Tokamaks and Tokamak Physics Part B

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Outline

- **Instabilities limit plasma performance**
  - **Introduction in collective, magnetohydrodynamic (MHD) model of plasmas ⇒ plasma physics course**
- **Ideal and resistive instabilities**
- **Global and edge-localized modes, disruption**
- **Plasma transport**
- **Plasma purity and radiation**
- **Plasma performance in TFTR and JET DT plasmas**

What limits the performance in tokamaks?

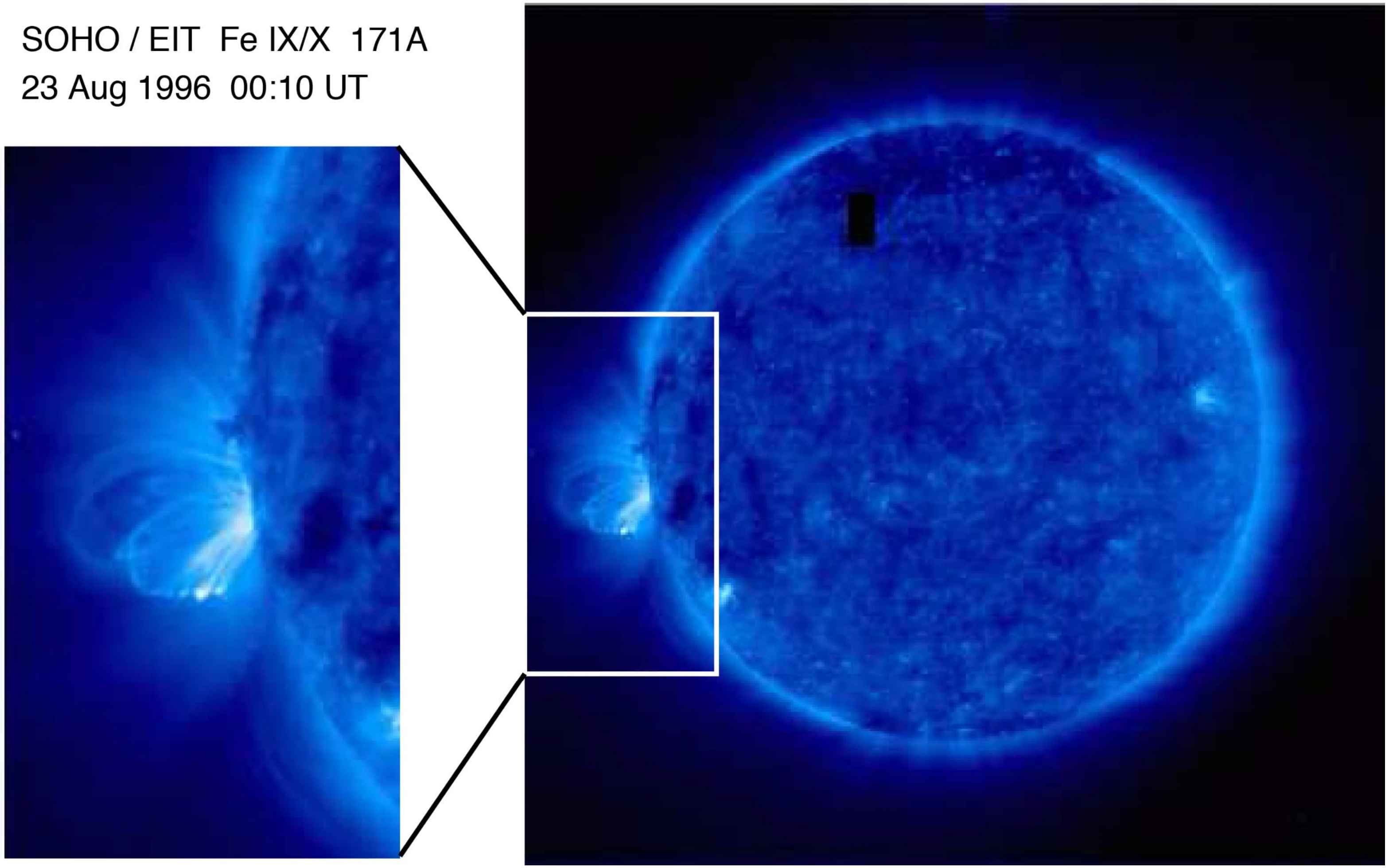
- (Linear) stability of the magnetic configuration against small changes in the parameters, such as magnetic field, pressure, etc.

$\Rightarrow$ Non-linear development of instability

- Ratio of kinetic to magnetic pressure (β-limit)
- Quality of the confinement (τ_E) $\Leftrightarrow$ transport of energy (particles, momentum) across flux surfaces
- Purity of the plasma

Instabilities on the sun’s surface lead to large expulsion of plasma into space

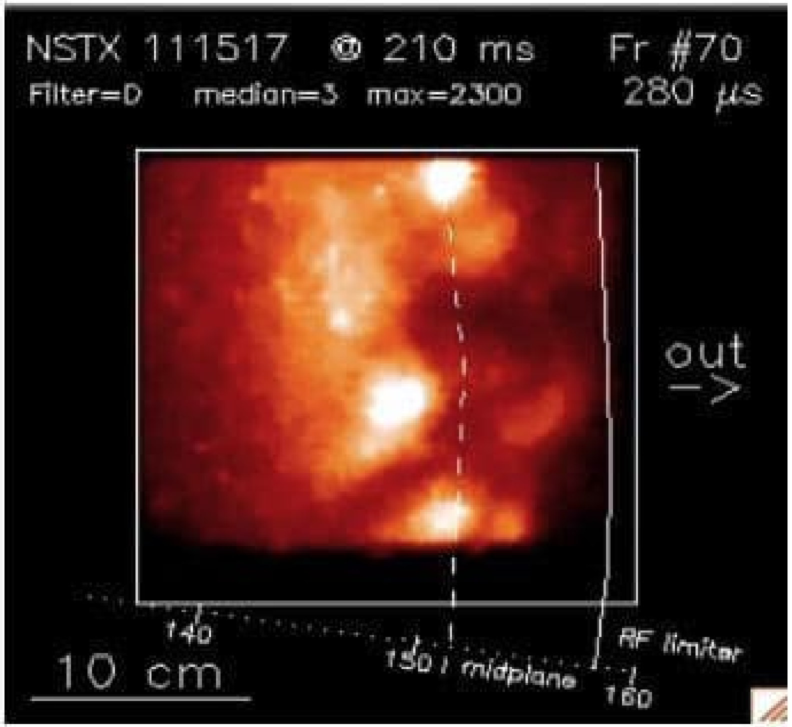
Lifetime: Hours (Inertial time scale: Seconds)



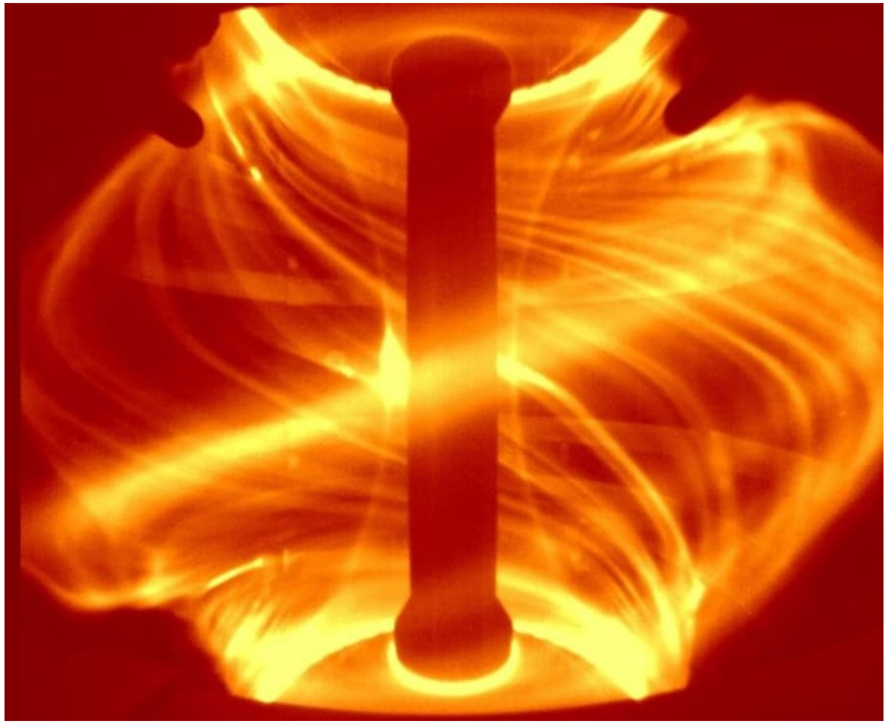
http://sohowww.nascom.nasa.gov

SOLAR flare video (1.31)

Similar phenomena are also observed in tokamaks



S.J. Zweben et al, Nucl. Fusion **44**,134 (2004)



ELMs in MAST tokamak (iter.org)

Edge localized modes (ELMs) can damage wall components by ablating them away due to their extremely high energy transfer rate (GW/m2) (video about ELMs later in the lecture)

A plasma can be described as a charged fluid by a set of magnetohydrodynamic (MHD) equations

- **MHD model describes collective behavior of plasma for macroscopic quantities, such as density, temperature, flow velocity (⇒ plasma physics course)**

- **MHD equations are derived from kinetic theory**

  - Distribution function $f(r,v,t) \rightarrow$ macroscopic density for given (r,v): $\int f\, d^3v$

- **Define other fluid quantities by taking moments of the distribution function:** charge and current densities, flow velocity, pressure (tensor)

⇒ **Continuity, momentum, and energy conservation equations + Maxwell's equations**

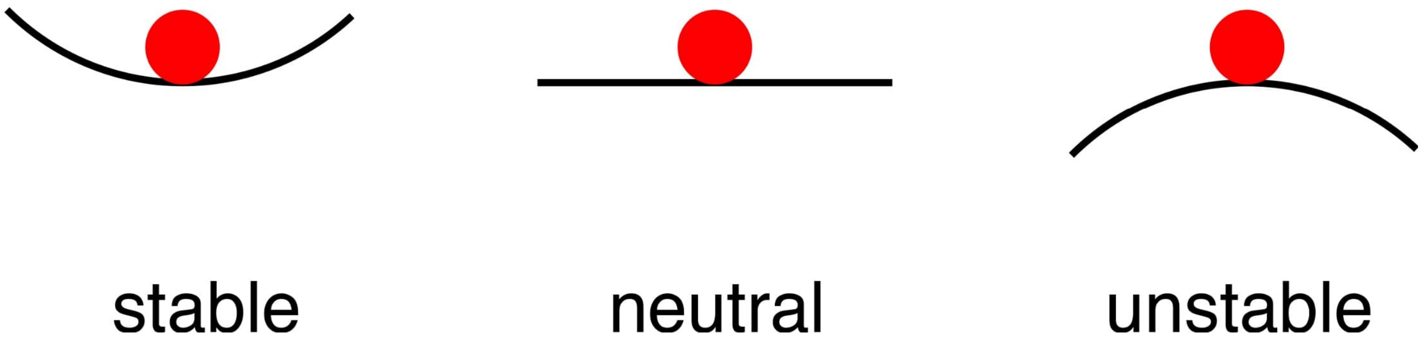
Global instabilities can even lead to complete loss of plasma

- **Destabilizing forces due to**
  - Current gradients (kink drive) ⇒ low β
  - Pressure gradients + adverse magnetic field curvature (interchange mode) ⇒ high/er β
- **Instabilities are divided into ideal modes (plasma perfectly conducting, no change in topology) and resistive modes (finite resistivity, change in topology)**
- **Instabilities start as small perturbations on the equilibrium ⇒ they grow to global instability, in particular on flux surfaces of rational q-value**

⇒ **Energy principle ($\delta^2 W>0$) and Fourier decomposition**

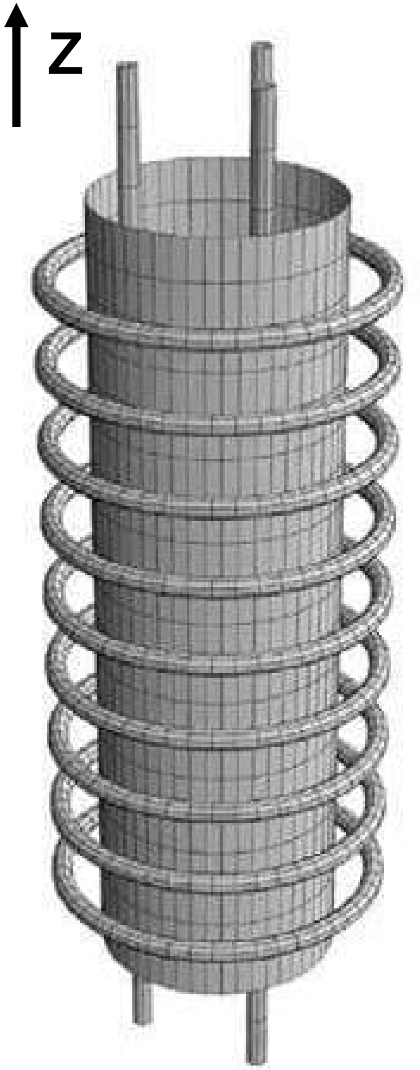
The stability of a system can be probed by applying small perturbations/displacements

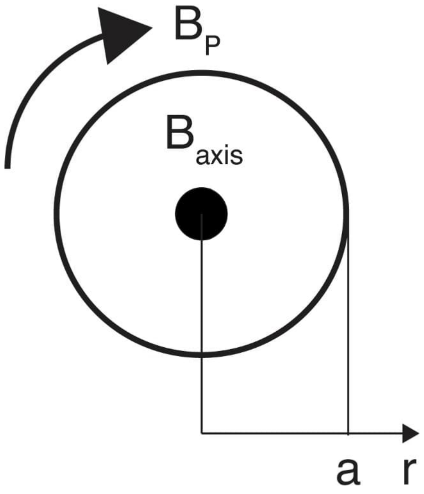
Force equilibria can be ...



- **For potential energy W, force balance is achieved when:** $dW/d\xi = F_{net} = 0$
- **Configuration is stable when for all possible displacements, $d\xi$:** $d^2W/d\xi^2 > 0$
- **Or unstable for one displacement:** $d^2W/d\xi^2 < 0$

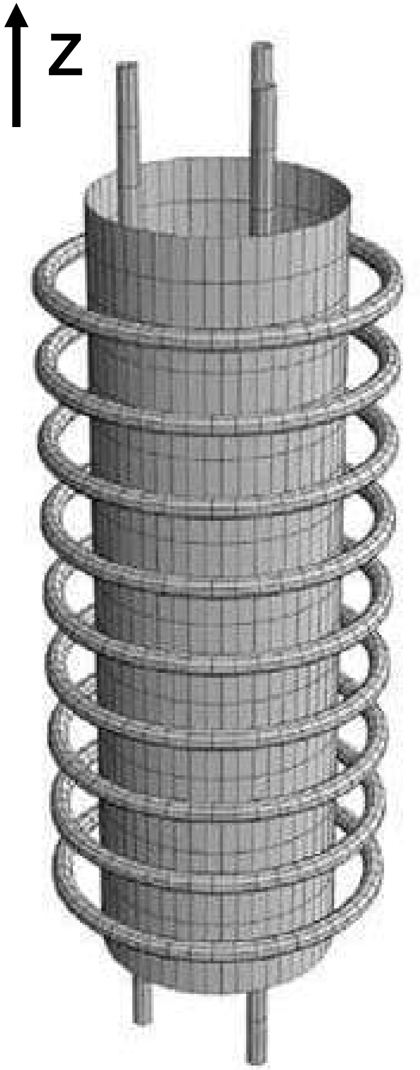
Consider a pressure-less cylinder with an longitudinal field in center, and poloidal outside

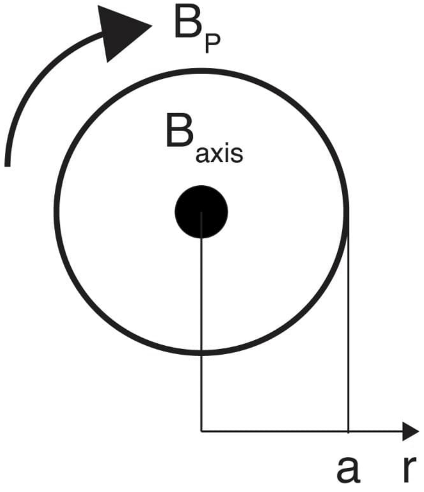




- **B =** $(0,0,B_Z)$ for $r<a$
  B = $(0, B_P(a/r),0)$ for $r>a$
- **Ideal 'pressure-less'**
- **Force balance at surface when $B_P = B_Z$**

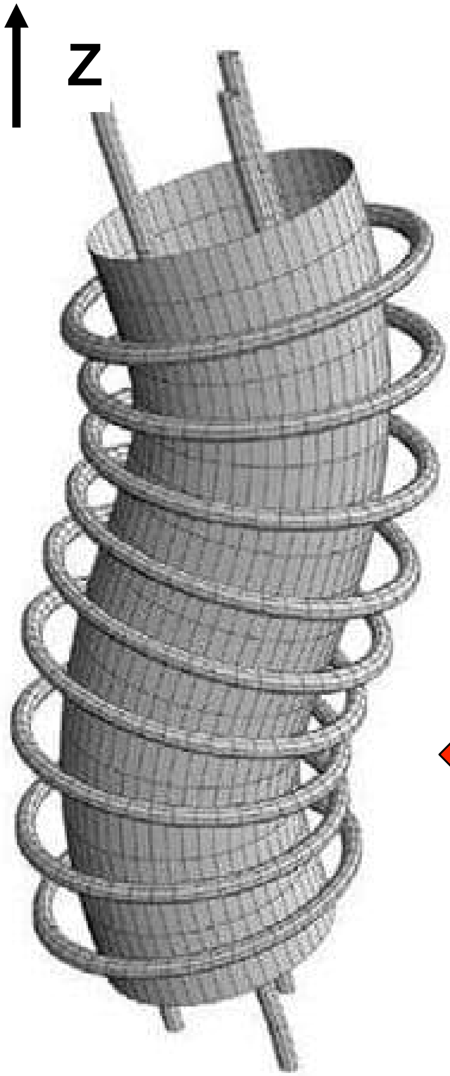
Probe stability of equilibrium by periodic force in Z-direction

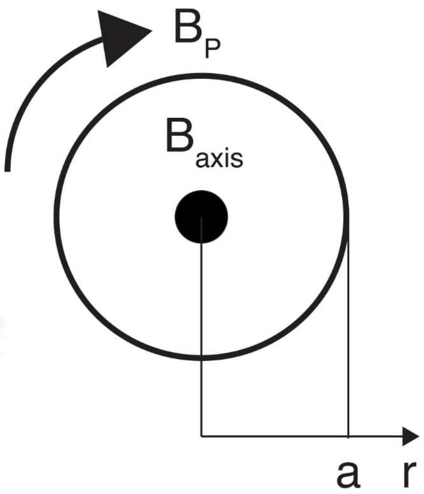


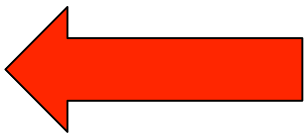


- **B =** $(0,0,B_z)$ for r<a
  B = $(0, B_P(a/r),0)$ for r>a
- **Ideal 'pressure-less'**
- **Force balance at surface when $B_P = B_Z$**
- **Longitudinal wavenumber k_Z**

Situation is destabilizing when $|B_P/B_Z| = 1 > k_Z a \Rightarrow$ internal kink

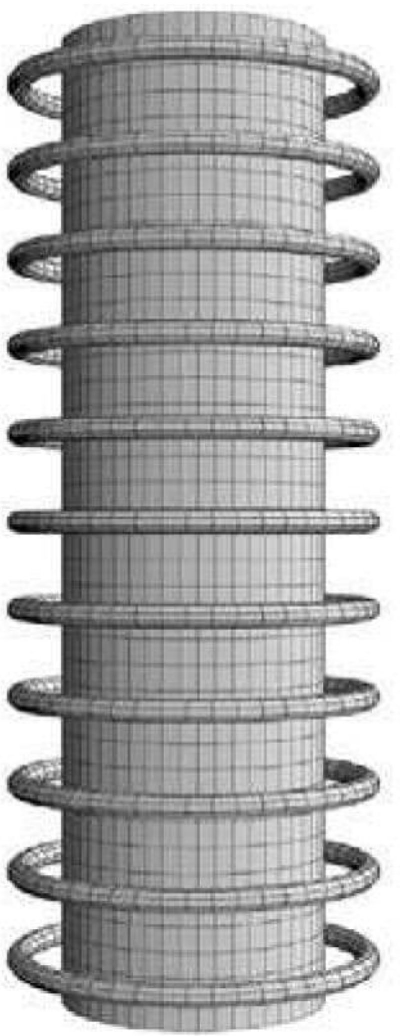


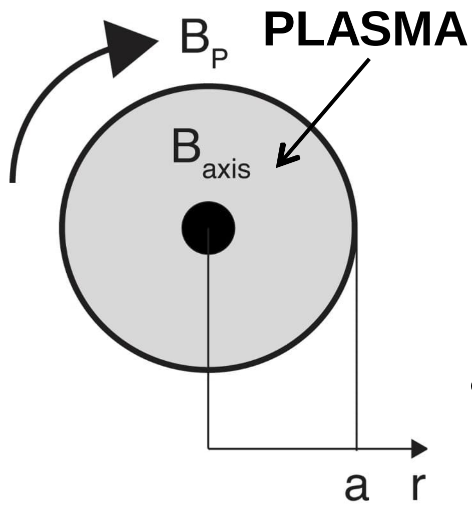




- **B =** $(0,0,B_z)$ for $r<a$
  B = $(0, B_P(a/r),0)$ for $r>a$
- **Ideal 'pressure-less'**
- **Force balance at surface when $B_P = B_Z$**
- **Longitudinal wavenumber k_Z**
- **Increase/decrease of B_P on the inside/outside of knees $\Leftrightarrow$ stretching of longitudinal field $\Rightarrow$ current re-arrangement**

Consider a plasma-filled cylinder with an longitudinal field in center, and poloidal field outside



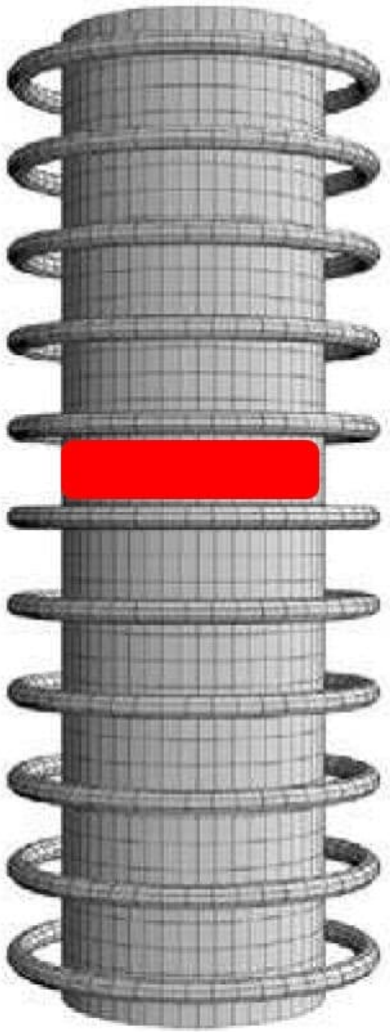


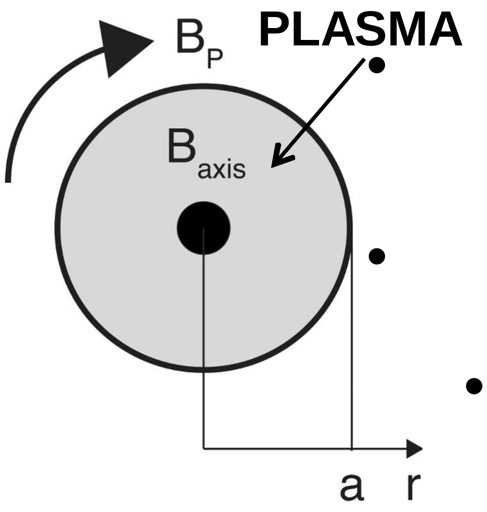
B = (0,0,B_Z) **for r < a**
B = (0,B_P(a/r),0) **for r > a**

$$B^2(a)/2\mu_0 \gg p$$

- **Force balance at surface when $B_P = B_Z$**

Apply a poloidal perturbation to the cylindrical system





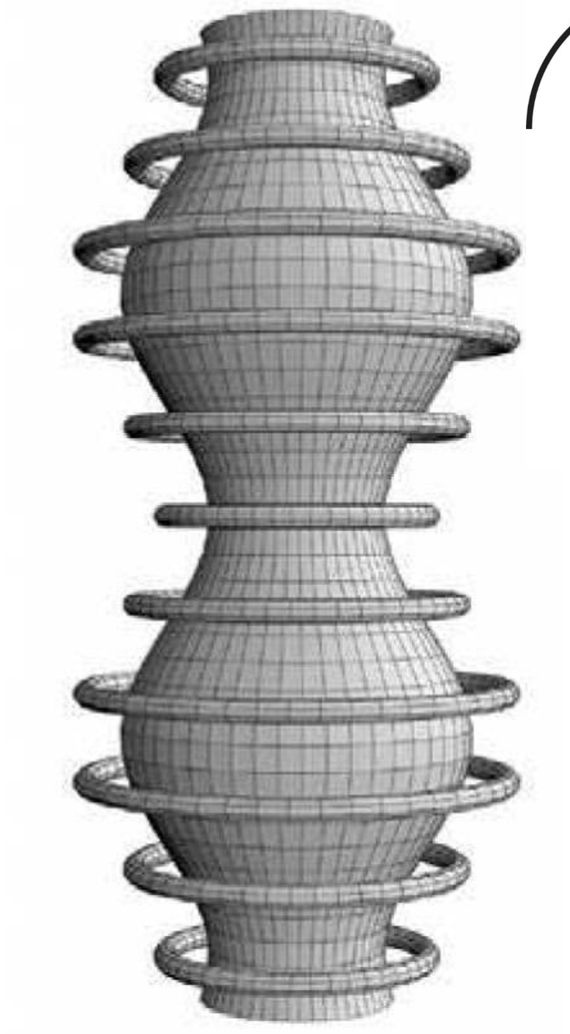
$\mathbf{B} = (0,0,B_Z)$ **for r < a**
$\mathbf{B} = (0,B_P(a/r),0)$ **for r > a**

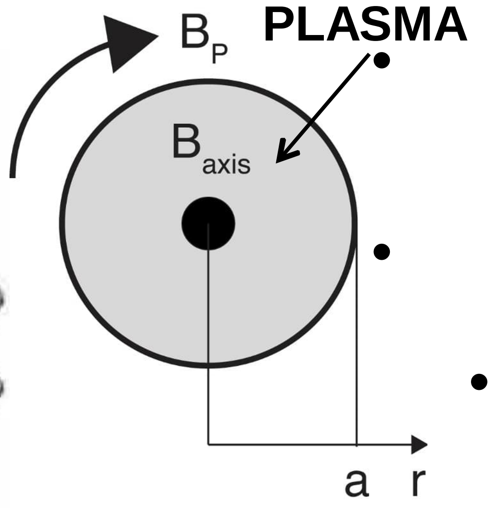
- $B^2(a)/2\mu_0 \gg p$

- **Force balance at surface when $B_P = B_Z$**

- **Poloidal perturbation**

System is unstable when curvature vector points away from plasma



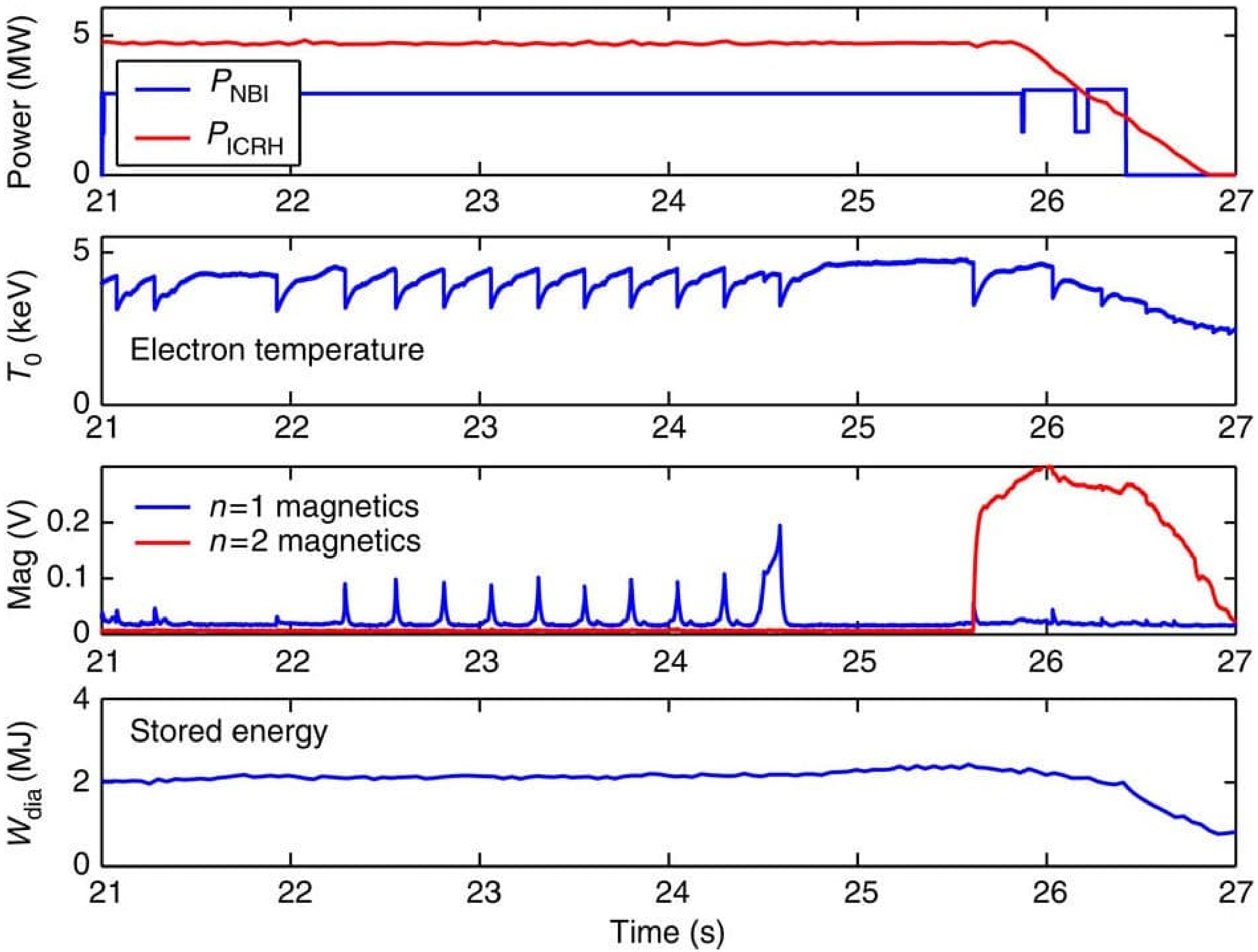


$\mathbf{B} = (0,0,B_Z)$ **for r < a**
$\mathbf{B} = (0,B_P(a/r),0)$ **for r > a**

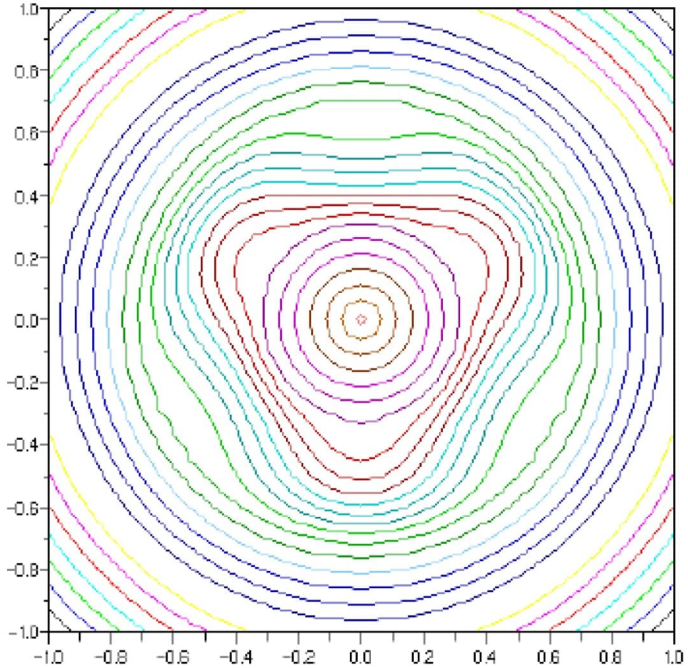
$B^2(a)/2\mu_0 \gg p$

- **Force balance at surface when $B_P = B_Z$**
- **Poloidal perturbation**
- **Retain axisymmetry, but B_P increases in waist, decreases in bulge**
- **Field-line curvature vector k $\equiv (b \cdot \nabla) b$**

Toroidal mode (n=1) instabilities (sawteeth) limit the central plasma temperature



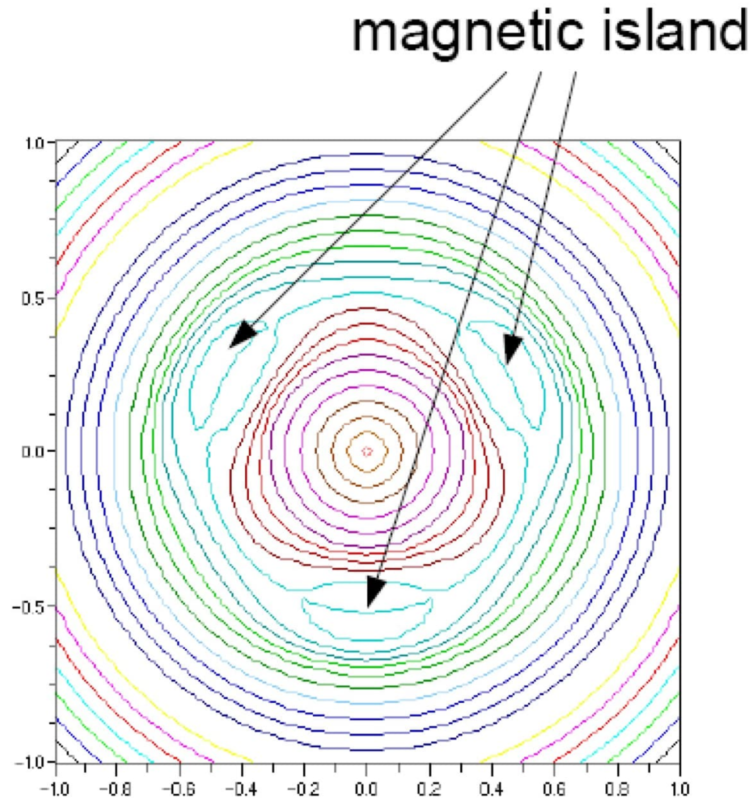
Finite resistivity of the plasma leads to reconnection of flux surfaces = magnetic islands



Ideal MHD: $\eta = 0$

flux conservation

topology unchanged

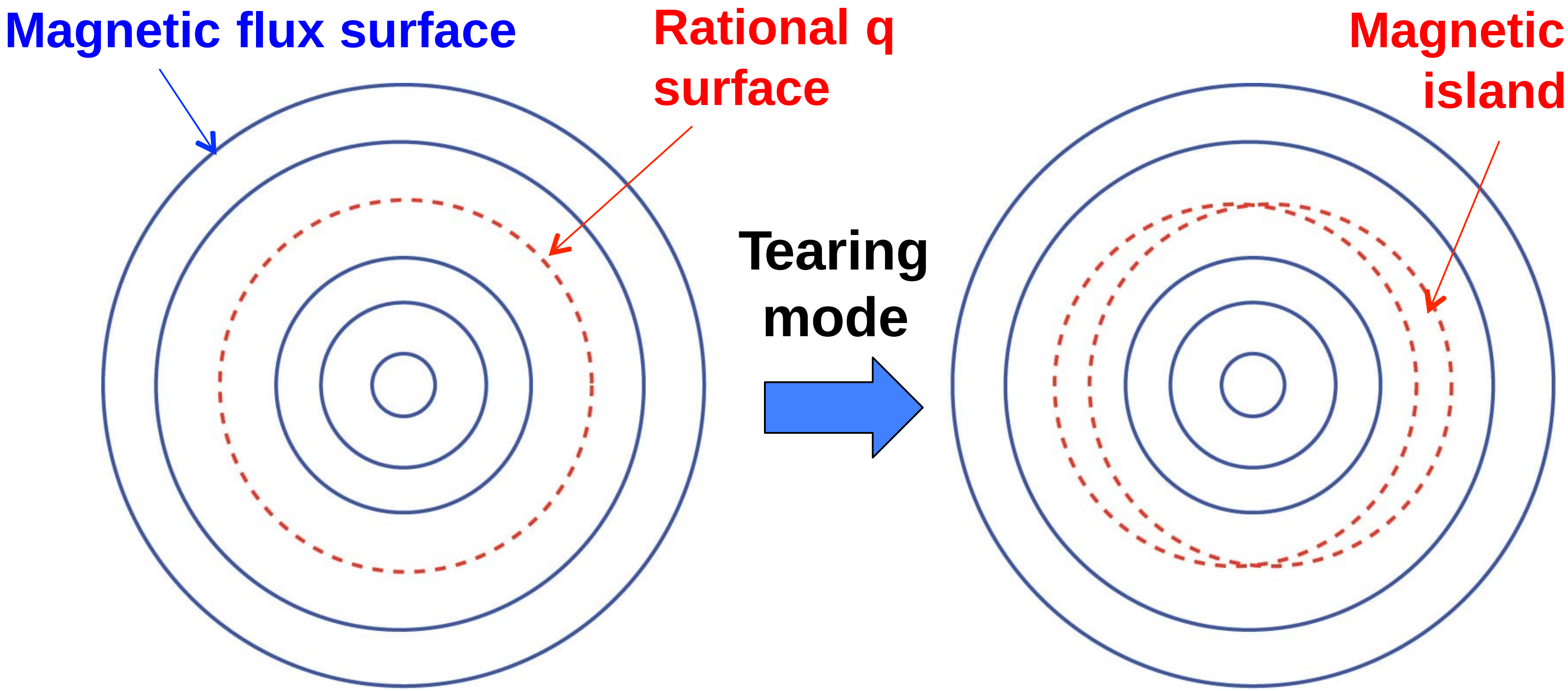


Resistive MHD: $\eta \neq 0$

reconnection of field lines

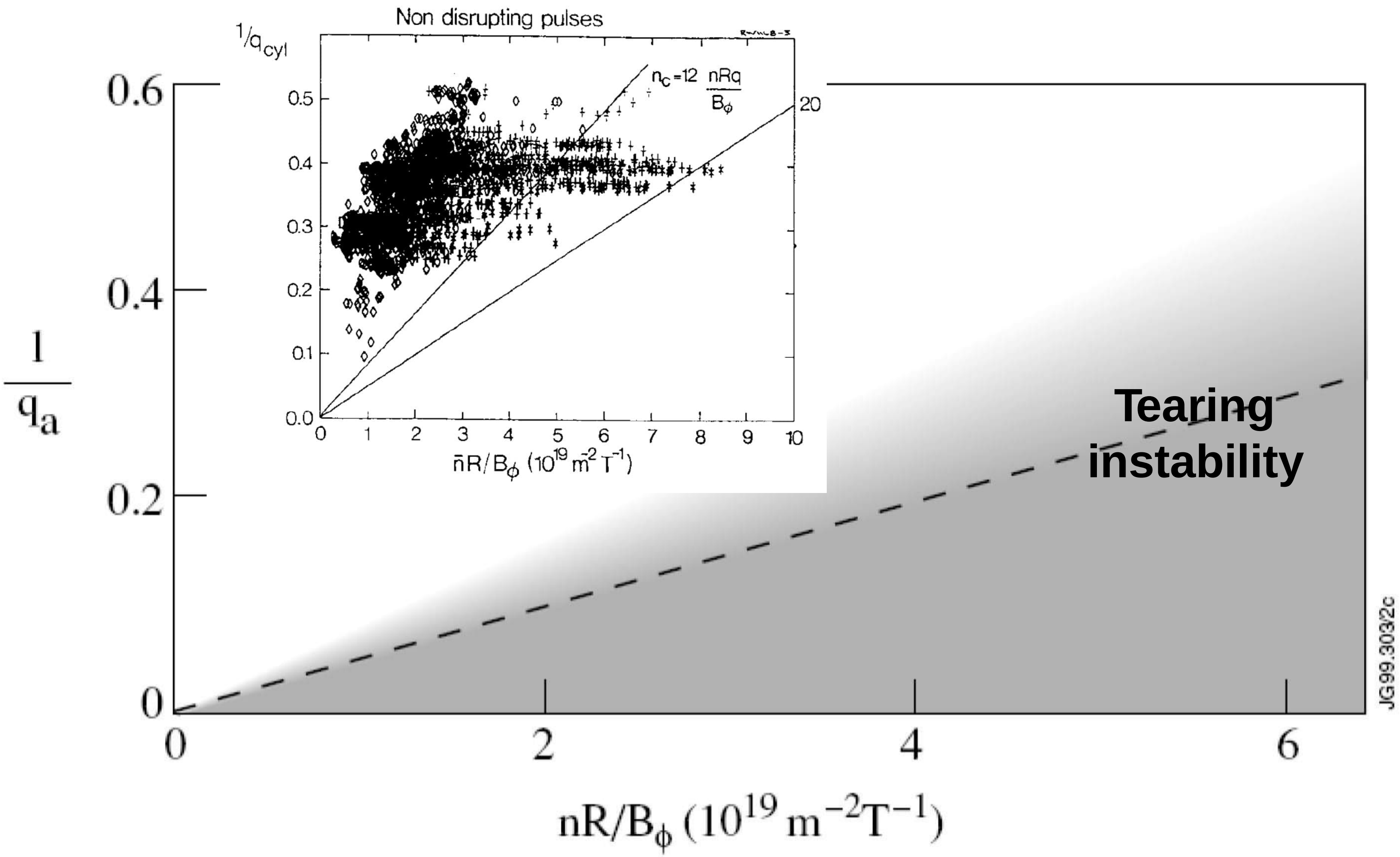
topology changes

Tearing modes lead to enhanced energy transport across island

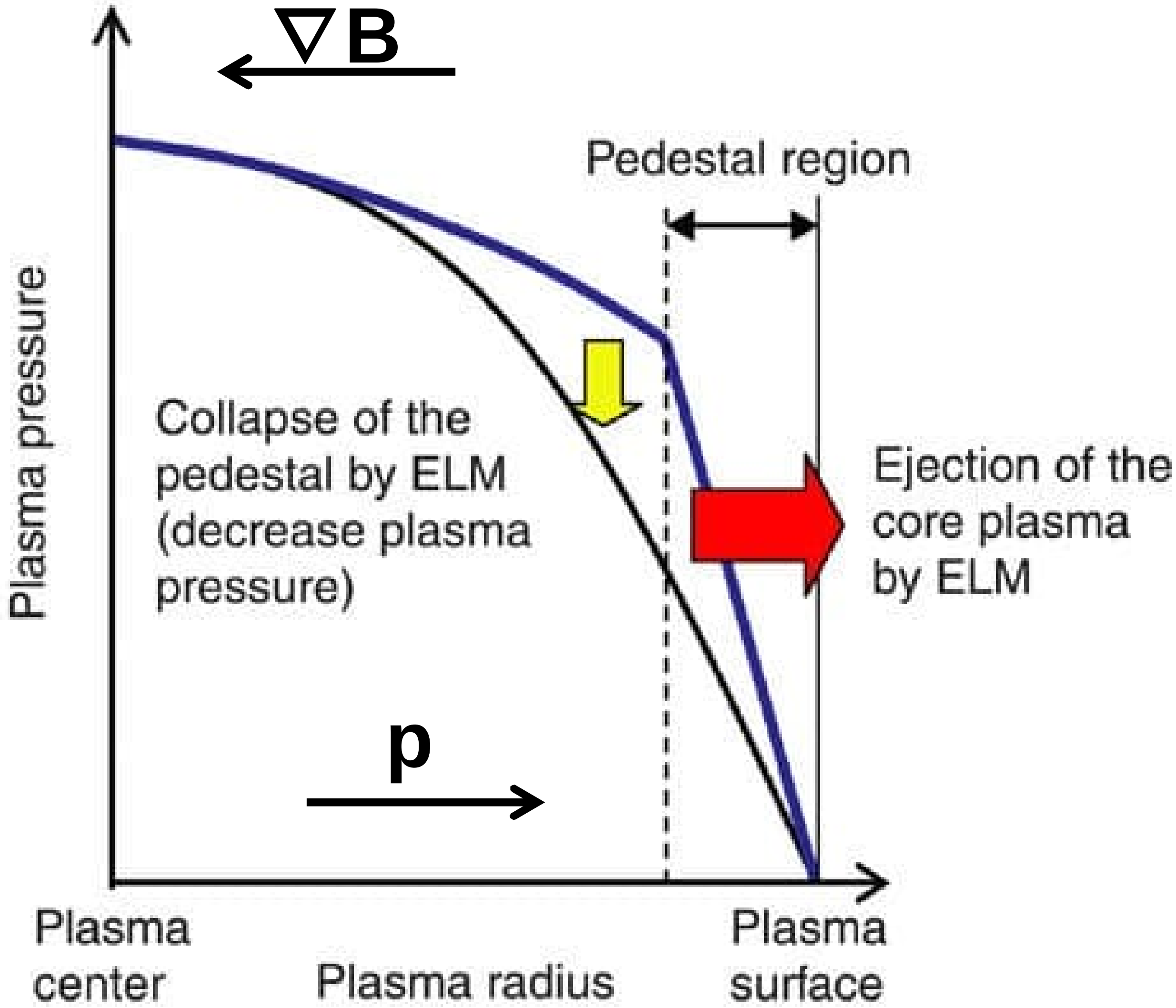


- **Plasma is resistive ⇒ reconnection of neighboring flux surfaces due to current gradients**
- **Resistivity increases with n ⇒ islands grow ⇒ loss of confinement and disruption**

Instabilities limit the maximum achievable density for a given field, current and major radius

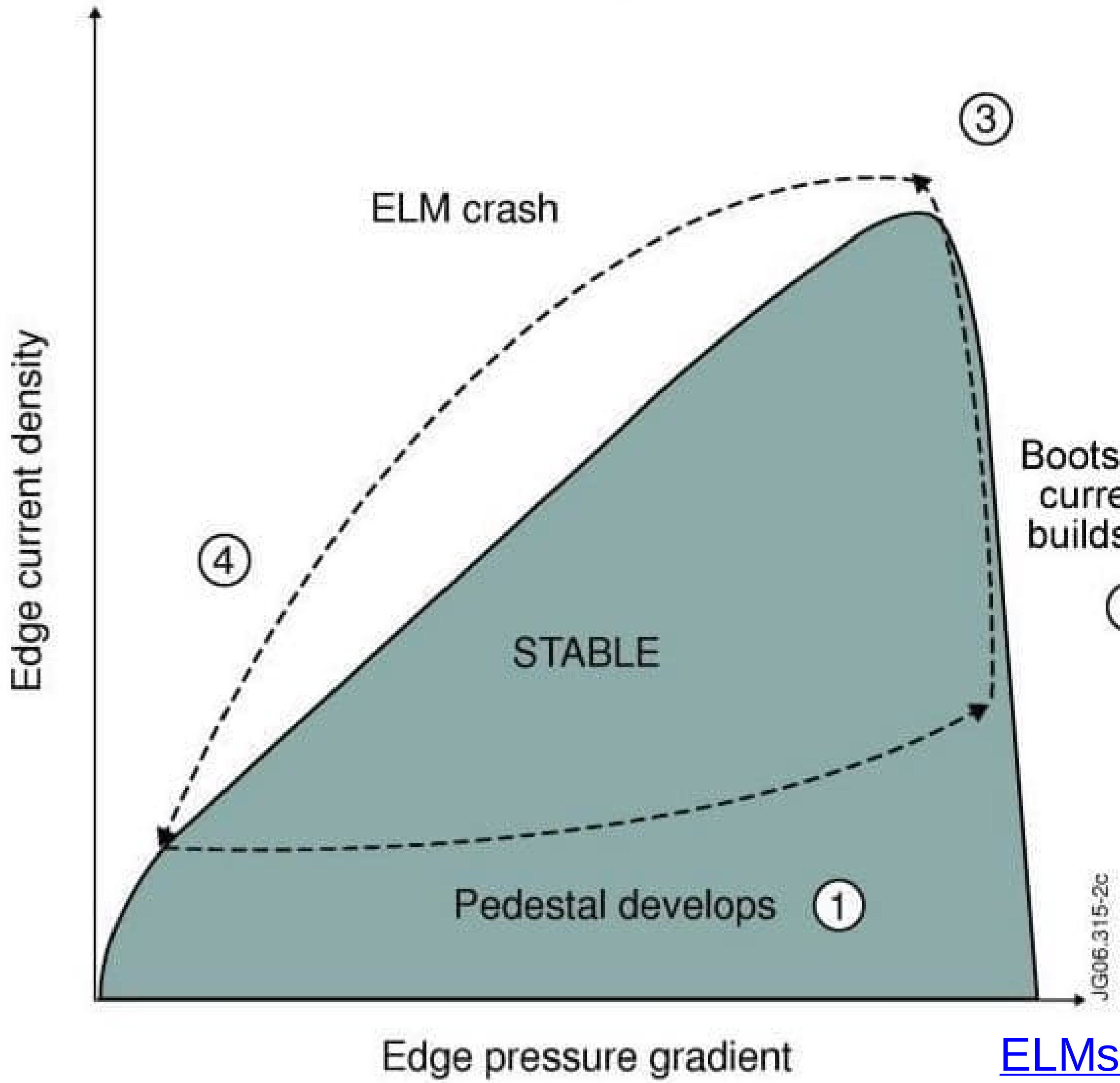


The steep pressure gradient region in edge leads to a ballooning instability and plasma injection



- **Pedestal region ⇔ steep plasma pressure region**
- **Beyond critical pressure, plasma is periodically ejected into scrape-off layer ⇒ enhanced plasma-wall interaction**

Maximum pressure in the edge is limited both by currents and its pressure gradients



- **Maximum achievable β:**

$$\beta_{max} = const\,\frac{I_p}{aB_T}$$

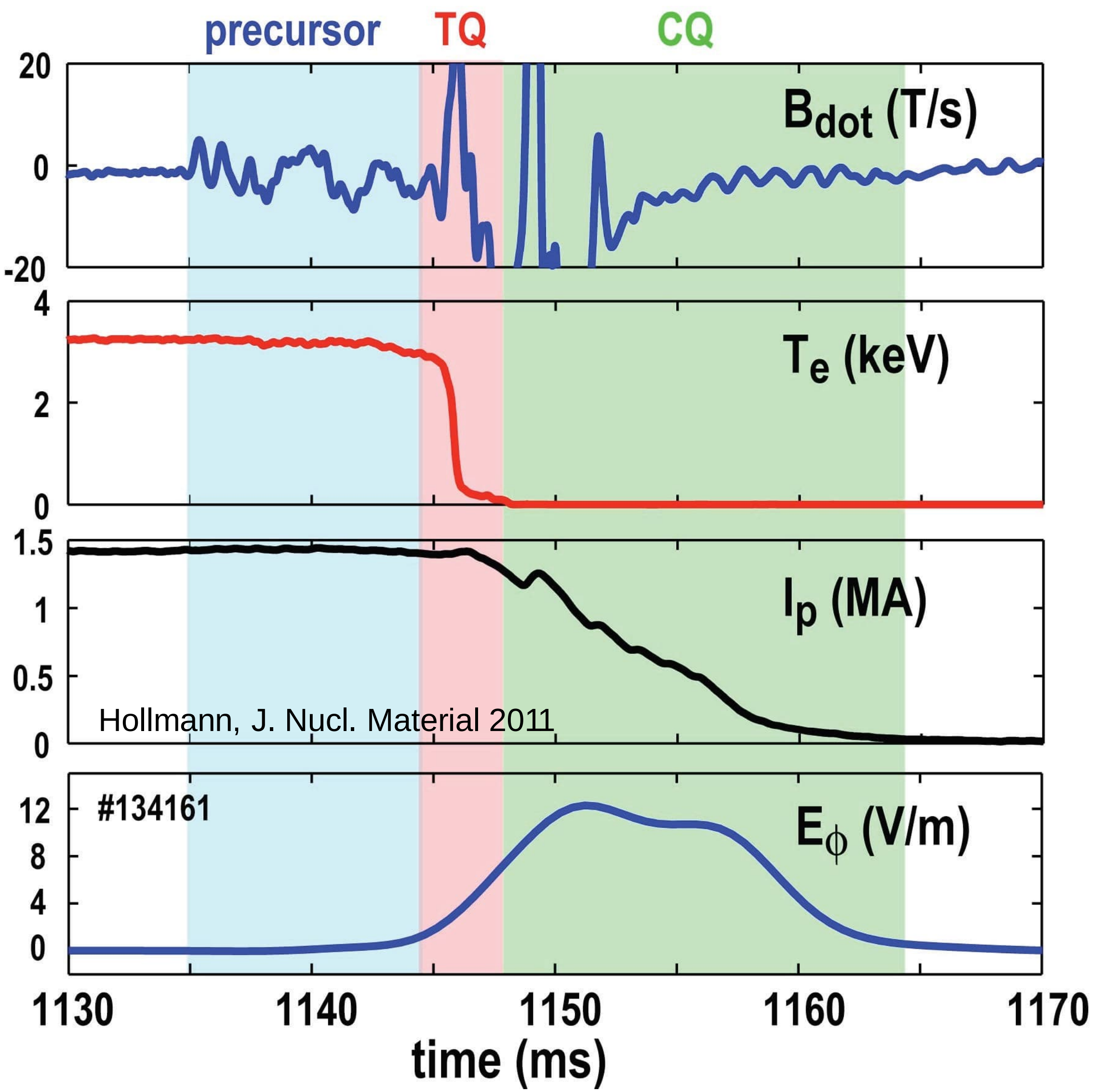
- **Constant depends on shape of plasma (secondary stability)**

ELMs and how to control them (3.22)

Presemo quiz #1

https://presemo.aalto.fi/fet/

A disruption is a global MHD event that terminates the plasma discharge

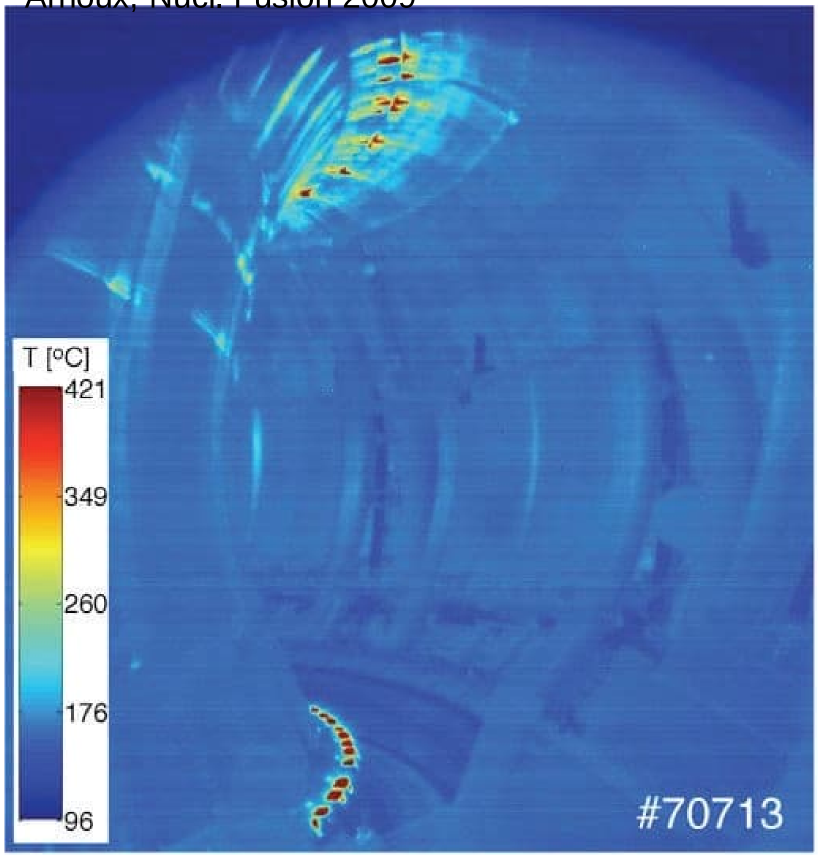


- **Pre-cursor:** instability develops
- **Rapid thermal quench:** plasma stored energy collapses
- **Longer current decay:** magnetic energy is dissipated

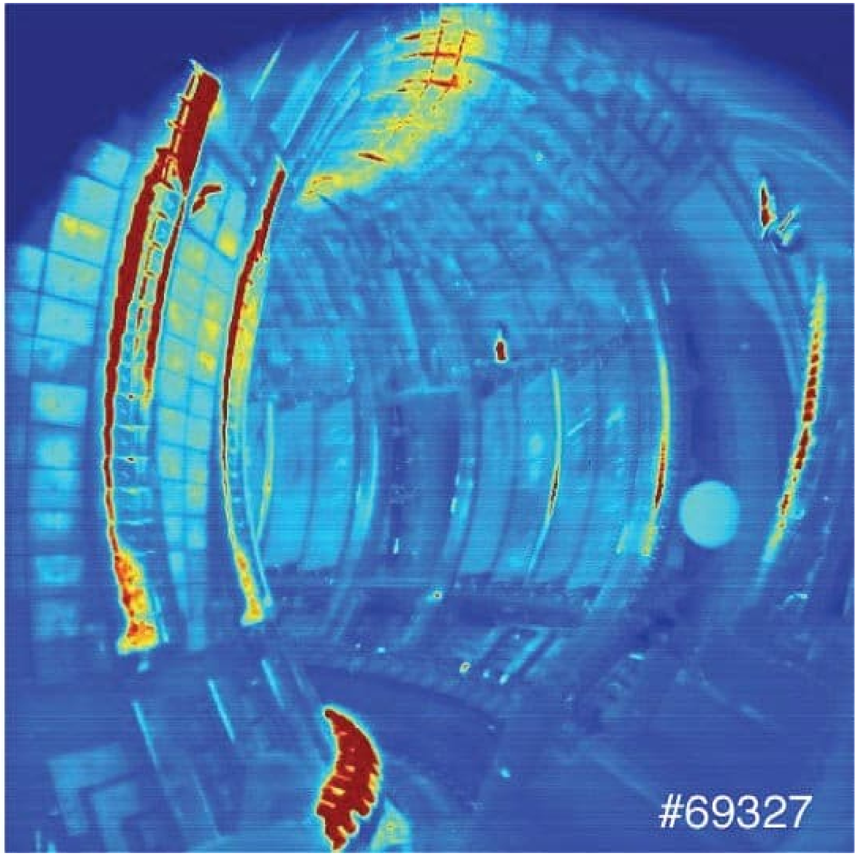
A disruption produces strong (over)loading of the tokamak walls + vessel forces + runaway electrons

Vertical displacement to the top

Arnoux, Nucl. Fusion 2009



Density limit to inner wall and inner divertor



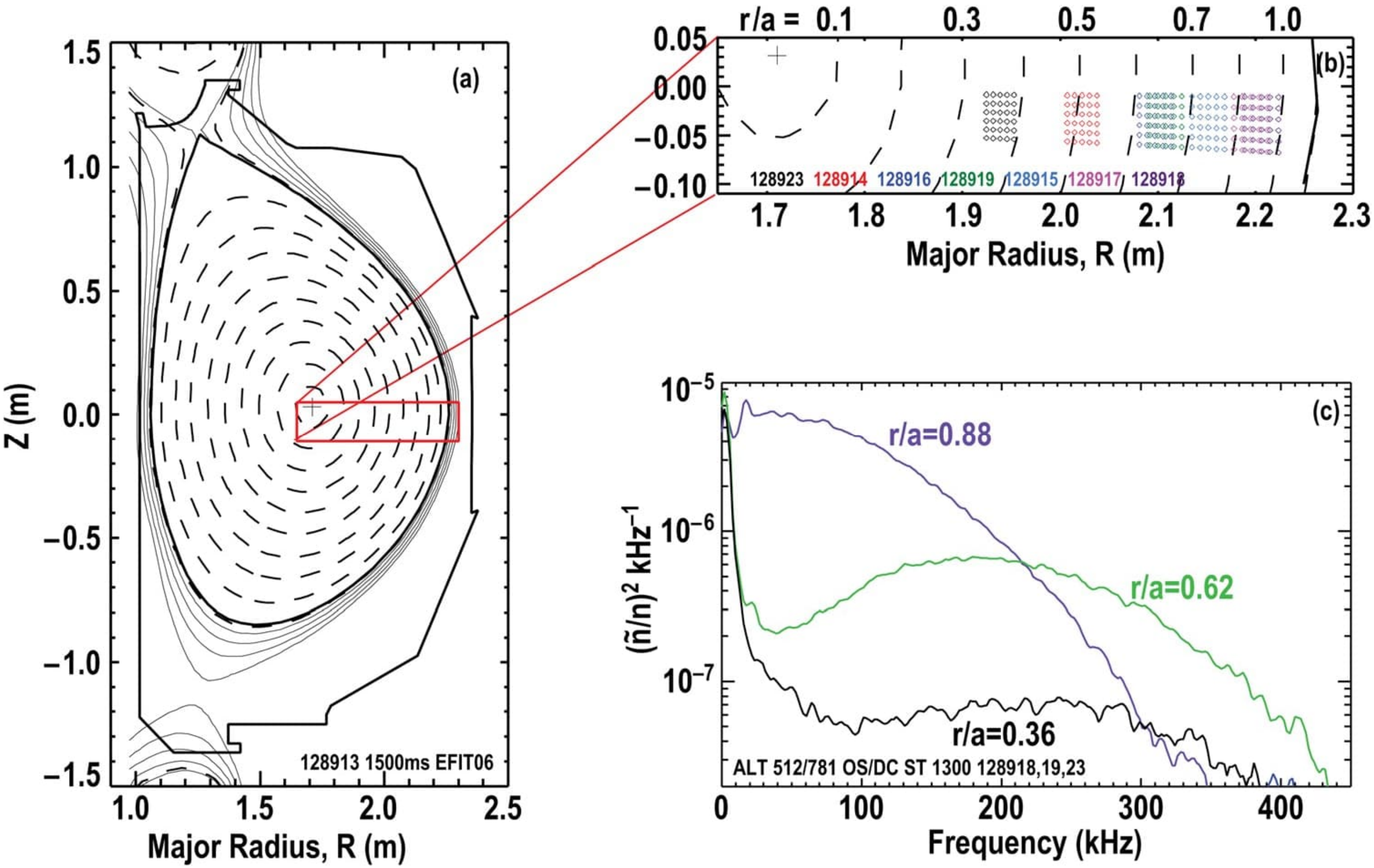
Collisions and drifts lead to radial transport of energy, particles and momentum ⇒ different confinement times

- **Classical transport described by diffusion and convection**

⇒ Transport coefficients $D_\perp$ and v_{pinch}

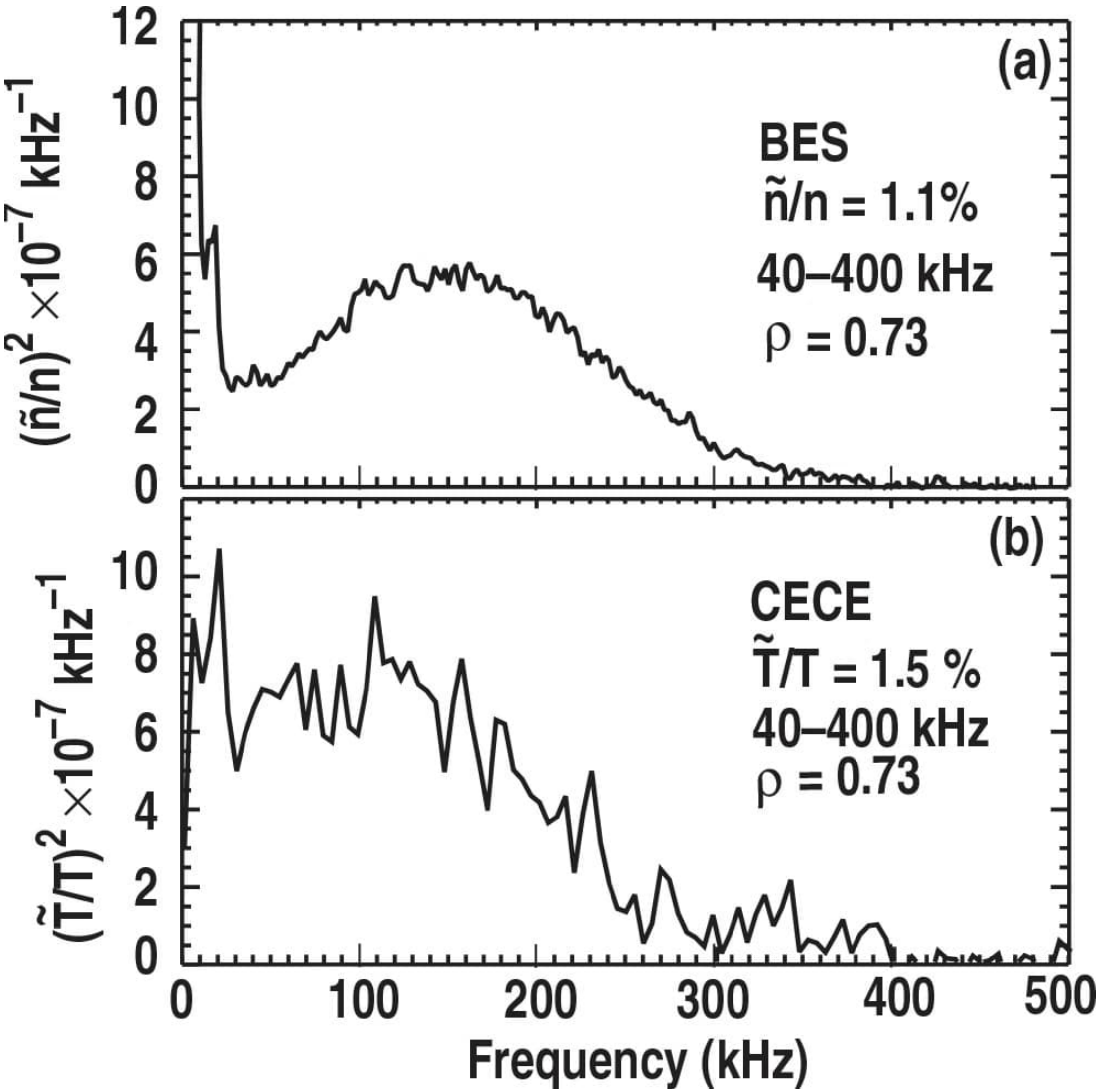
- **Classical diffusion too small to describe experiments**
- **Neoclassical transport due to toroidal geometry:** trapped and passing particles, banana orbits: Much larger than classical diffusion but **still do not describe measurements!**

Anomalous cross-field transport is dominated by small-scale collective micro-instabilities



M. Shafer, et al., Phys. Plasma 2012

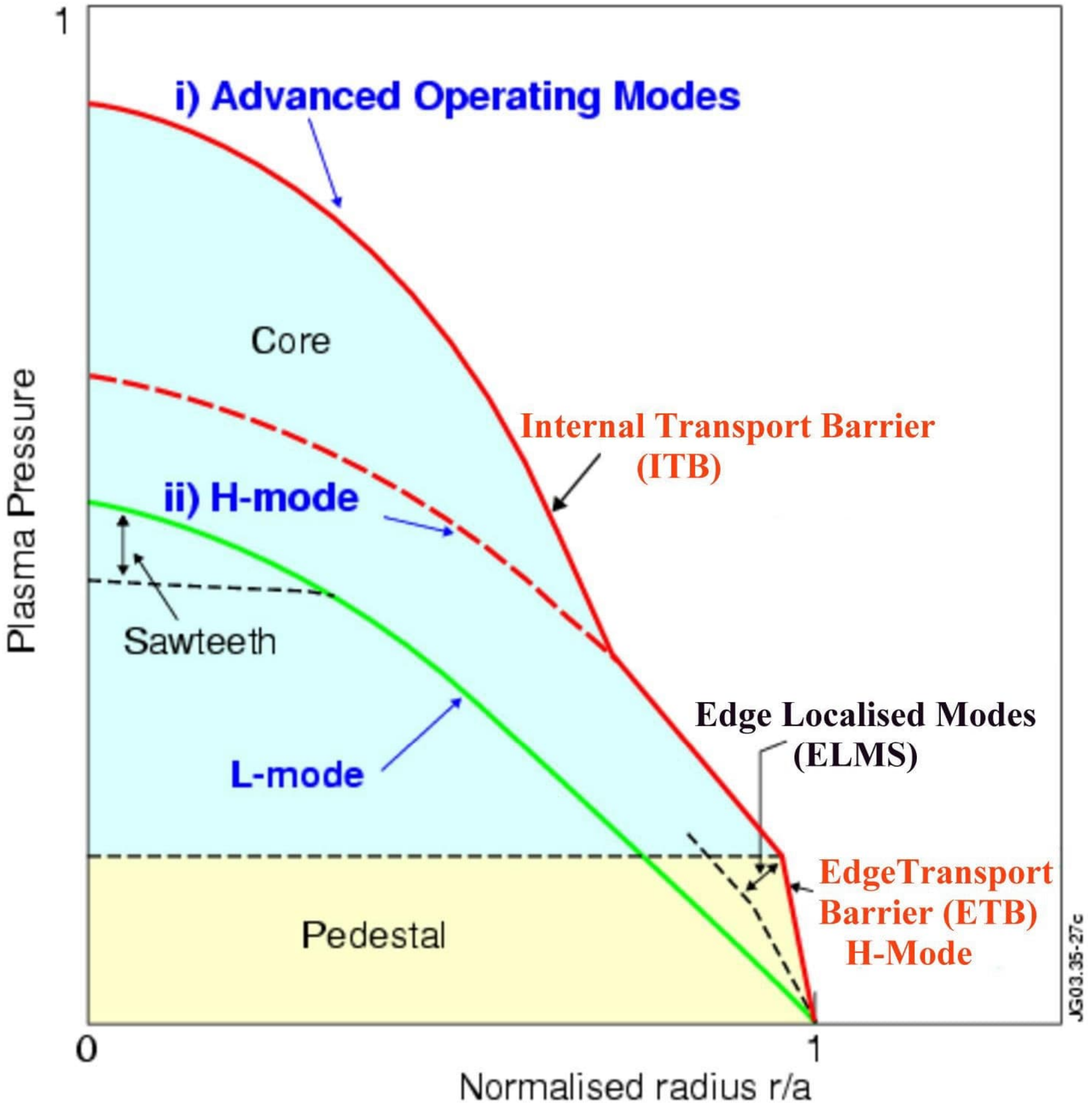
The plasma fluctuates in density, temperature, and electromagnetic field



A.E. White, et al., Phys. Plasma 2008

- **Fluctuations are generally small: $\lesssim$ 1% in the center → can reach 10% at the edge**
- **Root cause lies in particle precession resonance, collisions, and bad curvature**

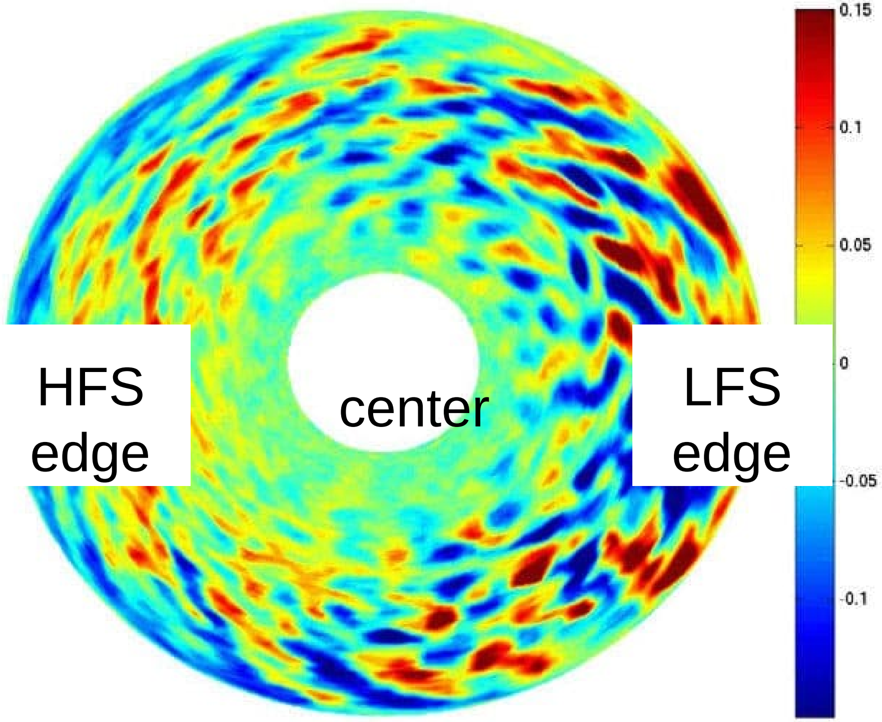
Global transport barriers develop due to suppression of turbulence



- **Low confinement mode** has an almost monotonic pressure profile ⇒ sawteeth instabilities
- **High confinement mode** with edge localized and core (internal) transport due to shear flow
- **Edge transport barrier formation still not explained**

Micro-turbulence and its effect on global, cross-field transport is studied in massively parallelized codes

ELMFIRE density fluctuations



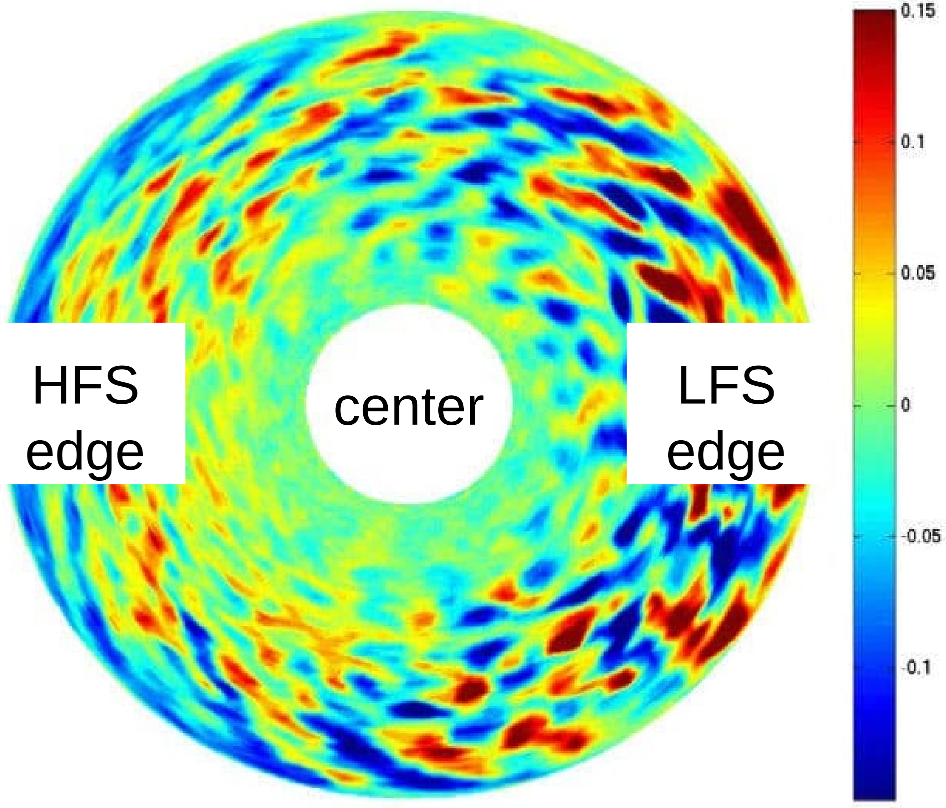
Courtesy of S. Leerink, J. Heikkinen, et al.

- **Simulation choices:**
- **Vlasov vs. PIC (~10 particles)**
- **Kinetic vs. adiabatic electrons**
- **Full-f or delta-f**
- **Circular or realistic geometry**
- **Just closed or also open field lines**
- **Linear or non-linear**
- **Time scale? (coll., turb., confinement?)**

HPC: days with 1000 prosessors → Video: Elmfire turbulence (31 s, L. Chone)

Micro-turbulence and its effect on global, cross-field transport is studied in massively parallelized codes

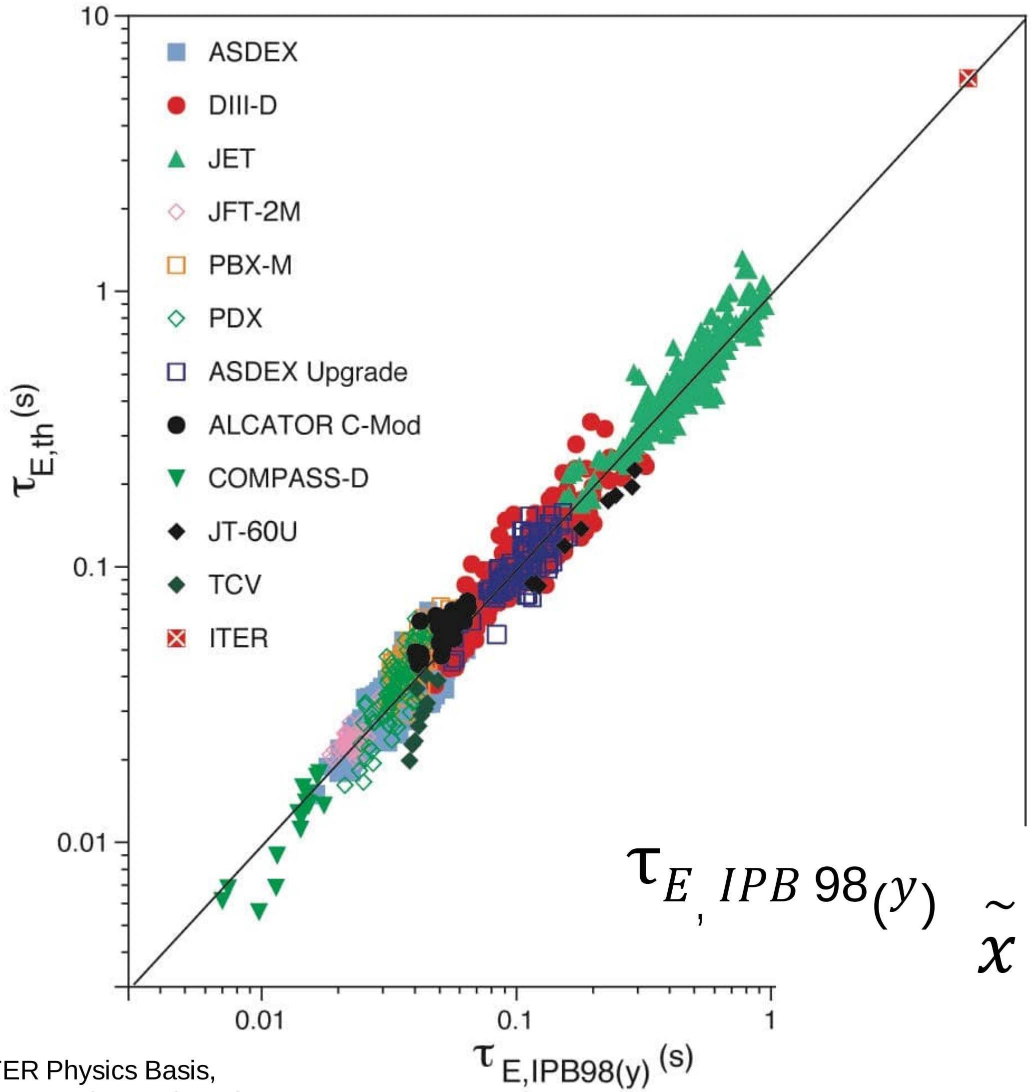
ELMFIRE density fluctuations



- **Predator-prey type processes of micro-turbulence and large-scale convective motion**
- **Stronger turbulence/ streamers on low-field side of plasma**
- **Poloidal shear can break up convective cells**

Courtesy of S. Leerink, J. Heikkinen, et al.

The lack of physics understanding forces scaling experiments toward future devices



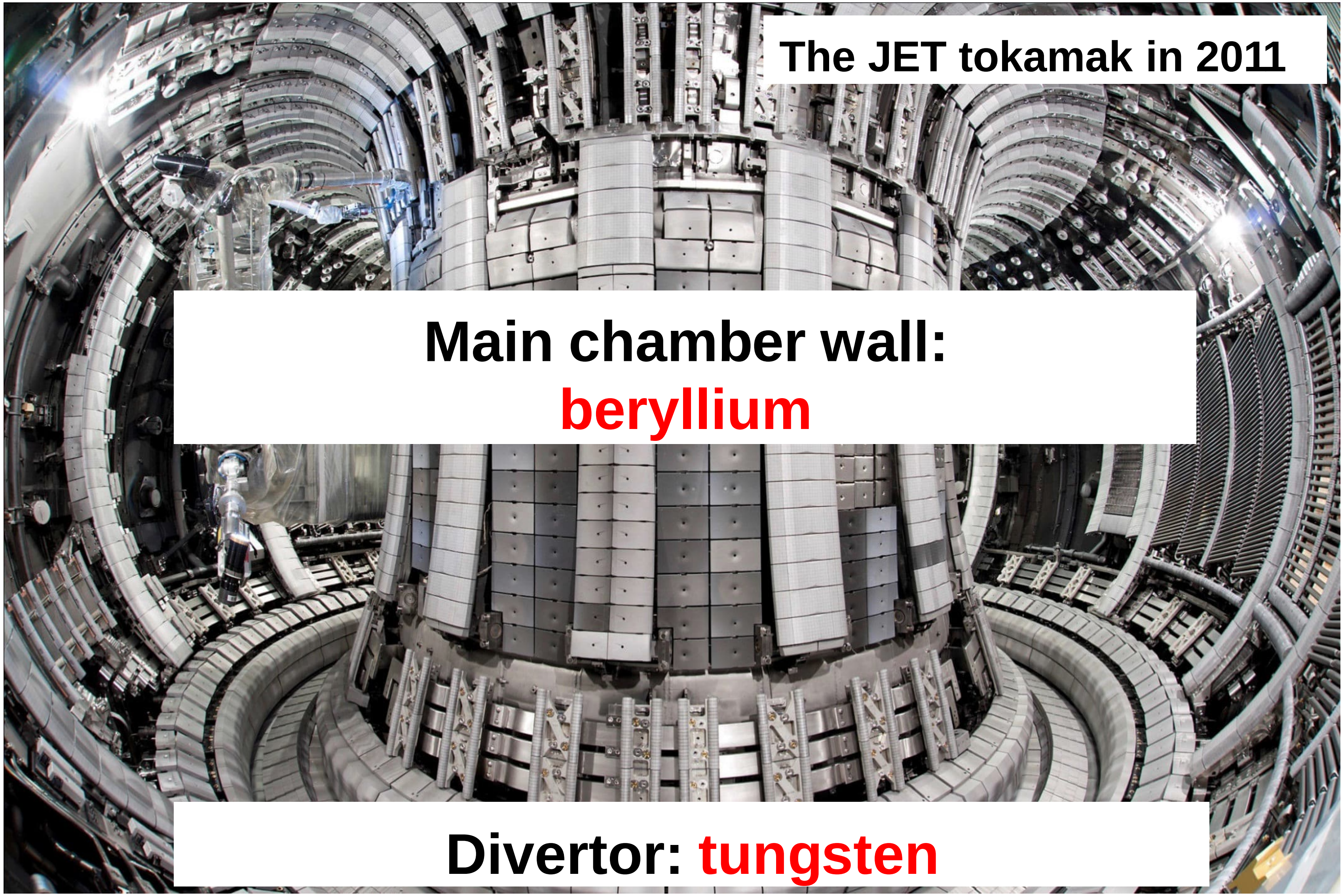
ITER Physics Basis,
Nucl. Fusion **39** (1999) 2175.

- **Confinement times of close to 1 s have been achieved in tokamaks**

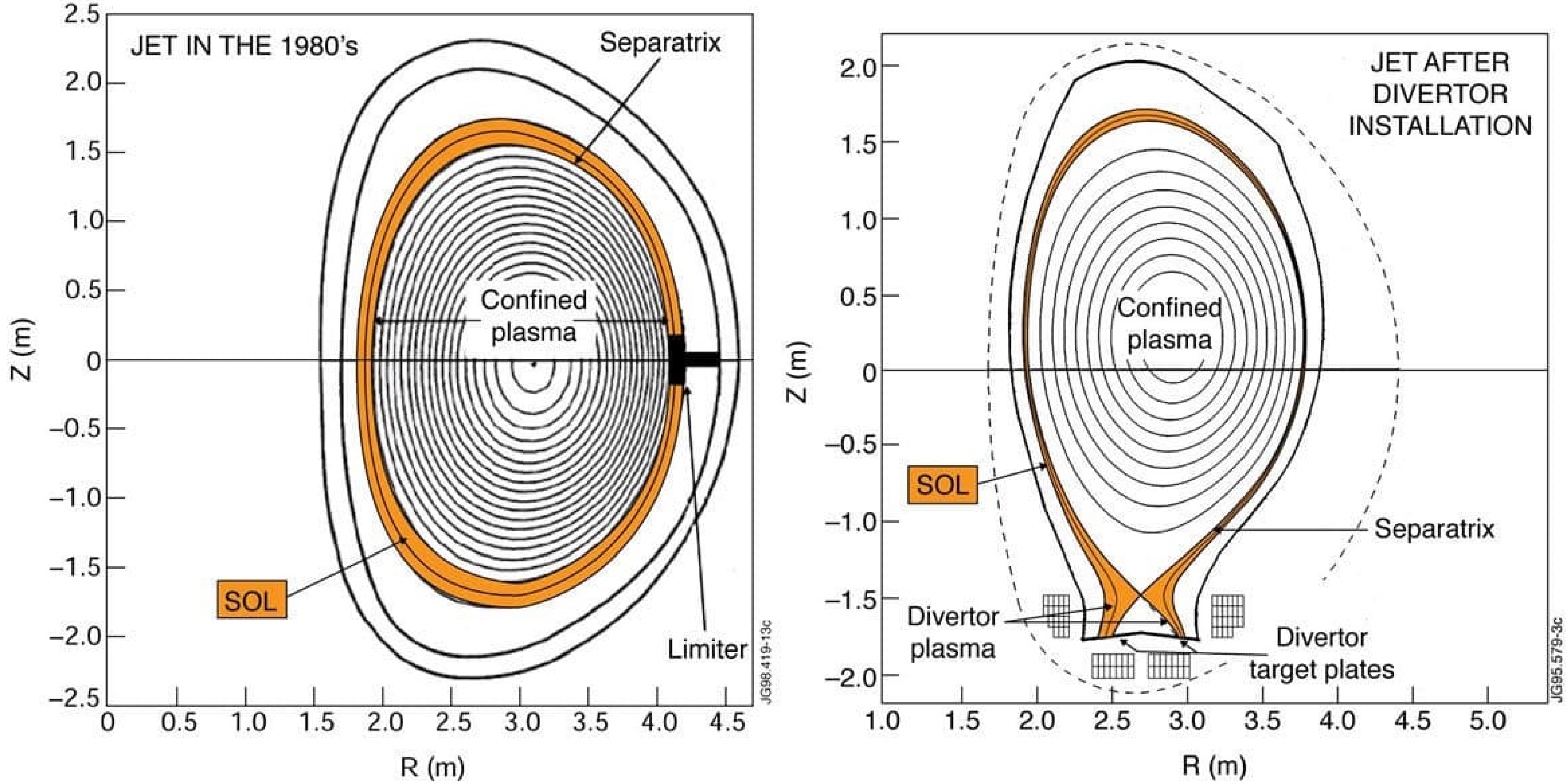
⇒ Next-step devices are expected to reach 8 s, due to larger size (R)

$$\tau_{E,\,IPB\,98(y)} \;\tilde{x}\; I^{0.97}\, B^{0.08}\, P^{-0.63}\, n^{0.41}\, M^{0.20}\, R^{1.93}\, \varepsilon^{0.23}\, \kappa^{0.67}$$

The plasma will inevitably interact with the surrounding walls injecting impurities into plasma

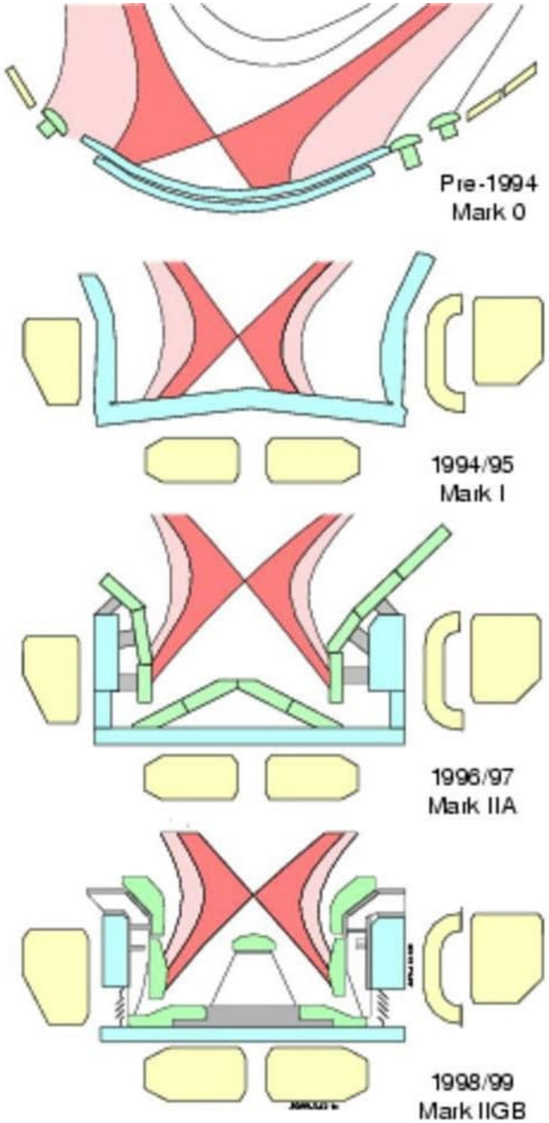


Divertor configurations (generally) produce purer and better performing plasmas



- **Plasma-wall interaction occurs via the (small!) scrape-off-layer ⇒ release of impurities and hydrogen neutrals into confined plasma ⇒ radiative cooling and dilution**

The divertor structural and magnetic geometries play key role in retaining neutrals and impurities

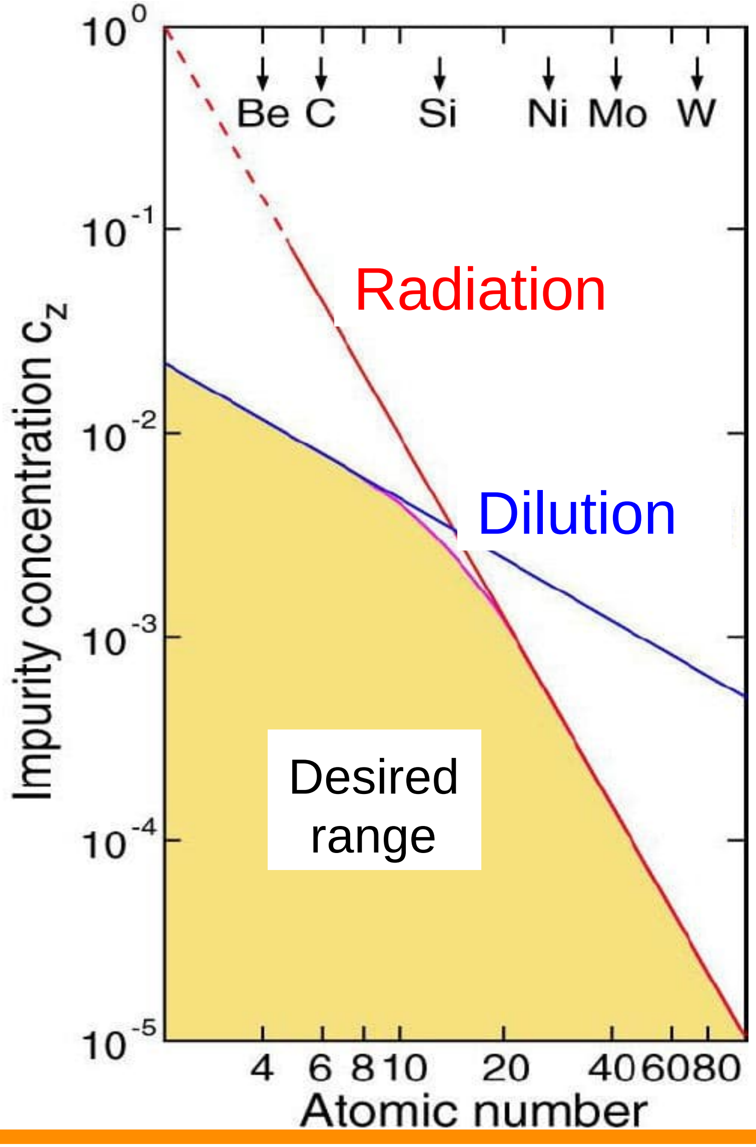


- **Additional poloidal field coils (inside vacuum chamber!) to divert magnetic field lines**

⇒ Divertor materials are chosen to withstand highest heat fluxes

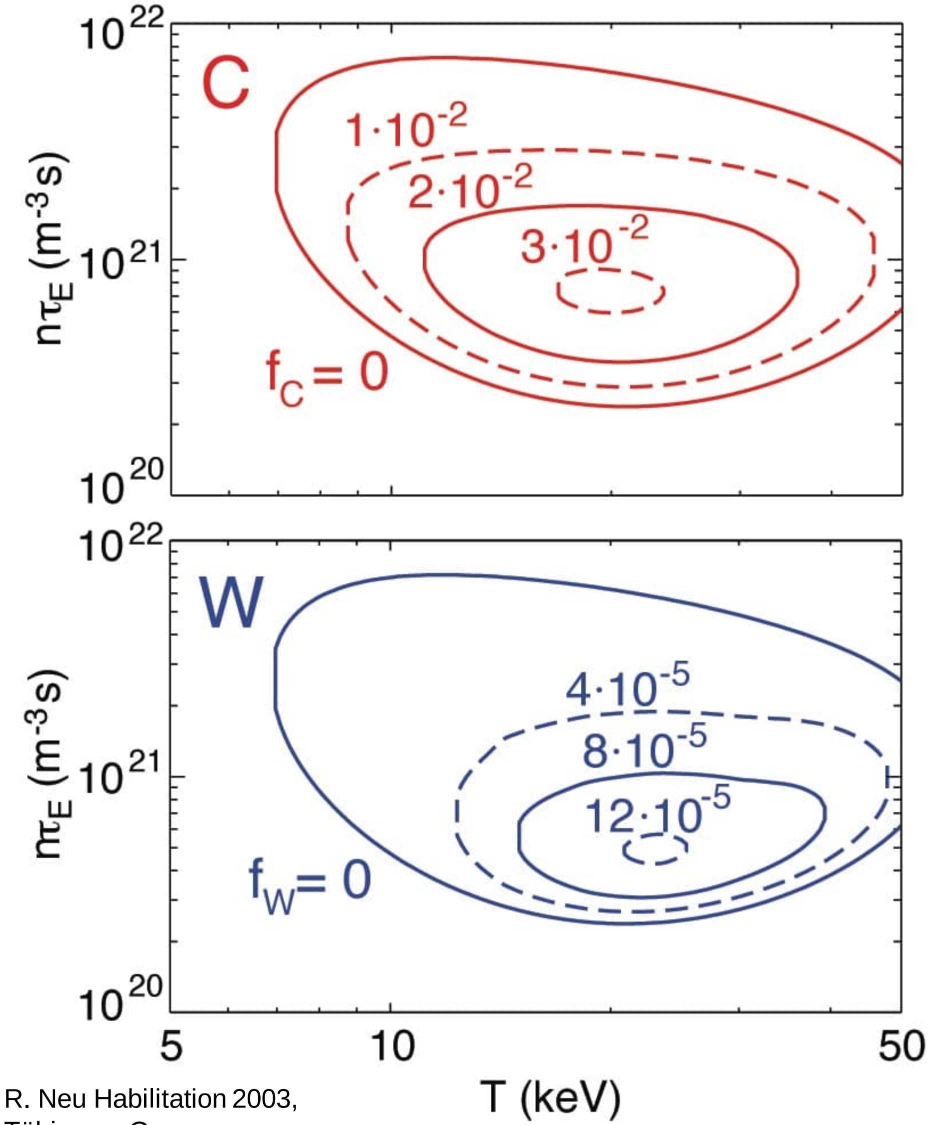
- **In-vessel cryogenic pump to control density**
- **Vertical plasma configurations with dome-like and septum to constrain neutrals to divertor chamber**

A certain purity of the (core) plasma is required for high fusion gain



- **Helium always present as reaction product of D-T**
- **Low-Z materials are most beneficial**
  - Few additional electrons
  - Low line radiation
  - Least dilution
- **But, low-Z materials have poor thermo-mechanical properties (melting point)**
  - Tritium co-deposition with carbon

Lawson criterion becomes very stringent when considering impurities



R. Neu Habilitation 2003, Tübingen, Germany

$$\rho \equiv \tau_{He}^{*} \,/\, \tau_E = 5$$

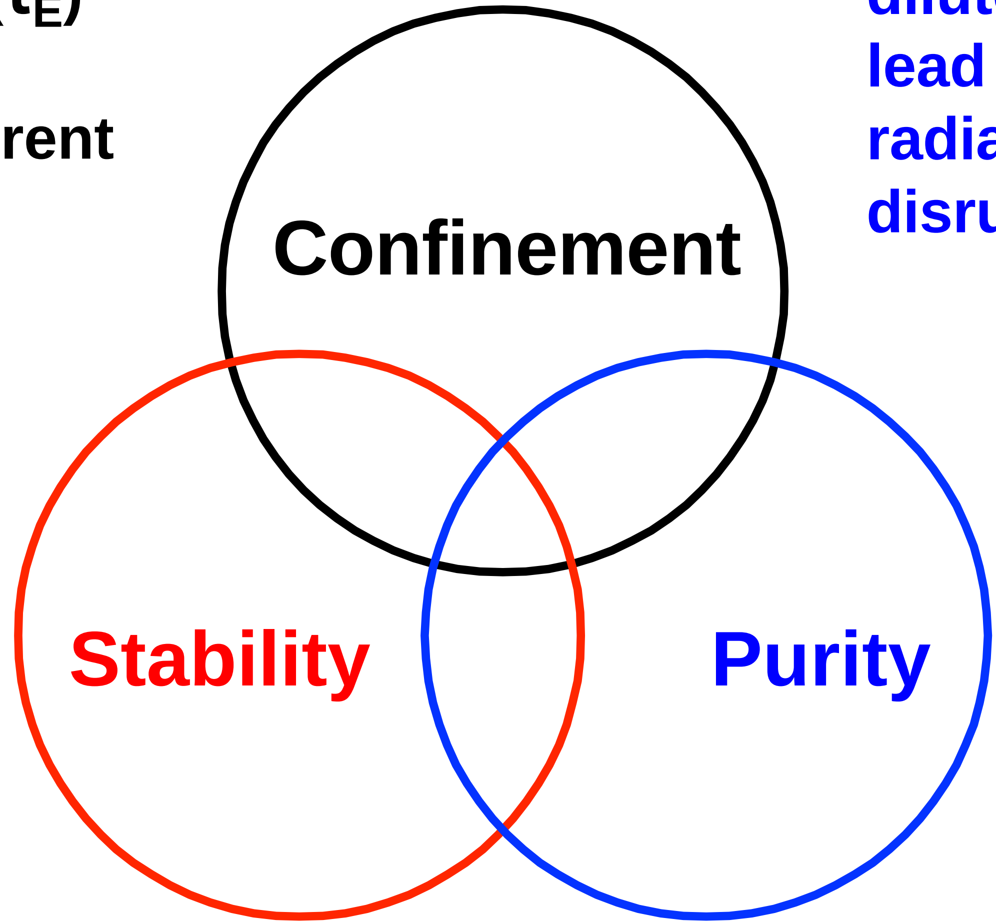
- **Additional dilution and radiative losses due to impurities ⇒ upper limit of nτ_E**

⇒ Only very small concentrations of high-Z impurities, such as W, can be tolerated (< 5x10^{-5})

Optimizing fusion performance requires a balance between stability, transport and plasma purity

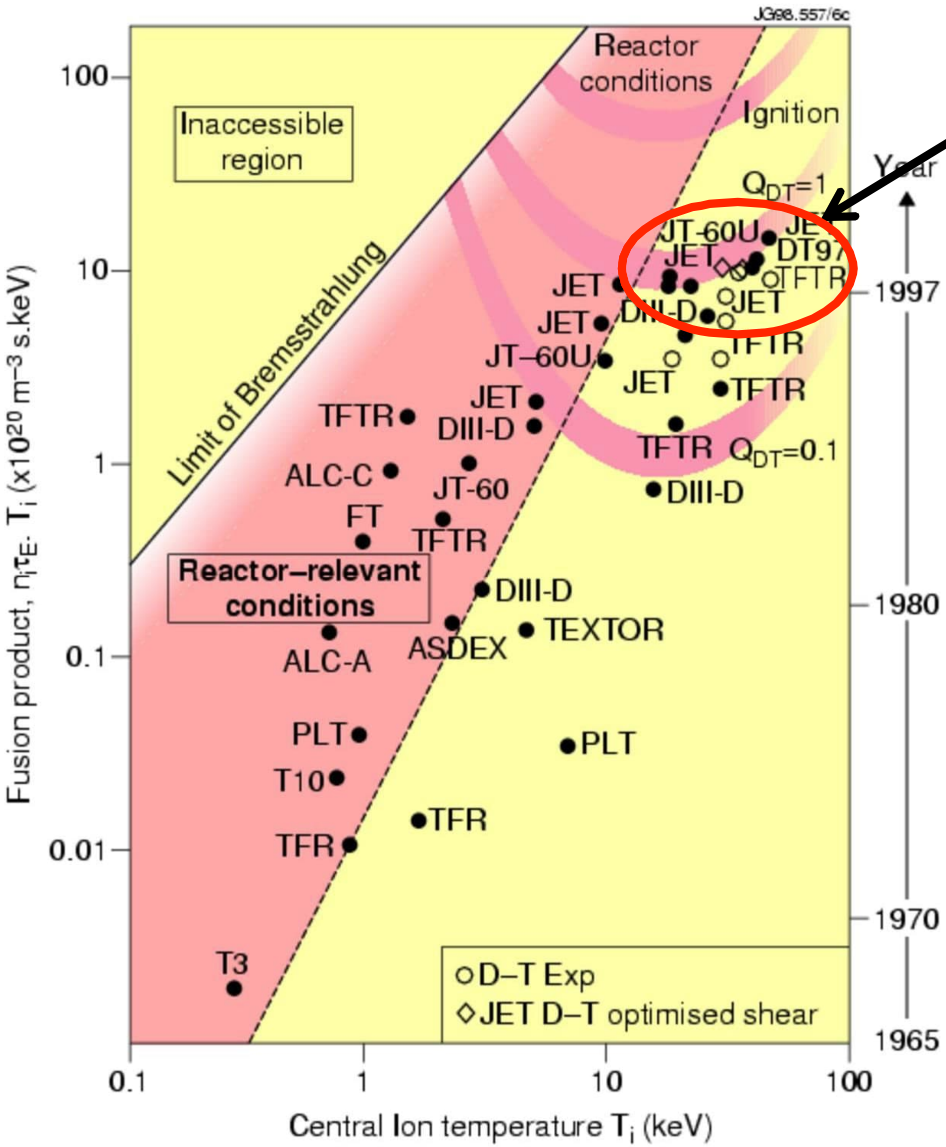
- **Good energy confinement (τ_E) requires maximum current**

- **Impurities dilute fuel, and lead to high/er radiation and disruptions**



- **Maximum density, current, pressure, and disruption limit**

Fusion performance in tokamaks has been pushed close to break-even ($P_{fus} \approx P_{aux}$)

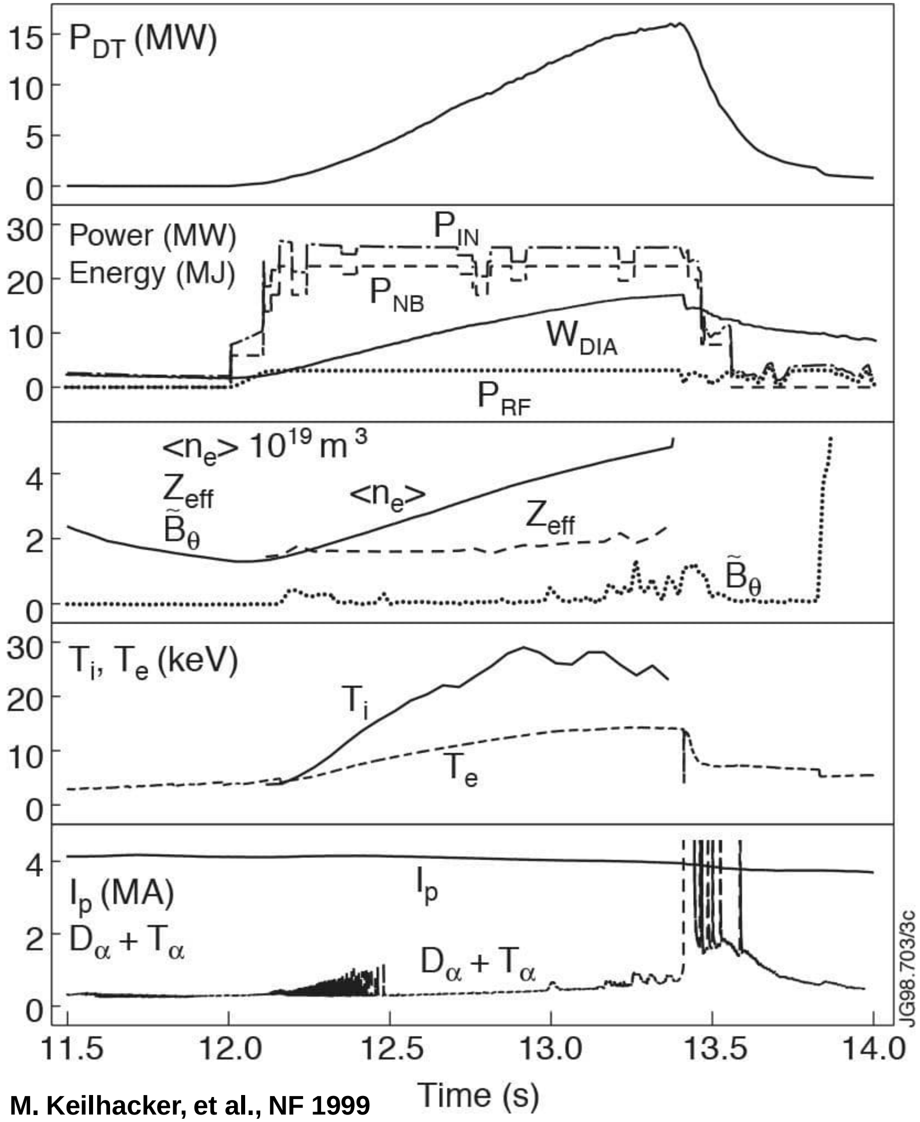


- **Cluster of high- performance pulses in the late 90s w/ carbon- based walls**
- **"The bigger the machine, the better the performance"**

⇒ JET tokamak in the UK (EURATOM device) is currently the front-runner

- DTE1 campaign in 1997/98 set world record in fusion power and Q
- DTE2 campaign in 2021/22 set world record in fusion energy

JET set the fusion record power in 1997 by producing more 16.1 MW



M. Keilhacker, et al., NF 1999

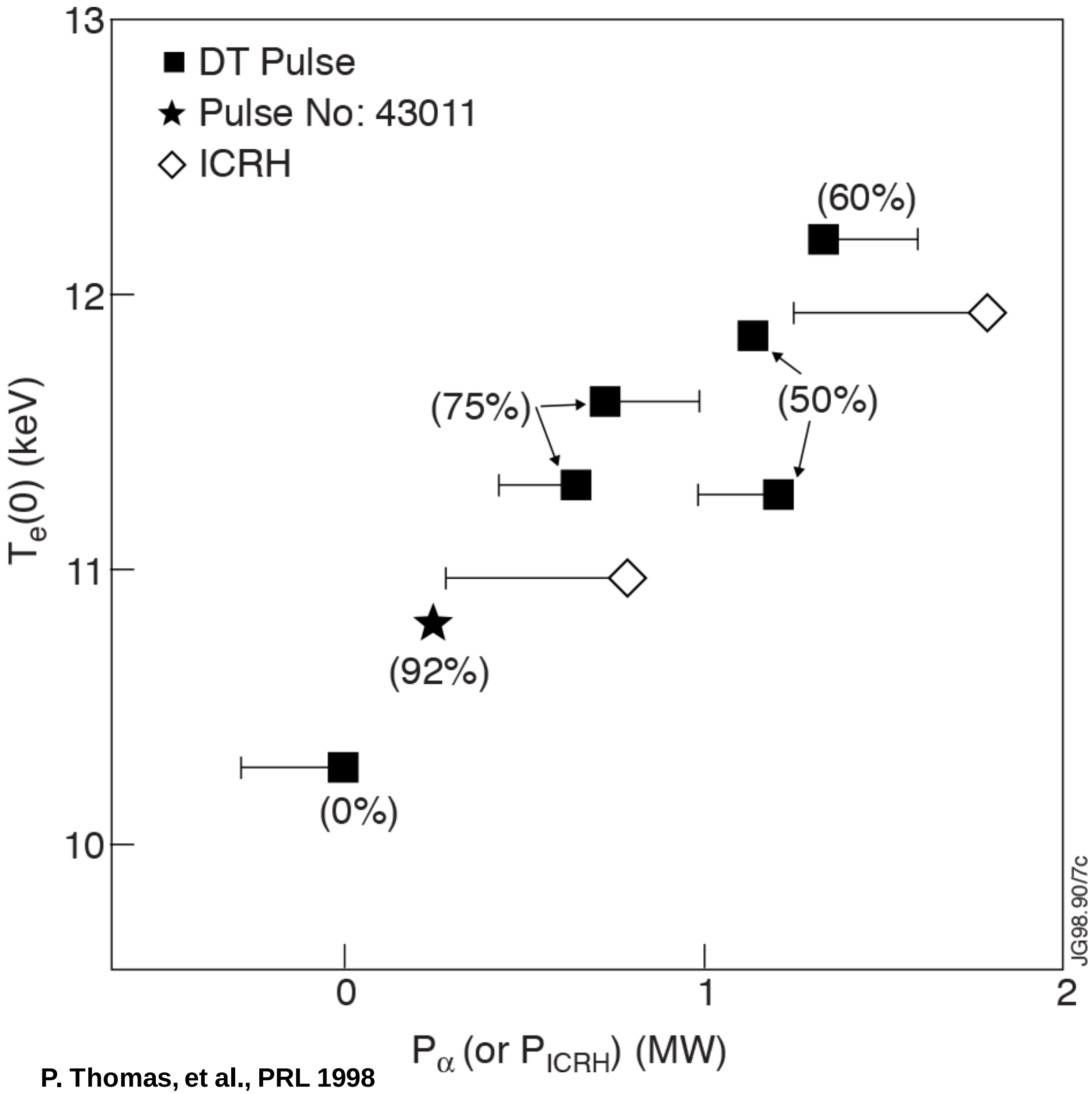
- **Continuous increase in P_{DT} with heating power (of total 25.4 MW)**

⇒ P_{fus}/P_{aux} ≈ 0.64 at the end of discharge (transiently, limited by heating systems): still the record in magnetic devices!

- **Carbon is the primary impurity species (Z_{eff} ≈ 2)**

- **"Hot ion" H-mode: T_i > 2xT_e**

Alpha-particle heating power, and thus central temperature are highly sensitive to fuel mix

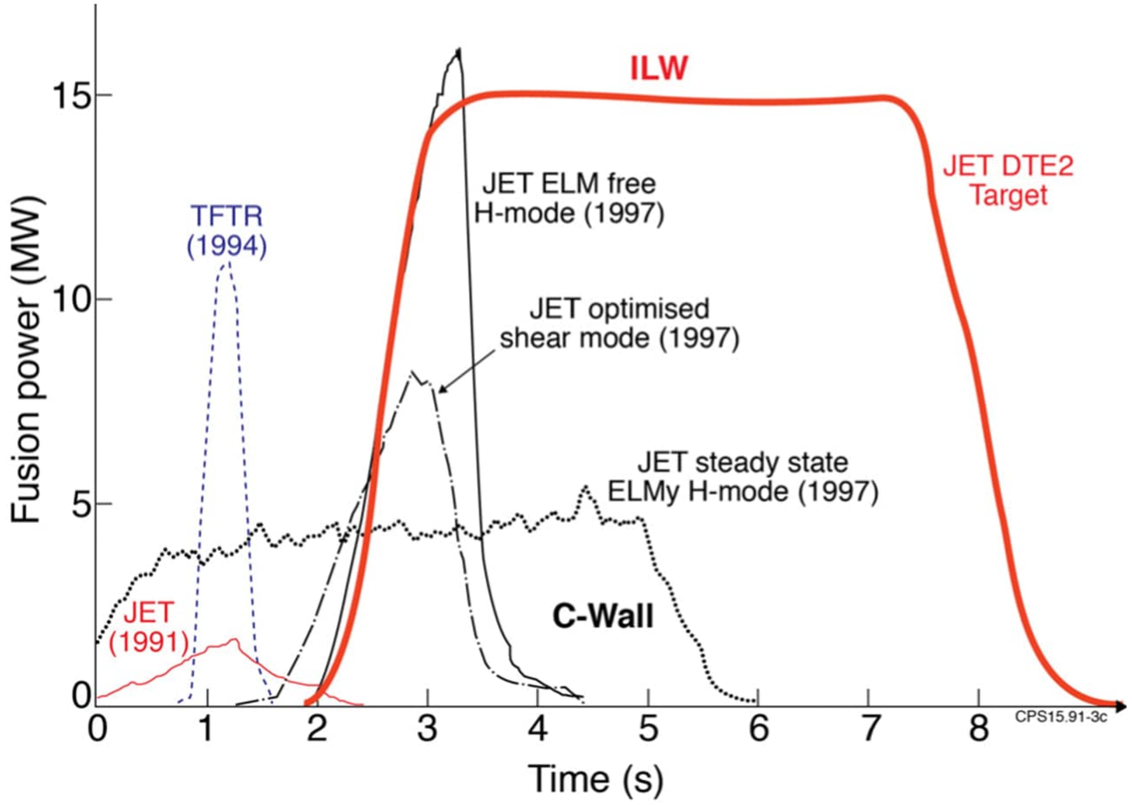


P. Thomas, et al., PRL 1998

- **Both TFTR and JET demonstrated α-particle heating in D-T plasmas**
- **D-T mixture varied in neutral beams**
- **Transfer of P_α to electrons, limited by instabilities (sawteeth)**
- **Maximum fusion power of 6.7 MW**

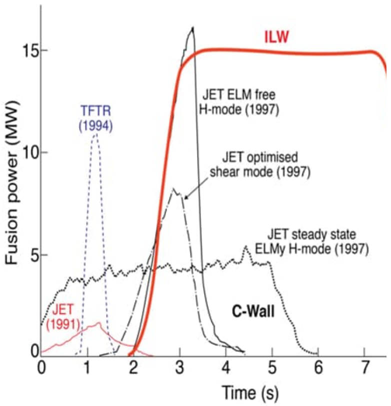
DTE1 (1997): In steady-state, i.e., for more than 4s, JET achieved 4.5 MW of fusion power in D-T

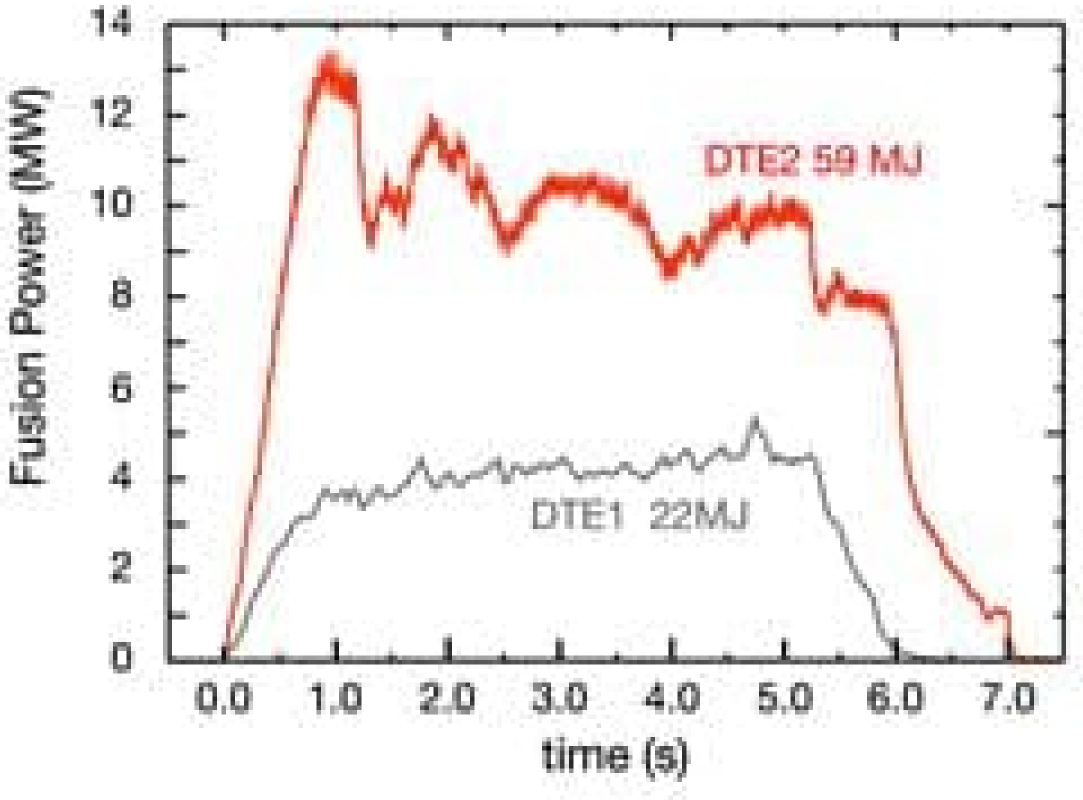
P. Thomas, et al., PRL 1998, X.Litaudon et al, IEEE Transactions, 2016



- **Previous record set by TFTR (US) in 1994 at 11 MW (also in DT),**
  3 MW in steady-state
- **Preliminary DT campaign in JET in 1991 for testing of system and establishing baseline**

DTE2 (2021-22): New fusion energy record of 59 MJ





The new energy record of 59 MJ (DTE2, in red) is >2.5x the previous record (DTE1, in grey).

Credit: EUROfusion consortium

Goals and background for DTE2 campaign

- **Usually, experiments at JET are fueled by deuterium (sometimes hydrogen) plasmas**
- **JET is preparing for another high-power DT campaign, the first since 1997**
- **JET is the only fusion device that is able to operate DT (TFTR was shut down 1997) due to own tritium plant (also: efficient confinement of alphas due to R and I_p)**
- **→ unique opportunity to prepare for ITER. Goals e.g.:**
  - **a) benchmark the ITER relevant 14-MeV neutron detection calibration**
  - **b) calculate of the neutron fluxes and machine activation**
  - **c) investigate radiation damage of functional materials for ITER etc.**

D-T campaign 2022 (DTE2) vs 1997 campaign (DTE1)

	DTE1	DTE2
Wall material	Carbon	Iter-like wall (Beryllium, Tungsten)
Input power	25 MW	40 MW
Reprocessed tritium gas	35g	700g
14 MeV neutron budget	3×10^{20}	1.7×10^{21}
Steady state fusion power	4MW (16 MW transiently)	15 MW for 5s (planned...)

Also, set of diagnostics "dramatically" improved.

E. Joffrin, et al., NF 2019

Video about 59MJ world record D-T campaign (DTE2)

JET's Deuterium-Tritium Experiments Set New Fusion Energy Record (Video 1:58s):

https://www.youtube.com/watch?v=ibMG5iUtF6w

Presemo quiz #2

https://presemo.aalto.fi/fet/

Summary

- **Fusion performance is limited by …**
  - Global and edge localized instabilities, e.g., sawteeth modulating core temperature
  - Micro-turbulence and large-scale convection of heat (particles, momentum)
  - Core radiation and fuel dilution due to edge neutrals and impurity influxes from walls
- **Solution has to be found in an integrated fashion, e.g., heating schemes, choice of wall materials, divertor geometry**
- **The TFTR and JET tokamaks have achieved plasma parameters close to breakeven (JET DTE1 P_{fus}=16.1 MW)**
- **Recent D-T campaign (DTE2) achieved new record in fusion energy record 59 MJ**