lawson 1957

Low density burn: ITER **Q = 10** $\Rightarrow$ $\tau_E \approx$ **5 s**



100 000 000 K

$\Delta T = 10^8$ K

a = 2 m

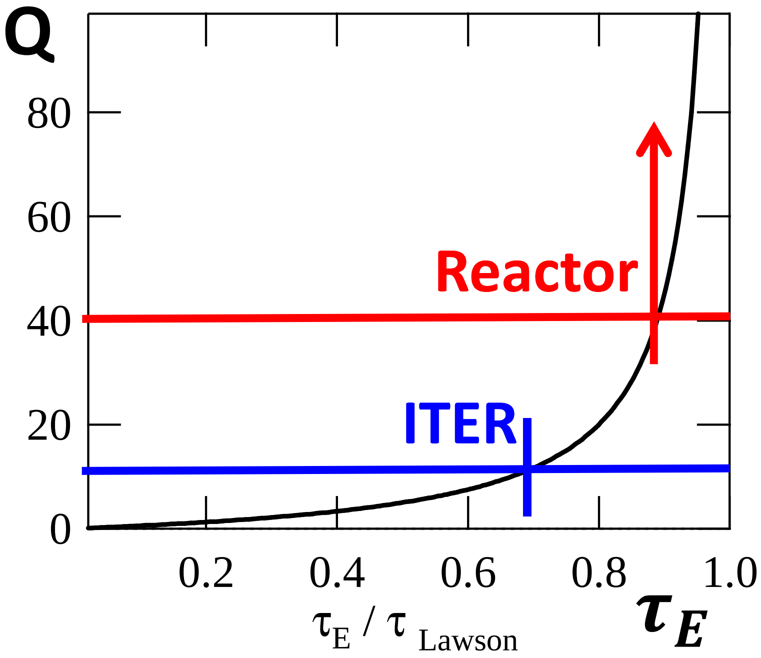
450 K

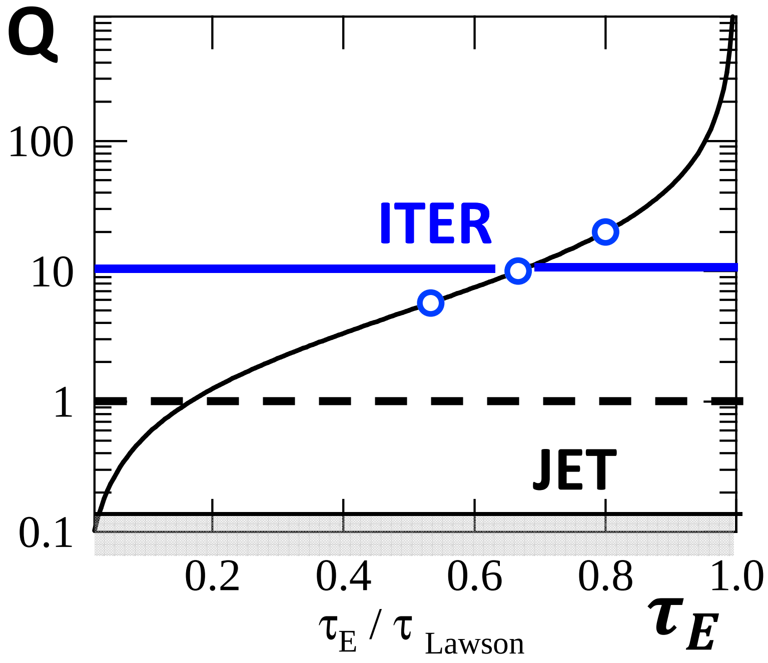
α heating power

≈ 100 MW / 1000 m^2

insulator = magnetic field

ITER a step towards a reactor





$Q_{ITER} \approx 10$ but $\tau_E \sim \pm 20\ \%$

$\Rightarrow 5.7 \leq Q_{ITER} \leq 20$

ITER operation: no free lunch

Why Q = 10? $P_\alpha = 2\,P_{add}$

= burning plasma condition

How Q = 10? $\tau_E \geq 5$ s

= H-mode regime

How H-mode conditions?

with Q = 10

ITER Complexity

Complexity is everywhere?

why?

= no margin

- Operation at nominal B mandatory
- Operation point: route via H-mode
- Neutrons: Too few to be relevant
  Enough to make a mess
- Etc...

Optimise + risk minimisation

Experiments in a nuclear facility

= optimisation

➡ minimise risks

➡ maximise benefits

Simulations

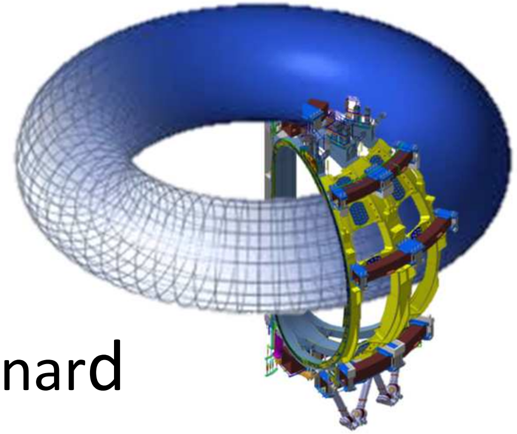
at all scales

of all kinds: physics, technology, system codes...

Simulations are strategic ➡ maths

B-geometry: tokamak

Free // motion: solution = torus

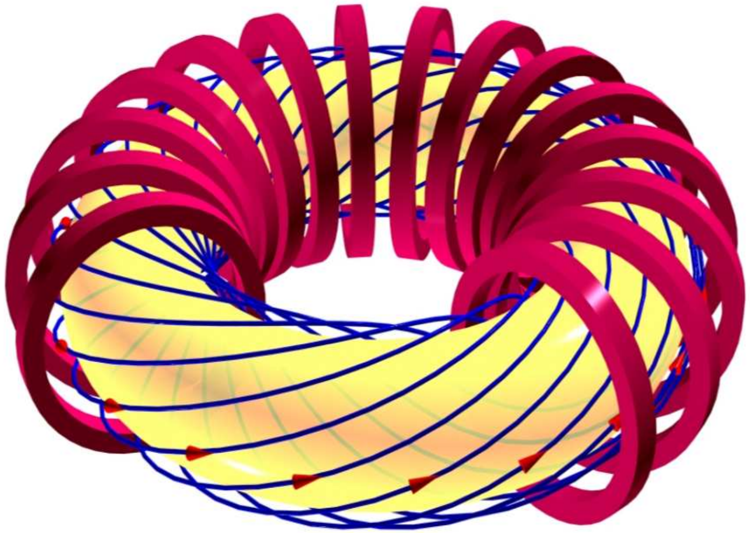


centrifugal force = **g-force**

drive of **interchange** instability

= Rayleigh-Taylor/Rayleigh-Bénard

High Performance Magnetic Geometry: **Tokamak** $\Rightarrow$ **ITER**



= alternating g-force

field B $\approx$ 5 T

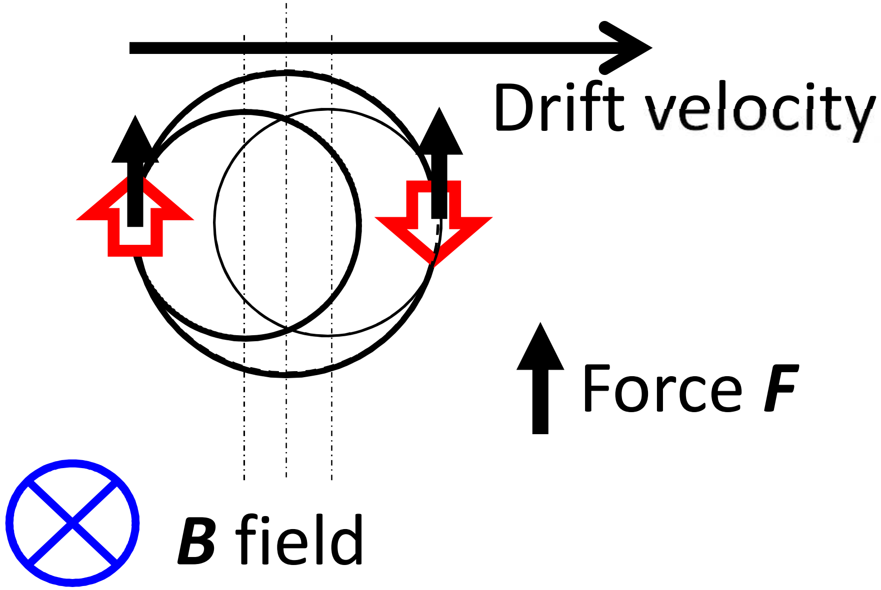
size : R $\approx$ **6 m,**

a $\approx$ R/3 = 2 m

height $\approx$ 4a = 8 m

$\mathbf{g \approx \rho_* = \rho_\perp / a = 10^{-3} << 1}$

Drift velocities



$$\vec{u}_\perp = \frac{1}{q_\alpha n B^2} \vec{\mathcal{F}} \times \vec{B}$$

Potential : $\vec{\mathcal{F}} = -n \vec{\nabla} U$

Stream functions: $\vec{u}_\perp \approx \vec{\nabla} \times \left(\frac{U}{q_\alpha B^2} \vec{B} \right)$

charge dependent = current

compressibility part = g term

Dimensionless parameters

Normalised Landau-Vlavov:

$$\partial_t f + \frac{V\tau}{L}(\vec{v}\cdot\bar{\nabla})f + \Omega\tau\left[\frac{E_0}{VB_0}\vec{E} + \vec{v}\times\vec{B}\right]\frac{\partial}{\partial\vec{v}}f = \tau\nu\frac{C_0}{f_0}C$$

Species dependent control parameters

- ❑ $\nu^* = \tau\,\nu$
- ❑ $\tau = L_\perp / V_\perp = L_{//} / V_{//}$ current loops
  - ▪ $V_{//} = v_{th}$; $L_{//} \propto R$
  - ▪ $L_\perp = \rho_L$; $\rho^* = \rho_L / a$ (Reynolds) ; $V_\perp = v_{th}\,\rho^*$
- ❑ $\Omega\,\tau >> 1$; Gyrokinetics framework
- ❑ E_0 plasma current 1V / m, breaking ambipolarity 1 kV / m

  breaking quasineutrality 1 MV / m

Asymptotic limits

Gyrotropy **Plasma turbulence:** $\Omega\tau \gg 1$

$$\vec{B}\cdot\left(\vec{v}\times\frac{\partial}{\partial\vec{v}}\right)f = B\frac{\partial f}{\partial\varphi_G} = 0$$

f = Gyrotropic

Vlasov:

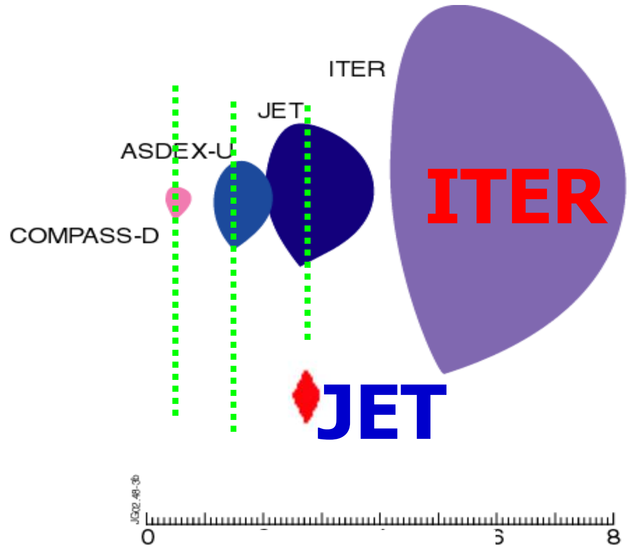
$$\partial_t f + \frac{v\tau}{L}(\vec{v}\cdot\vec{\nabla})f + \Omega\tau\left[\frac{E_0}{vB_0}\vec{E} + \vec{v}\times\vec{B}\right]\frac{\partial}{\partial\vec{v}}f = 0$$

Poisson: $\Delta\phi = n_e - n_i$

Quasineutrality:

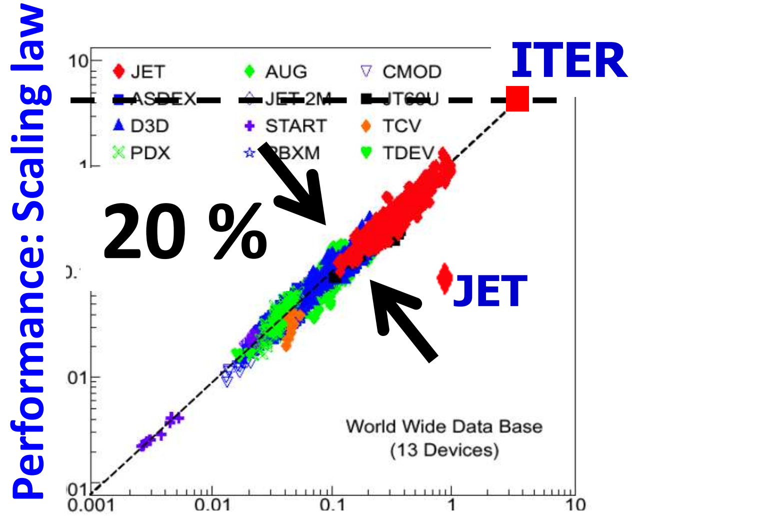
only one scale ρ **+** homogeneous in density

Modelling ITER confinement



size = cost

$\tau_{E\ law}$



Performance: empirical τ_E

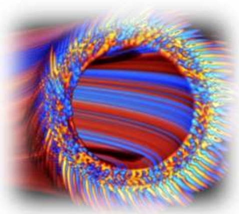
Dimensionless form:

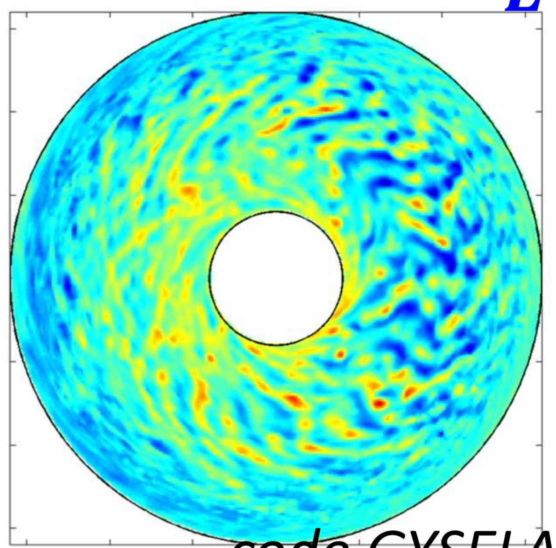
$$\Omega\tau_E \equiv \rho_*^{-2.7}\beta^{-0.9}\nu_*^{0.0}$$

ρ_* ≈ Reynolds number

β ≈ plasma pressure

ν_* ≈ collisionality





code GYSELA

Scaling laws: bad games

$$\Omega\tau_E \equiv \rho_*^{-2.7}\beta^{-0.9}\nu_*^{0.0}$$

Non-collisionnal
Electromagnetic

ITER 1998

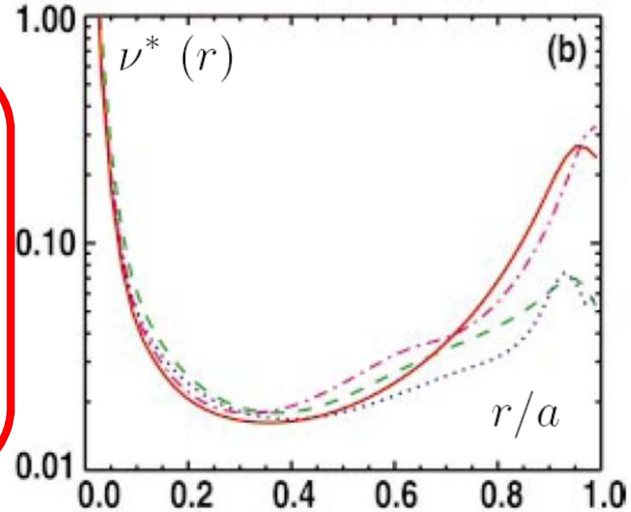
2.7 -0.9 0.00

Dedicated experiments: JET (EU) & DIII-D (USA)

3.0 0.0 -0.35

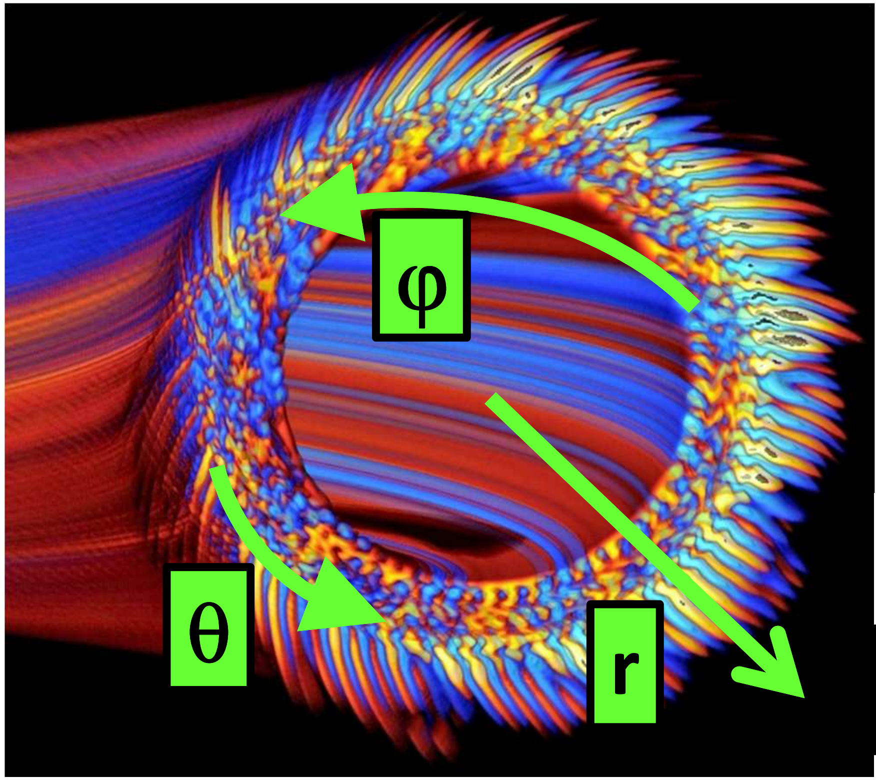
$$\Omega\tau_E \equiv \rho_*^{-3.0}\beta^{0.0}\nu_*^{-0.35}$$

Collisionnal
Electrostatic
GyroBohm



Artificial performance: **H98** = $\tau_{E\ exp} / \tau_{E'98}$

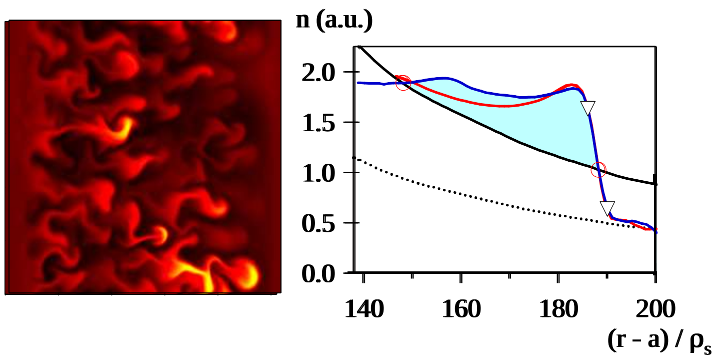
A guide to the various plots

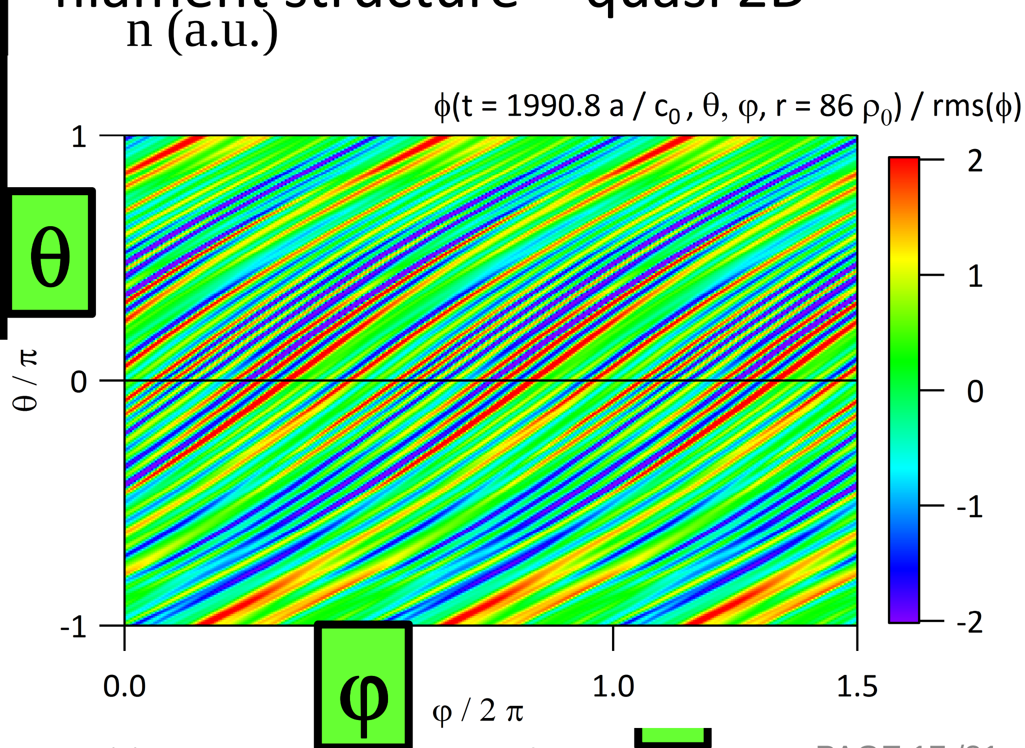


Torus = 2 angles + radial coordinate

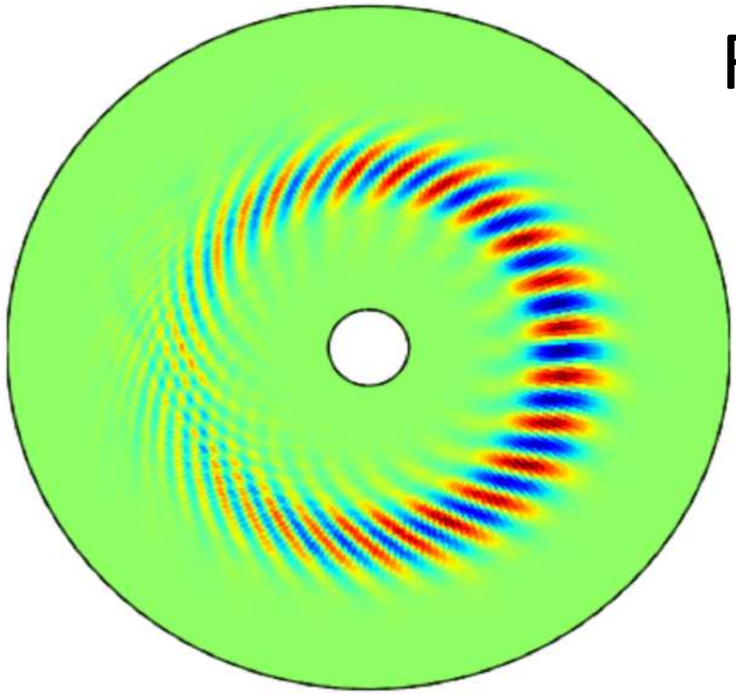
unfolding the angles 1-D & 2-D plots

filament structure ≈ quasi 2D

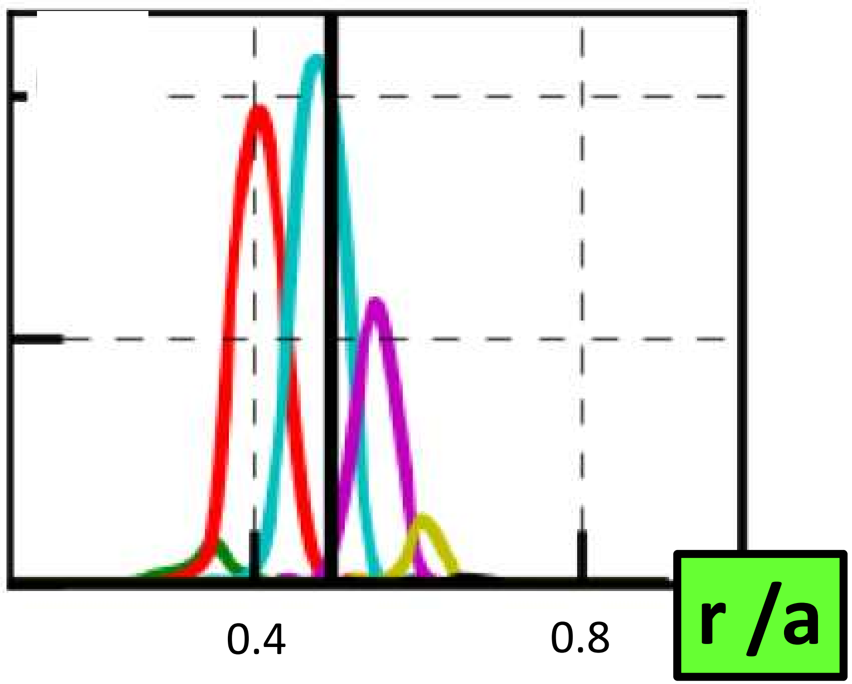




Interchange instability



Filtered Eigen mode (r, θ)
ballooned structure

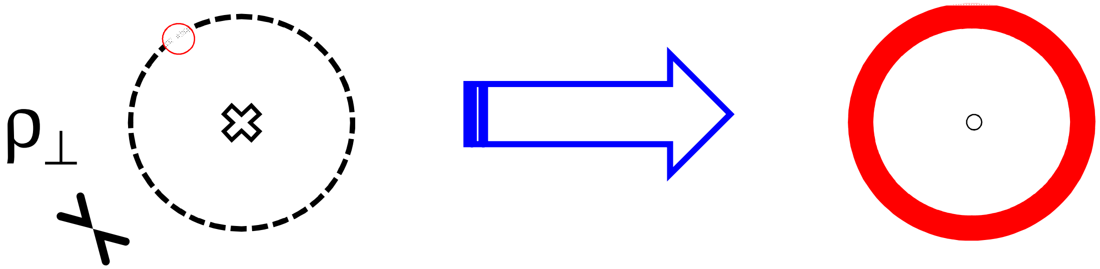


Symmetries

collisions = isotropic
gyration = cylindrical
equilibrium = toroidal axisymmetric
turbulence/MHD = non-axisymmetric

Kinetic effect: particle trapping

High frequency (Ω) = $\perp$ particle motion → gyroaverage



$\rho_\perp \approx 10^{-3}$ m

Particle trapping

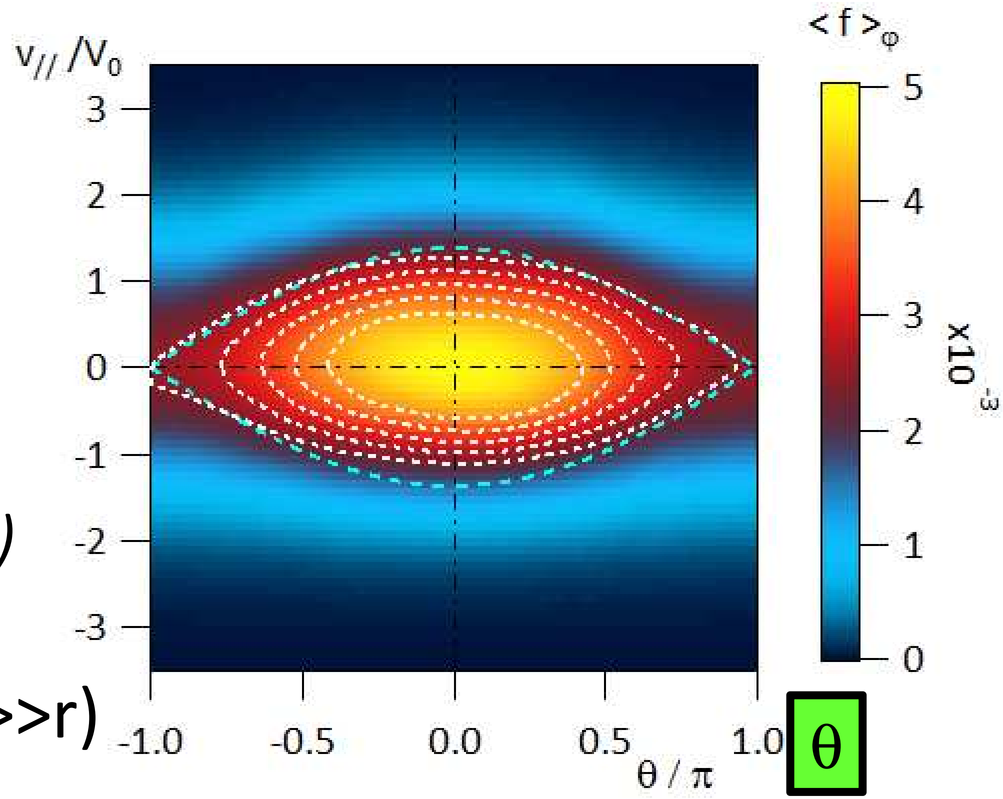
μ magnetic moment

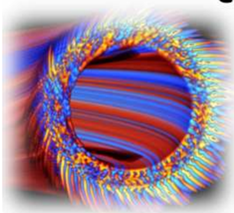
$$H = \frac{1}{2} m_\alpha v_\parallel^2 + \mu \, B$$

B ∝ 1 / R *(Ampère circulation)*

torus: $R = R_0 + r \cos\theta$

≡ pendulum ($R_0 >> r$)

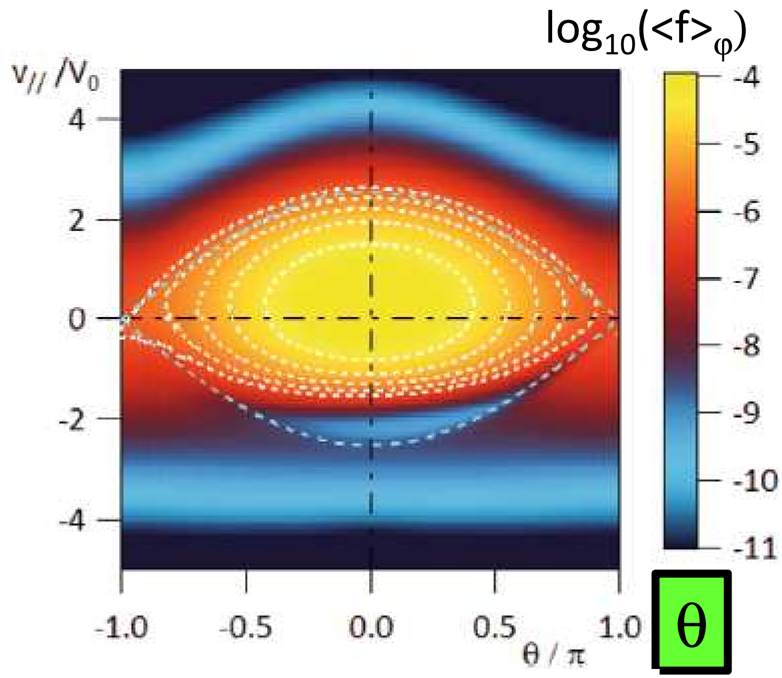


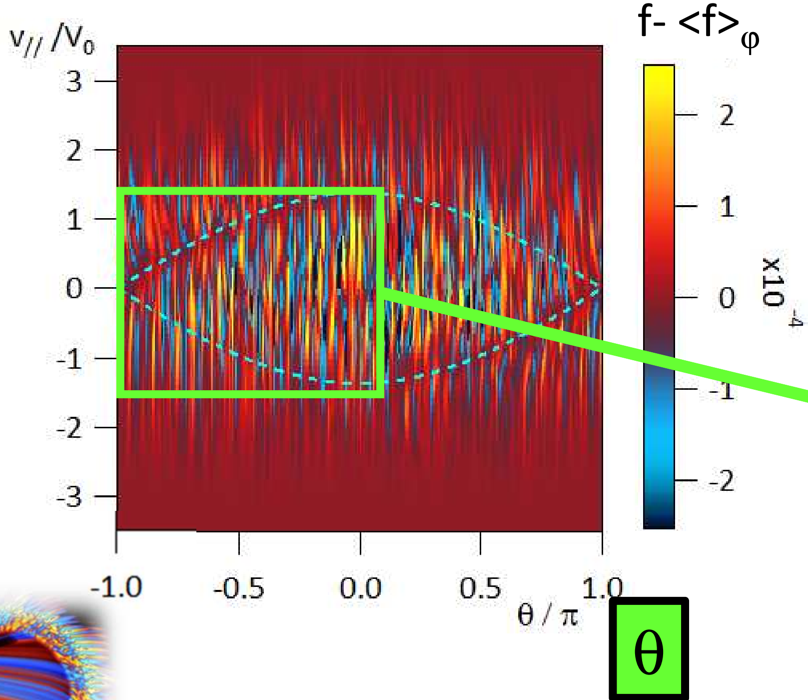


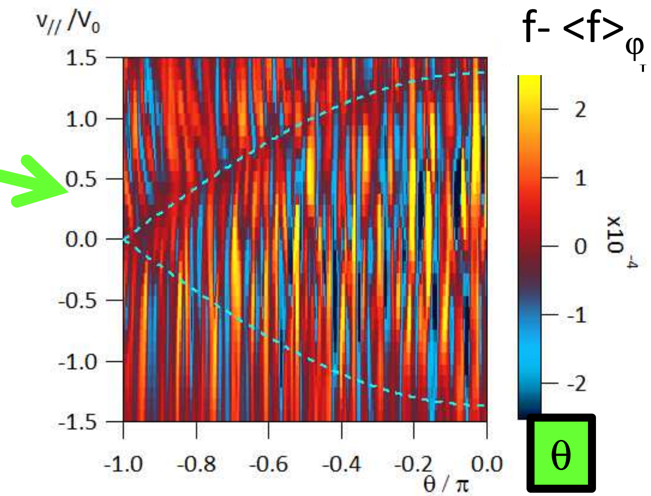
Kinetic effects: non-maxwellian f:

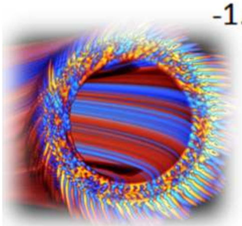
Particle trapping & turbulence

$$H = \frac{1}{2} m_\alpha v_\parallel^2 + \mu\ B + q_\alpha\ \phi$$

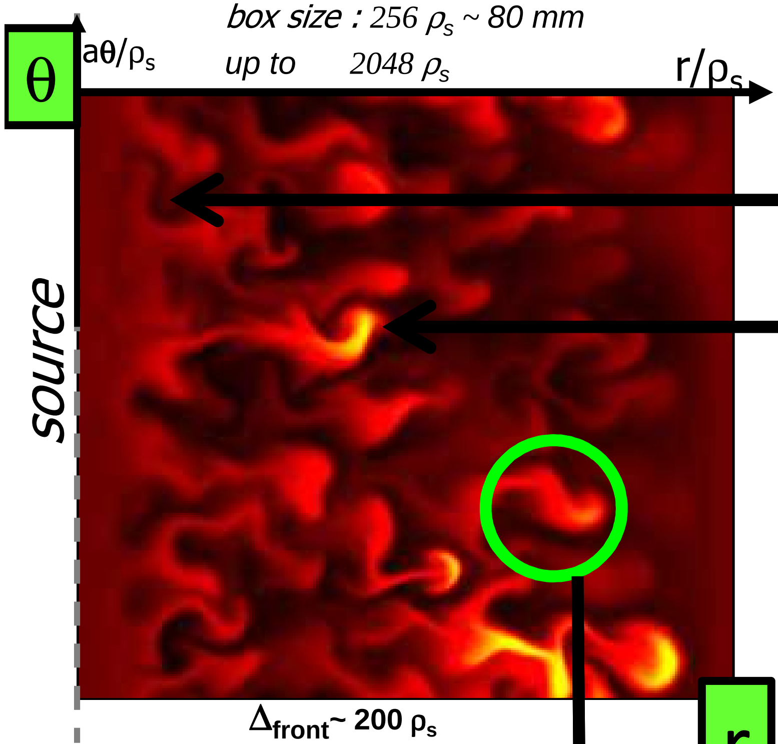








Avalanches: fronts & holes



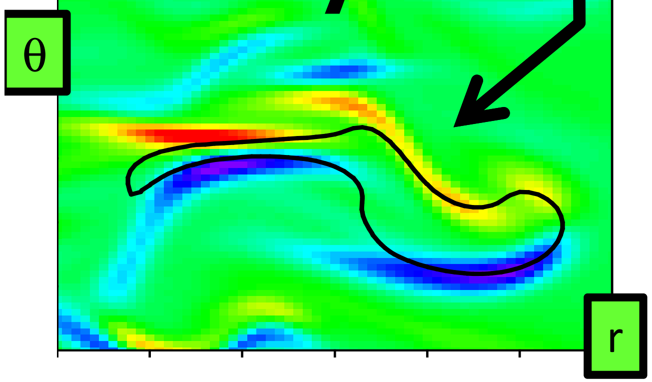
hole (sub-dense)

over-dense front

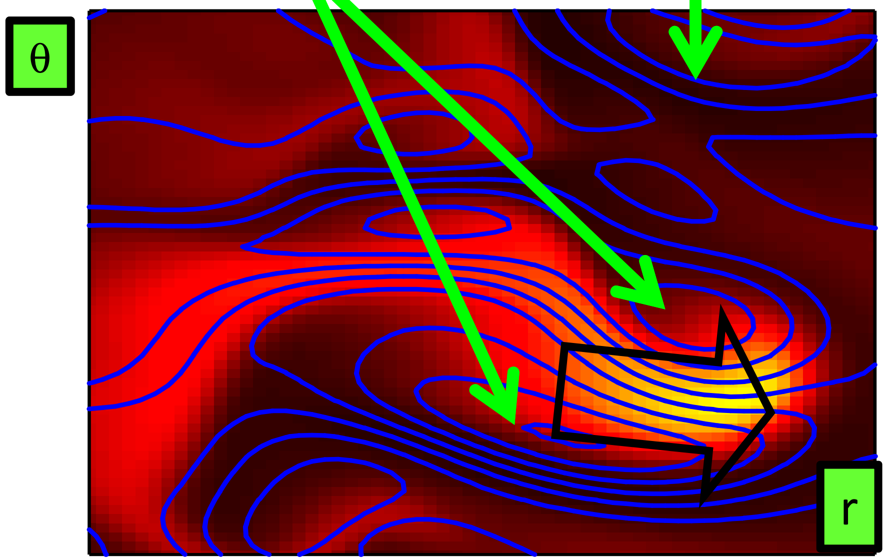
dipole nested in the wings of the front

iso stream function

vorticity source

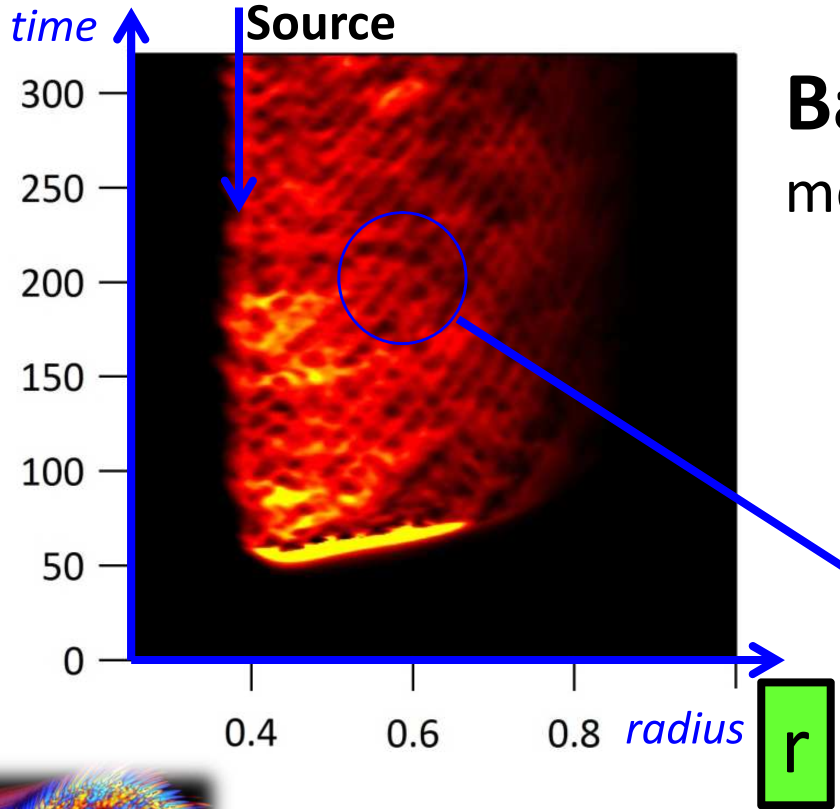


$\Delta\phi_{\perp} \propto \partial_{\theta} n$



Turbulent electric potential ϕ $\Rightarrow$ Turbulent heat flux

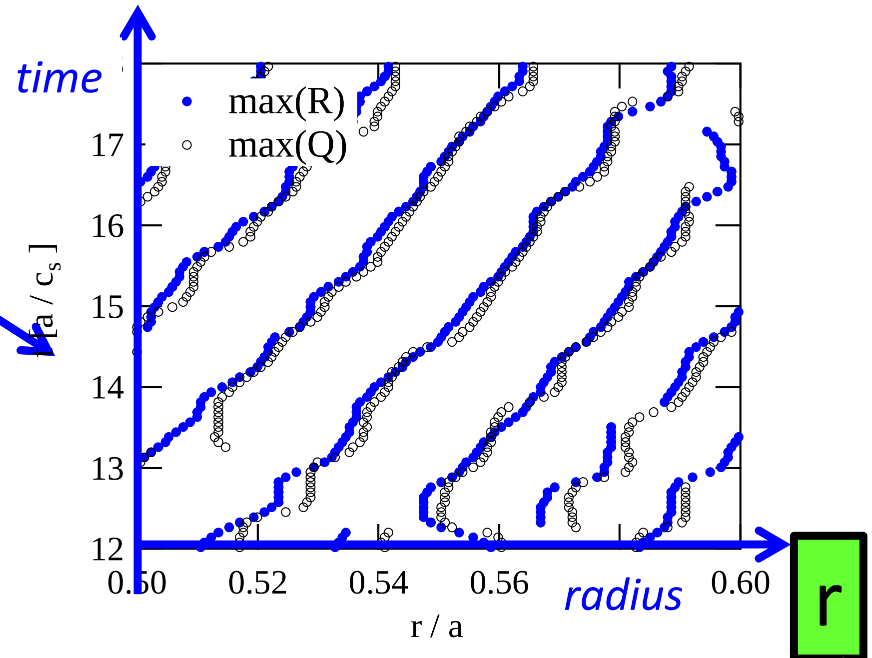
$\Rightarrow$ Turbulent Reynolds stress

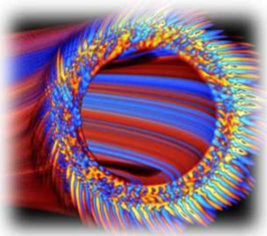


Ballistic transport events

more avalanche-like (SOC)

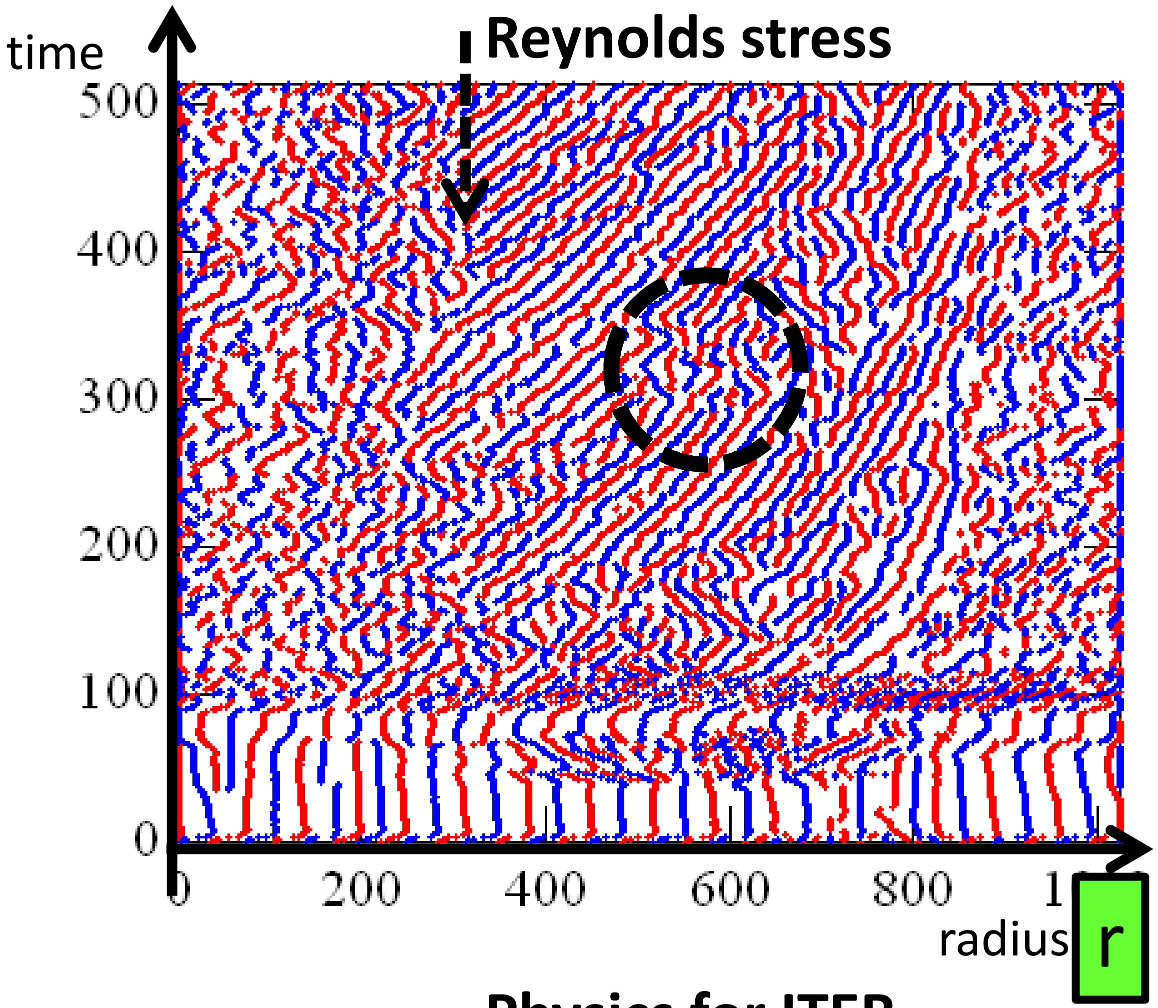
than Fourier-like heat transport

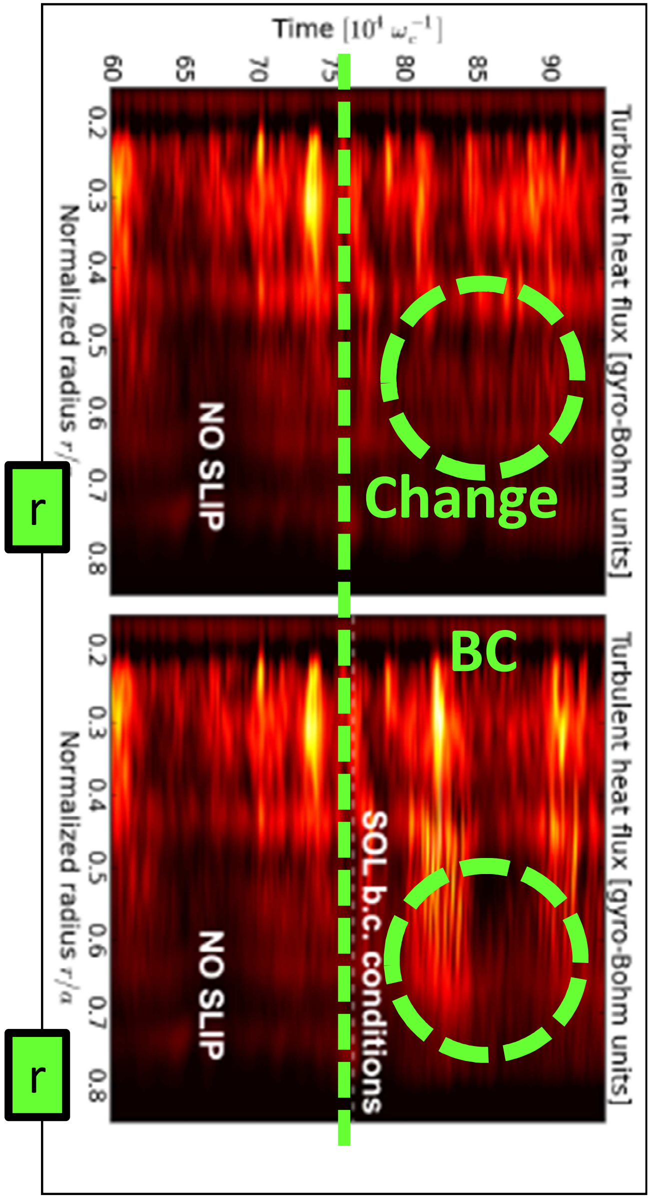




ANR GYPSI

Boundary layers



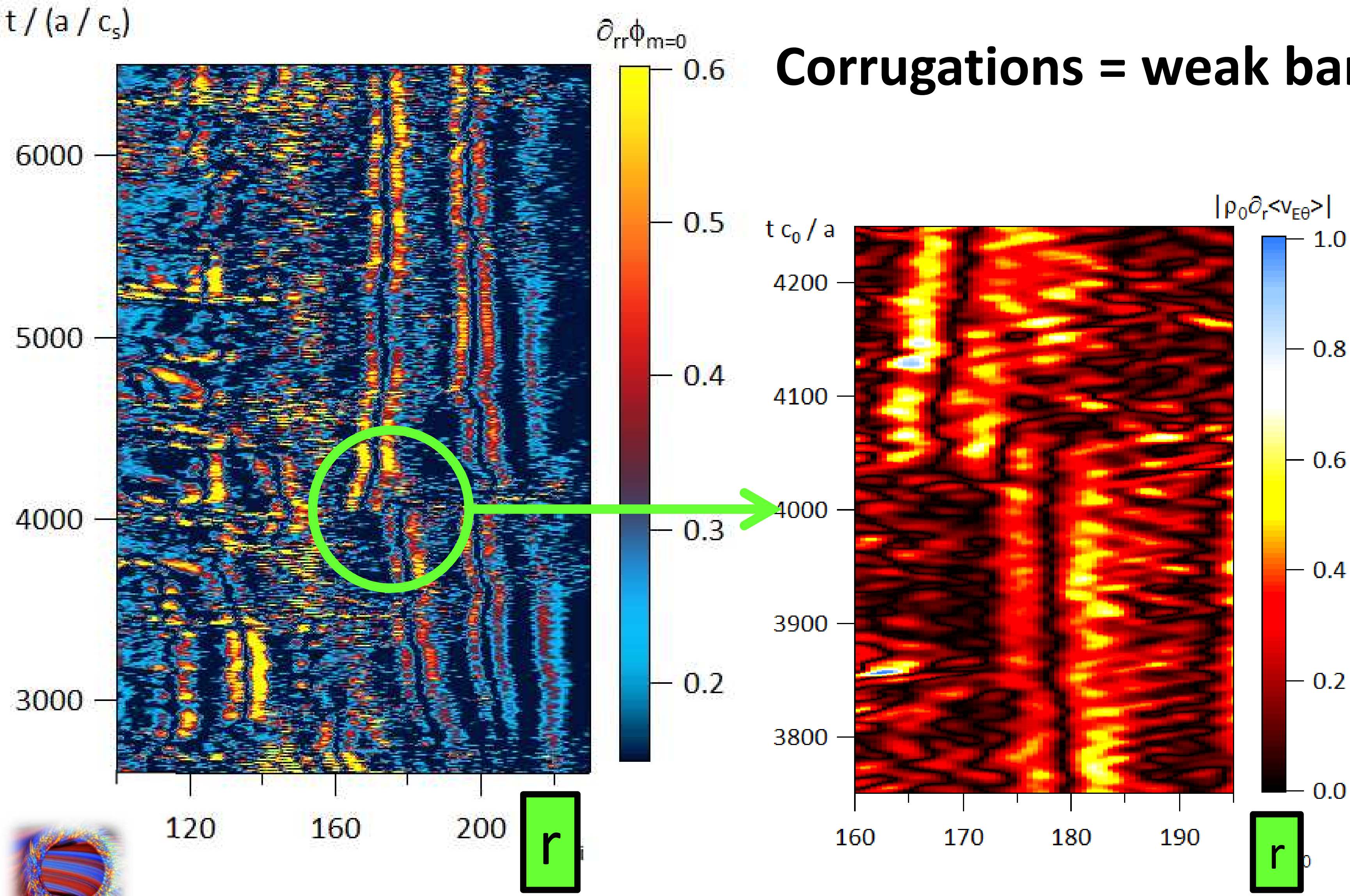


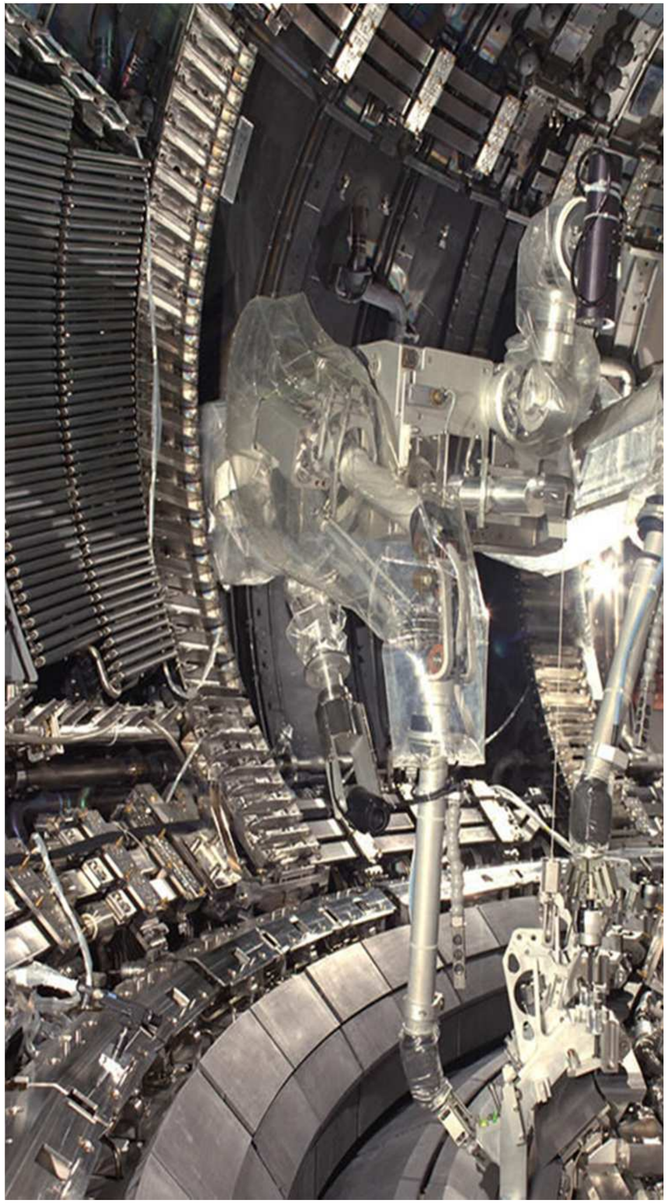
Physics for ITER

ANR GYPSI

Barriers & corrugations

Corrugations = weak barriers

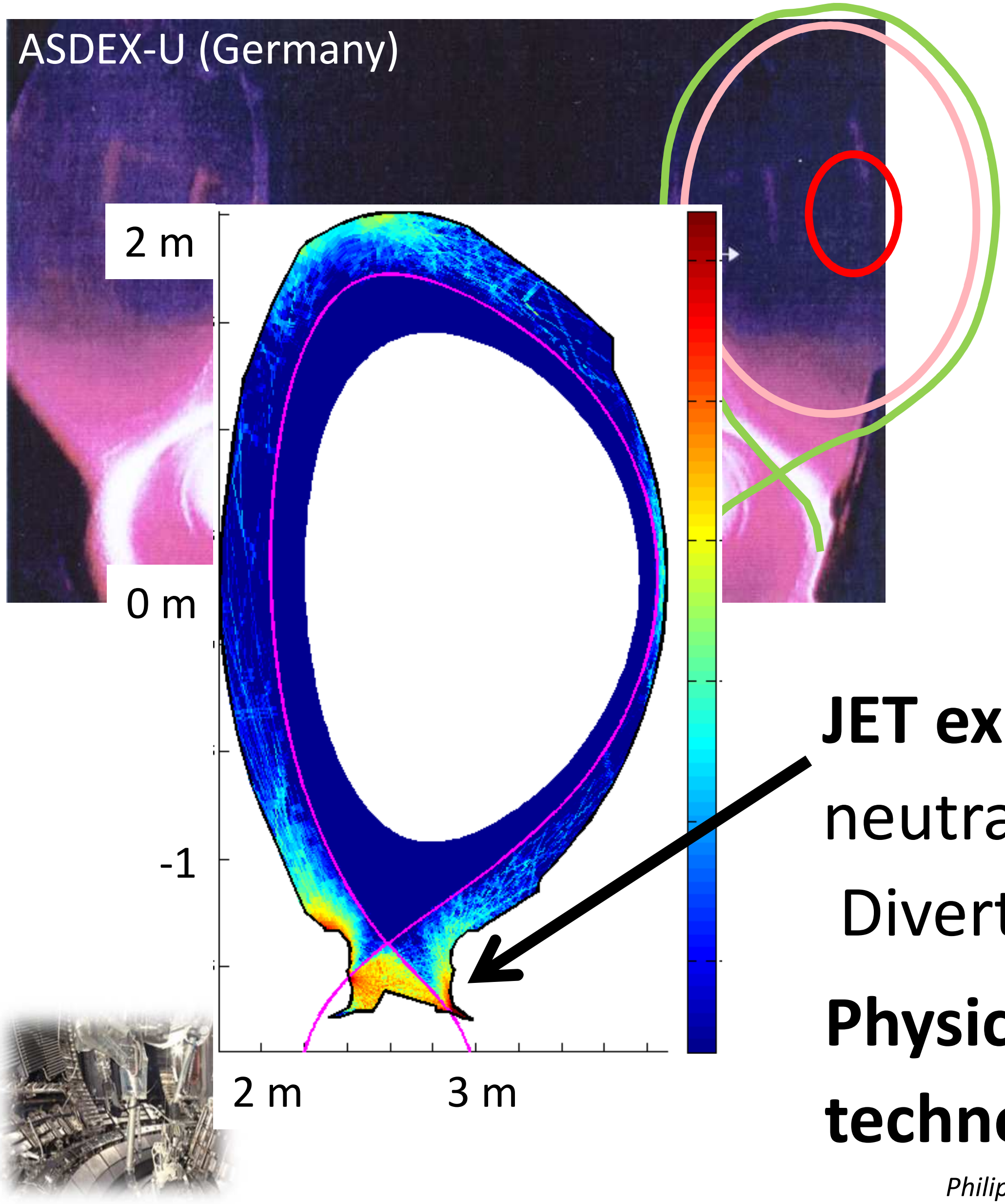


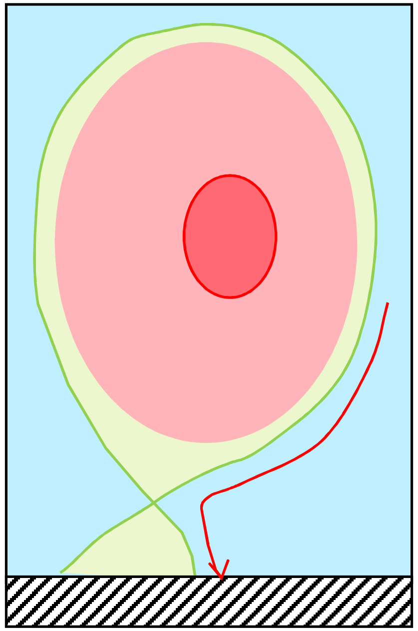


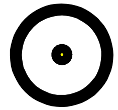
CONTROLLING HEAT EXHAUST

Ensuring long life time of Wall components

HEAT fluxes to ITER WALL?







// heat flux

100 MW/m^2

to 10 GW/m^2

JET experiment (EU)

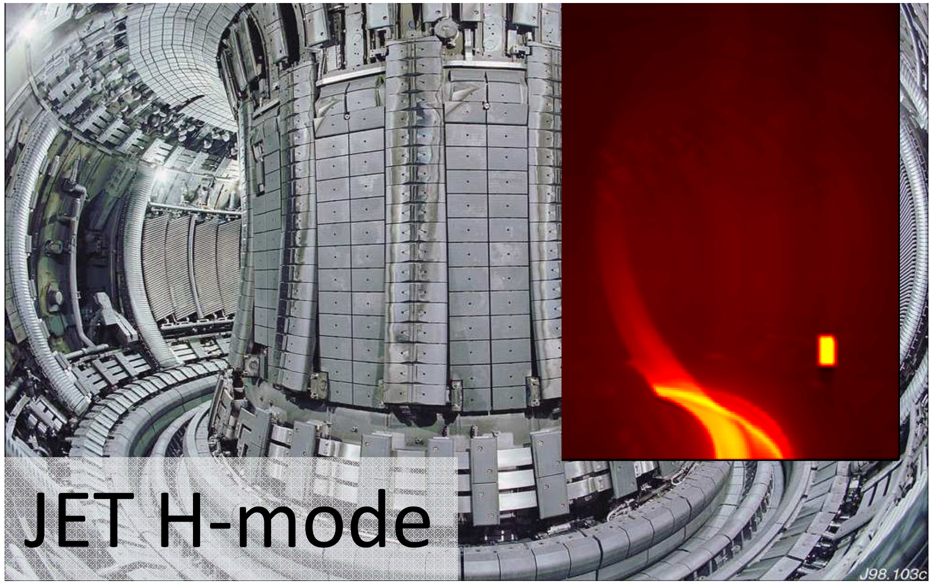
neutral particle pressure

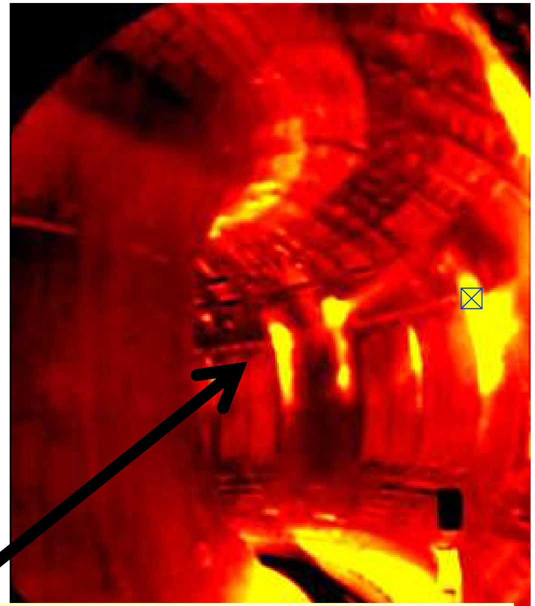
Divertor volume

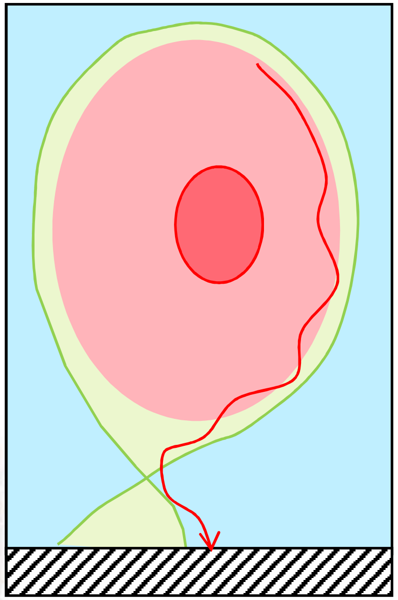
Physics meets Technology

technology limit 10 MW / m^2

ELMs: MHD relaxation events





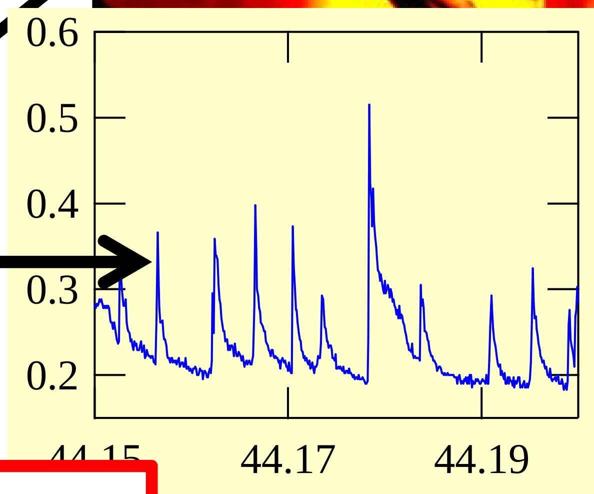


// heat flux

ELM wall impact

relaxation events

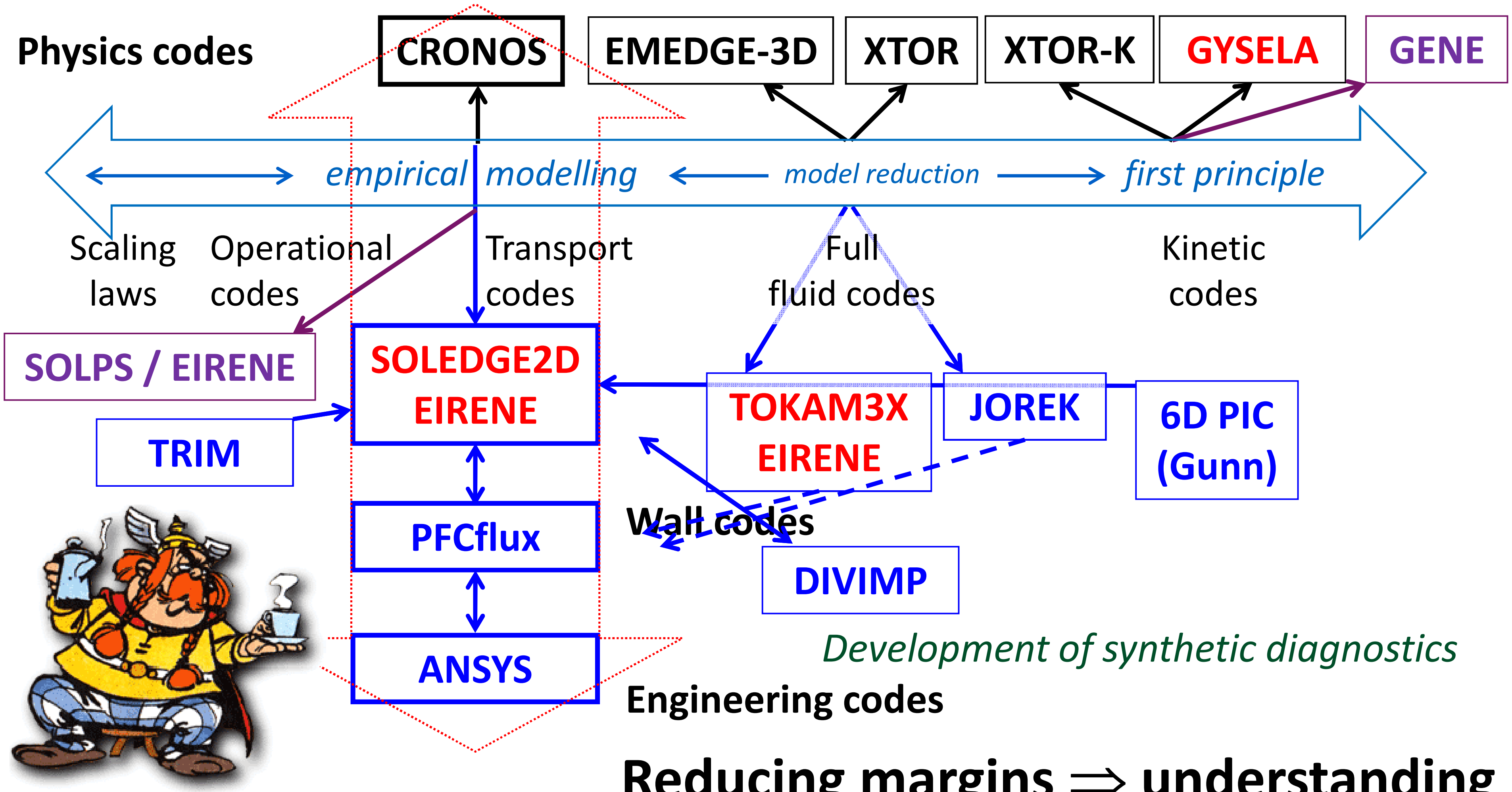
quasi-periodic



Must be controlled

Simulation effort: physics & engineering

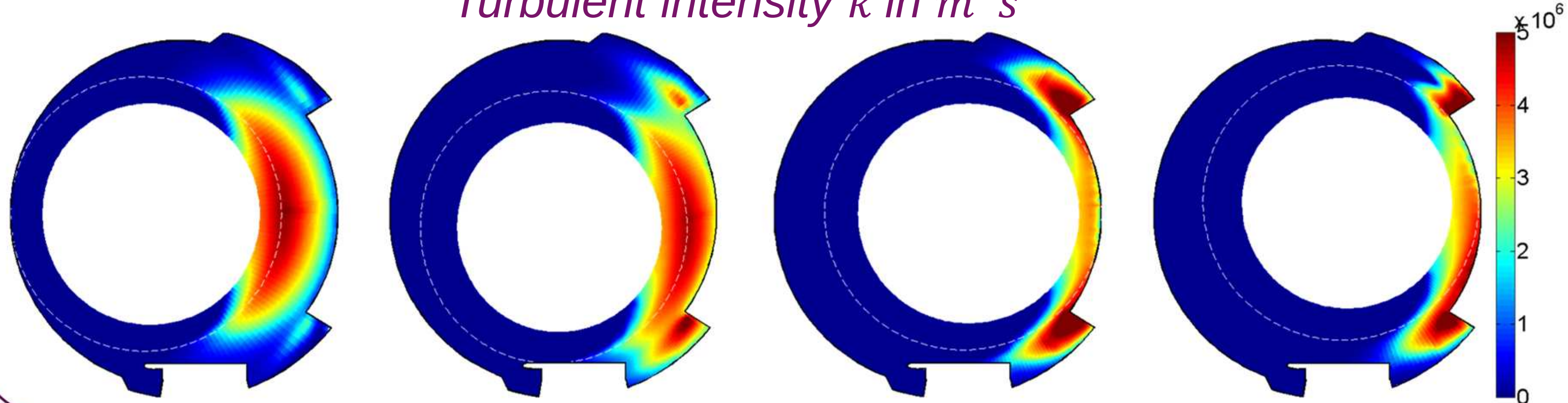
Reactor design with reduced experimental backing = ITER



Reducing margins ⇒ understanding

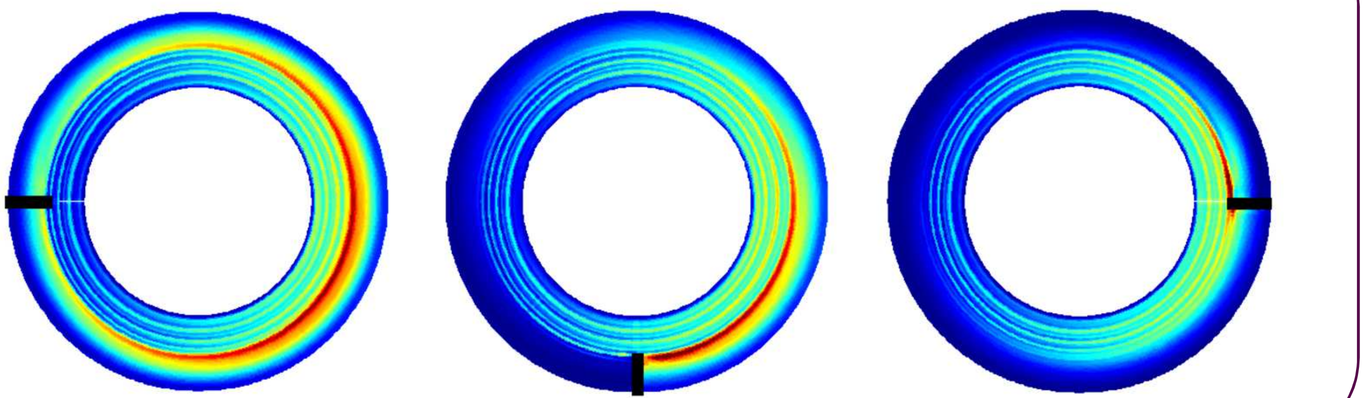
k-epsilon import in plasmas

Turbulent intensity k *in* $m^2 s^{-2}$



SOLEDGE2D

$k \approx 1/2\langle \tilde{v}_E^2 \rangle$ *(Arbitrary unit)*



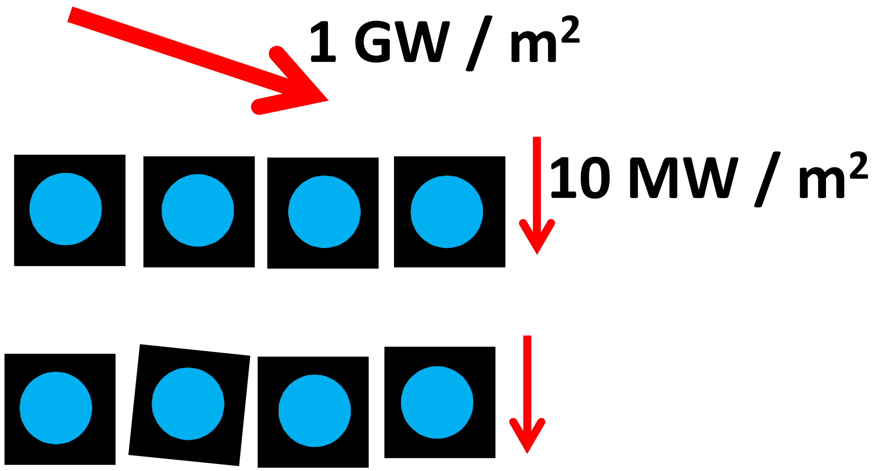
TOKAM3X

courtesy Hugo Bufferand

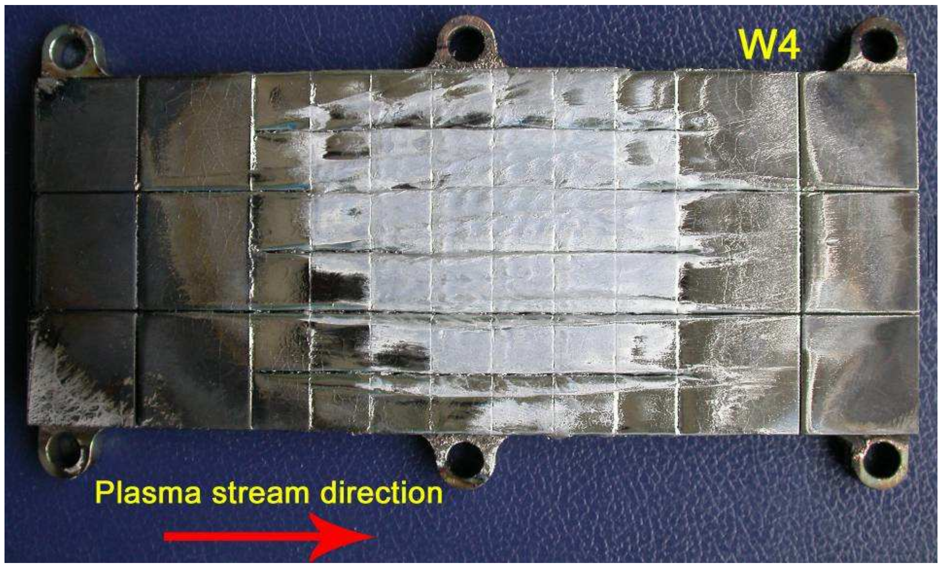
DIVERTOR nightmare

PLANNED: ITER divertor = first actively cooled W divertor
= first divertor to operate 10 years
= first at techno limit 10 MW/m²

Steady-state	Transients

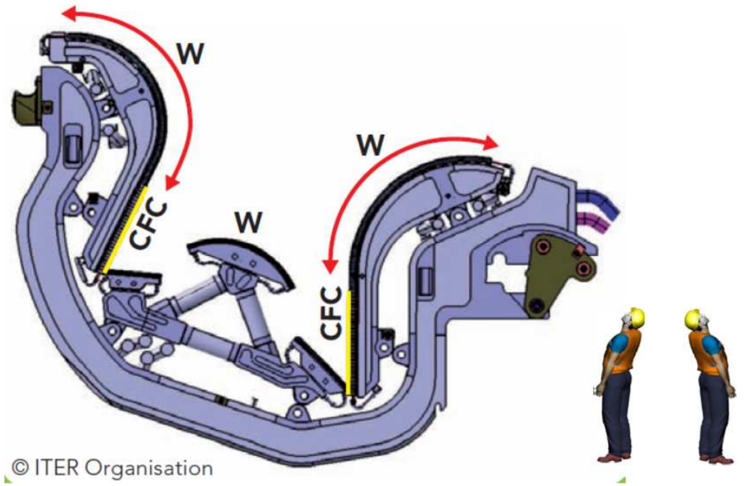


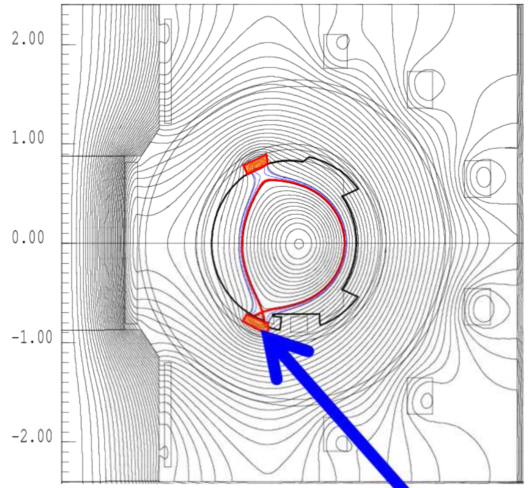
ITER ELM simulator



Solution shaping...
300 000 elements to shape

Just WEST of ITER





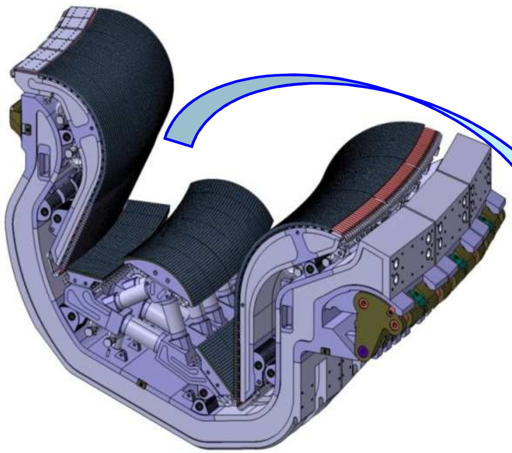
TORE SUPRA 2010-2012

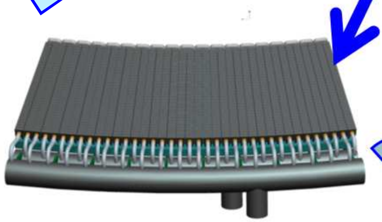
ITER divertor ≤ 10 MW / m^2

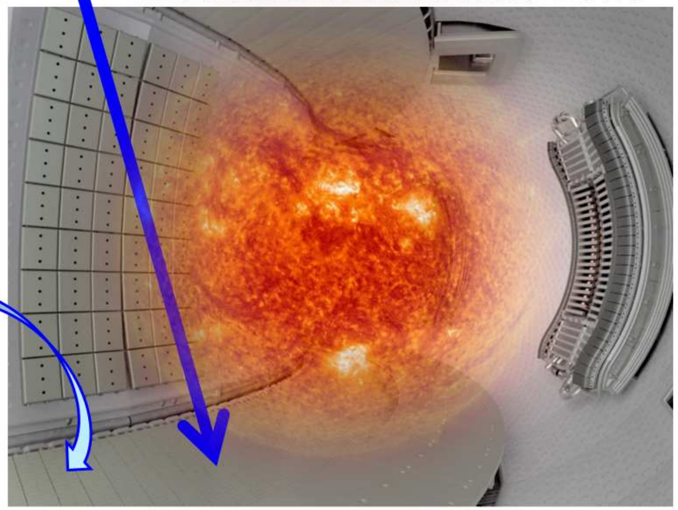
TORE SUPRA

WEST divertor

TORE SUPRA WEST 2016







Tungsten (W) technology

towards ITER

Grand challenge for plasma physics

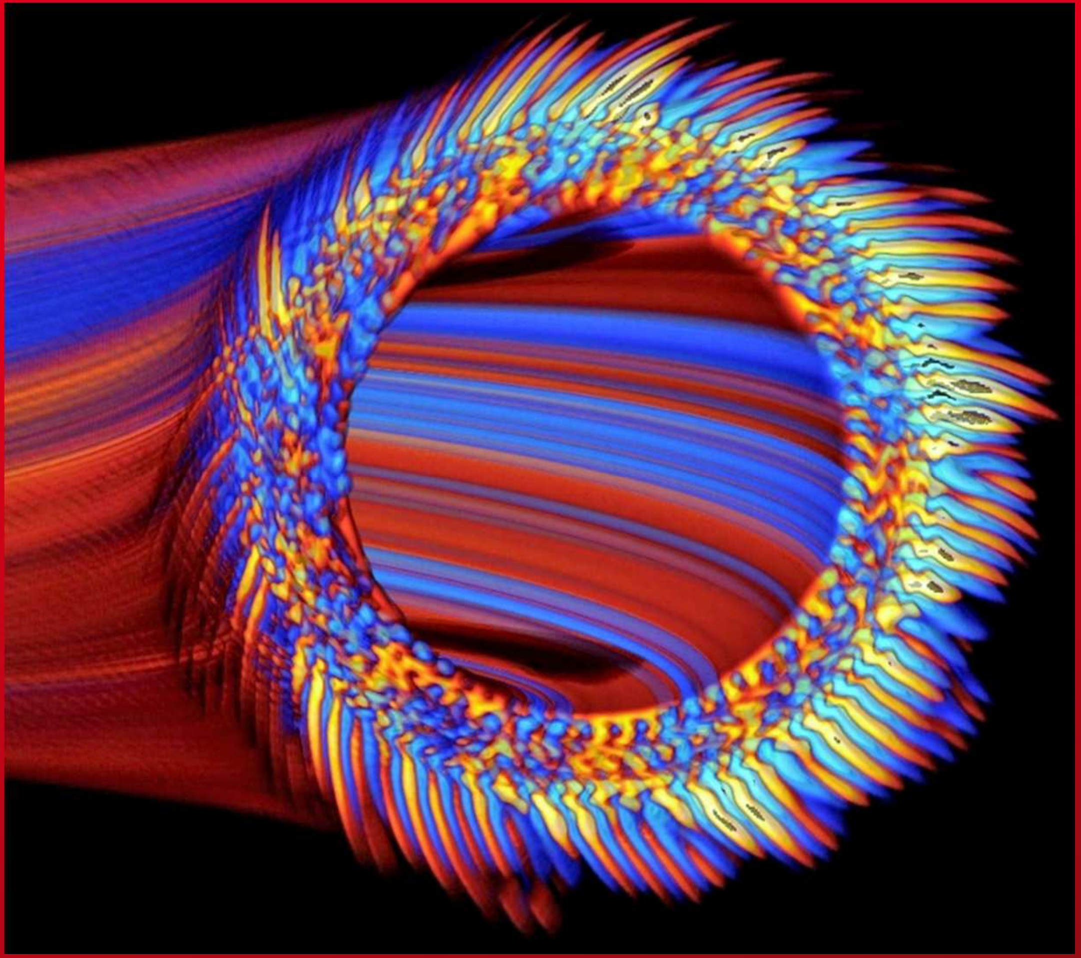
- *MHD*
- *turbulence*
- *plasma-wall interaction*
- *operation & safety*

Synergy

- *technology*
- *experimental physics*
- *theoretical physics*
- *advanced computing*

Simulations

- *Code development GYSELA long term effort: 15 years*
- ***key for ITER***



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