

# Plasma Instabilities

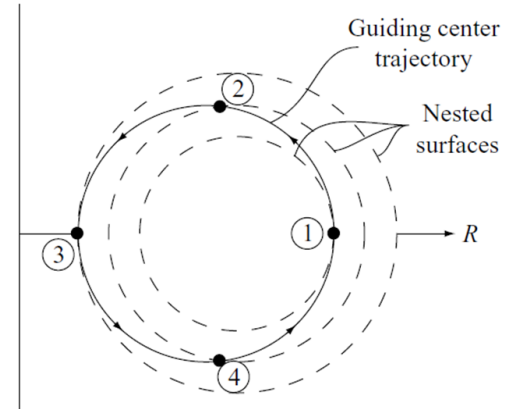
# Safety factor

If the poloidal angle between the  $k$  and  $k+1$  transits is denoted by  $\Delta\theta$

$$\iota = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{k=1}^N \Delta\theta_k$$

If  $\iota$  is a rational fraction of  $2\pi$  the **line is closed** (rational surface)

If  $\iota$  is not a rational fraction of  $2\pi$  the **line is ergodic**



For most axisymmetric toroidal configurations, an other important parameter is introduced in place of  $\iota$ , the **safety factor  $q$** , which measures the windiness of the magnetic fields in a reactor

$$q(r) = \frac{2\pi}{i} = \frac{rB_z(r)}{RB_\theta(r)} = \frac{d\phi}{d\theta}$$

**The higher  $q$ , the more stable the configuration is.** As the fields vary across the minor axis,  $q$  also varies and is often expressed as  $q(r)$ . On the inside of the cylinder on a typical tokamak it converges on 1, while at the outside it is nearer 6 to 8.

Some instabilities caused by small variations in the plasma shape have a natural pattern based on  $\iota$ . The plasma is stable to this major class of instabilities when  $q(r=0) > 1$

# Beta

The efficiency of the confinement by the magnetic field is represented by ratio of the plasma pressure ( $n k T$ ) to the magnetic pressure ( $B^2/2\mu_0$ )

$$\beta = \frac{n k T}{B^2/2\mu_0}$$

$\beta$  is normally measured in terms of the total magnetic field. Have as high beta as possible, it would imply the minimum amount of magnetic force needed for confinement. But in practice, in a tokamak, for a stable plasma,  $\beta$  is always much smaller than 1 (otherwise it would collapse), most tokamaks operate at  $\beta$  of order 0.01 (or 1% if expressed in percentage).

The strength of the field varies over the volume of the plasma, thus the average beta is sometimes referred to as the "beta toroidal". The costs of large magnets roughly scales like  $\beta^{1/2}$ . Therefore,  $\beta_{\text{tor}}$  can be thought of as a *ratio of money out to money in* for a reactor, and  $\beta_{\text{tor}}$  can be thought of (very approximately) as an economic indicator of reactor efficiency. For , betas of larger than 0.05 or 5% are desired for economically viable electrical production.

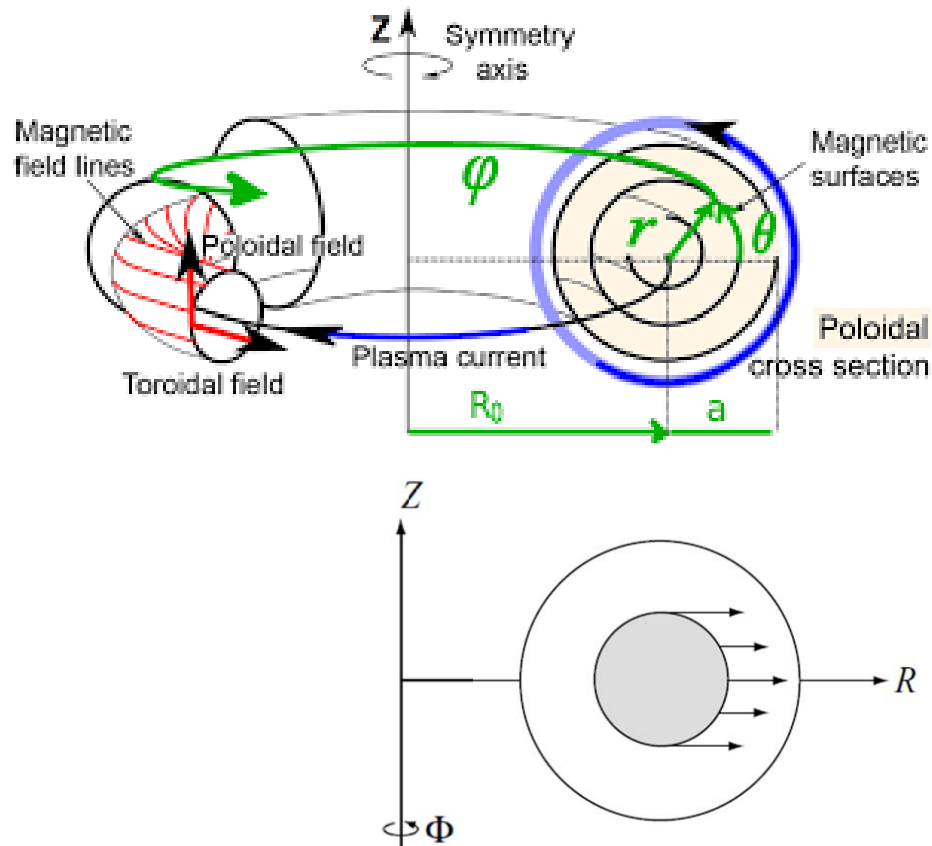
# instabilities

## Instabilities

- ❑ Radial and vertical instabilities of the plasma column position
  - ✓ The poloidal beta enters in the expression of the Shafranov shift and of the vertical field needed for equilibrium
  
- ❑ MHD instabilities
  - ✓ Can develop at the rational surfaces: integer poloidal ( $m$ ) and toroidal ( $n$ ) mode numbers
  - ✓ Experimentally it is found that the toroidal beta is limited by a disruptive instability
  
- ❑ Disruptions: can be caused by MHD instabilities and vertical instability (Vertical Displacement Events, VDEs)

# Toroidal forces

When a straight cylinder closed into a torus, of three toroidal forces directed outwardly along the direction of the major radius which acts to expand the plasma ring. These force are produced by



To hold the plasma in toroidal force balance, some additional force must be applied to counter the outward forces:

- ❖ **Perfectly conducting wall**
- ❖ **Vertical field**

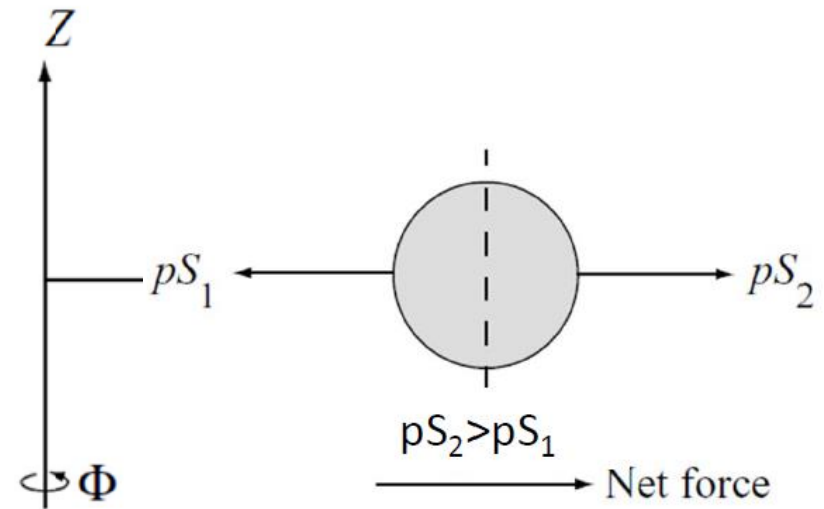
# Tire force

The tire tube force depends by the plasma pressure. The **internal pressure** stretches the outside surface area of the torus more tightly than the inner surface area ( as the air pressure in a inflated rubber tire tube.

The tire tube force is generated in both a Z-pinch and a  $\theta$ -pinch

The pressure produces an expansion  $F_1 = pS_1$ , on the inner half surface  $S_1$ , which points **inwardly** and a force  $F_2 = pS_2$  on the outer half surface  $S_2$  and which points **outwardly**.

A net tire tube force  $F_2 - F_1 > 0$  pointing outwardly along  $R$



# Hoop forces

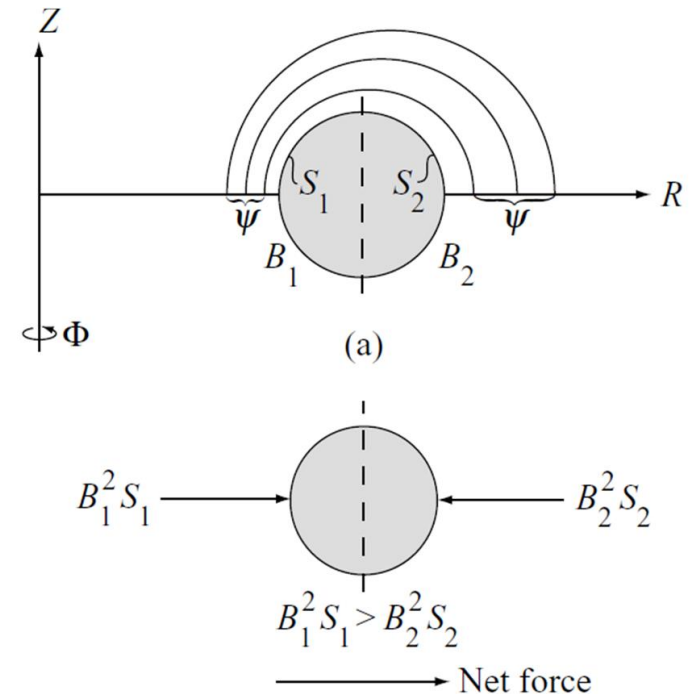
The Hoop force is an outward expansion force generated by the toroidal current flowing in the plasma surface, as for any current flowing in a circular wire loop

The hoop force is generated in a **Z-pinch** into a torus

In a toroidal configuration, the magnitude of the magnetic field is greater on the inside than on the outside:  $B_1 > B_2$  (inside the lines are packed more closely together).

$$F = p_{\text{magnetic}} \cdot S = \frac{B^2}{2\mu_0} \cdot S \propto B^2 \cdot S$$

The magnetic pressure has the same direction of the Kinetic pressure. The quadratic dependence of  $B$  dominates the expression for the forces:  $F_1 > F_2$ .



# 1/R dependence force

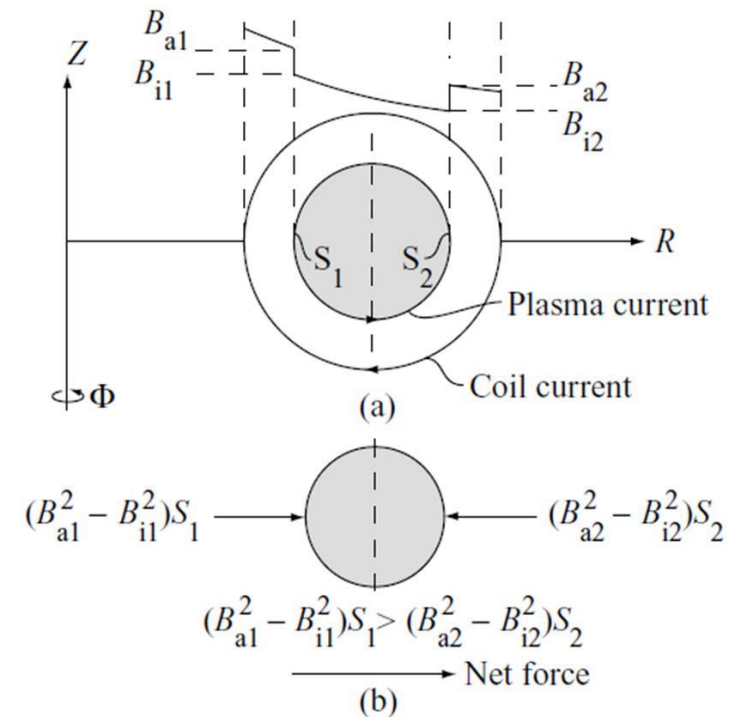
The «1/R» force arises because of the **1/R dependence of the toroidal field** resulting from the toroidal geometry.

Since only the toroidal magnetic field is involved, this force is generated in the **θ-pinch** configuration (but not the Z-pinch).

1/R dependence of the toroidal field  $B_a = \frac{\mu_0 I_c}{2\pi R}$  where  $I_c$  is the current in the toroidal coils

The induced current in the plasma  $I_\theta$ , flowing in an infinitesimally thin layer on the plasma surface, produces a field inside the plasma that partially cancels the applied field (diamagnetic effect)

$$B_i = \frac{\mu_0(I_\theta - I_c)}{2\pi R}$$



# Restoring force

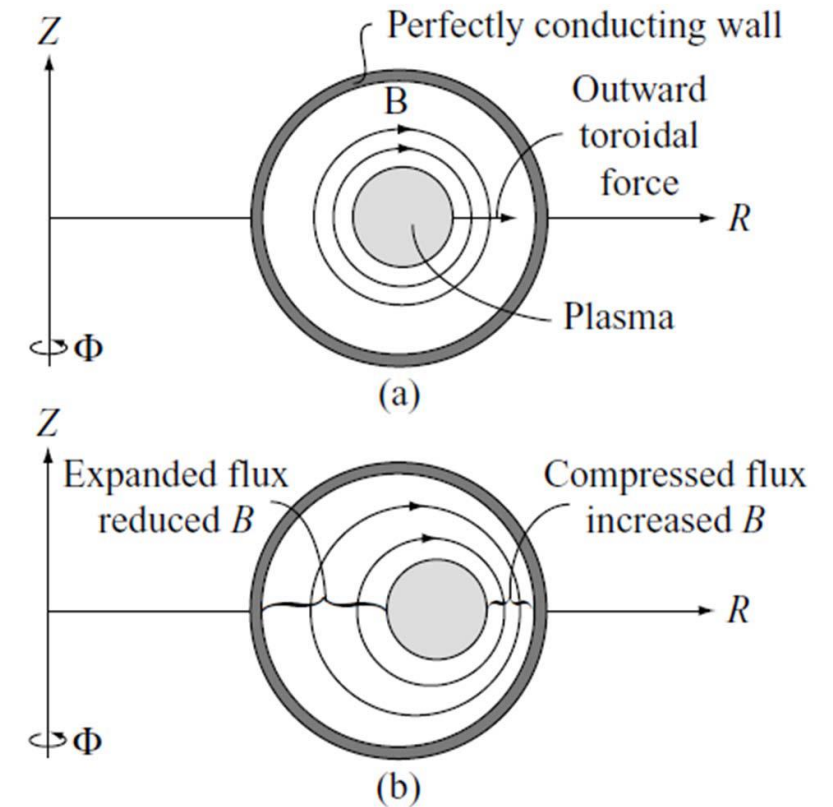
In a Z-pinch or screw-pinch there are two methods for balancing the outward expansion forces:

- **Passive stabilization** by perfectly conducting wall surrounding the plasma
- the application of an **external vertical field**.

## Passive stabilization

as the plasma starts to move outward along the major radius  $R$ , the poloidal magnetic field at the outer edge of the plasma increases in magnitude because of the poloidal **flux trapped between the plasma and the perfectly conducting wall**.

As the plasma continues to shift outward, it will reach a point where the magnetic pressure on the outer side of the plasma has increased to a large enough value to compensate the outward toroidal forces.



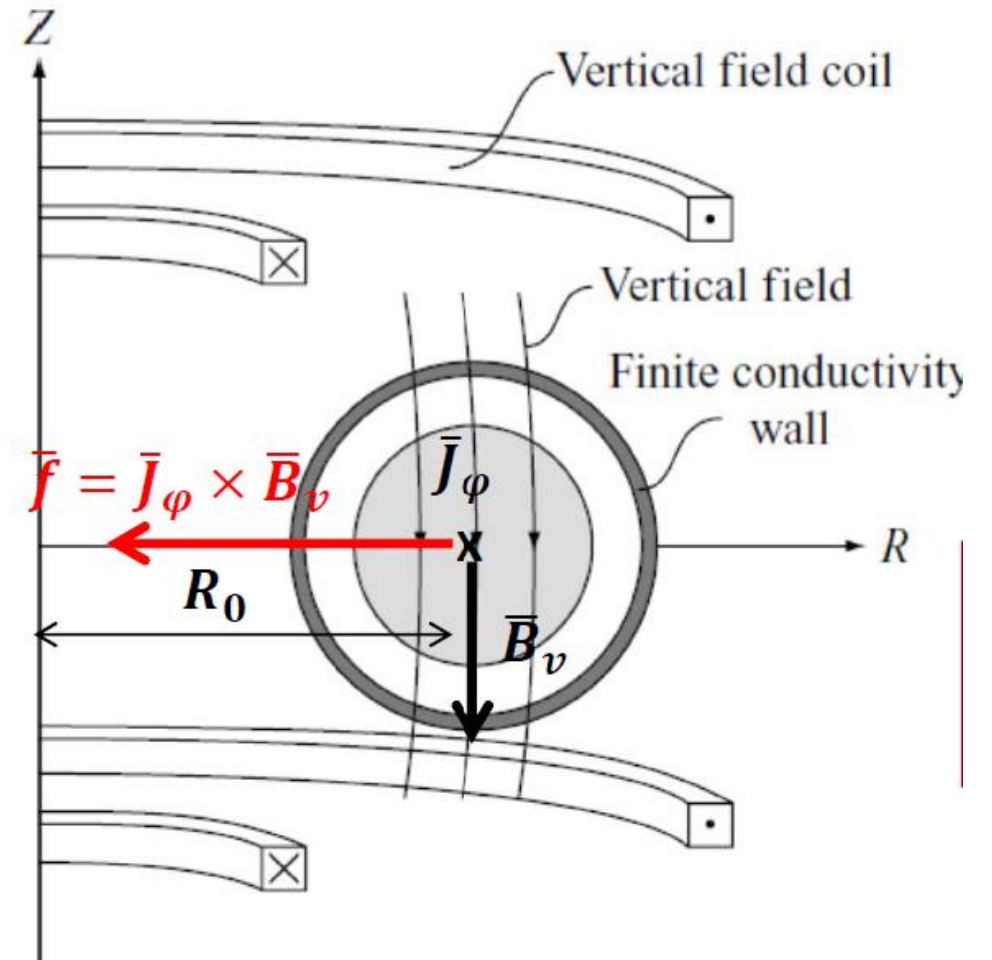
# Restoring force

It is not possible to indefinitely trap poloidal field between the plasma and the wall if the wall has a finite conductivity

By choosing the magnitude and sign of the vertical field  $\bar{B}_v$ , in magnetic configurations with a net toroidal current  $I_p$  (current density  $\bar{J}_\phi$ ), an inward restoring force:

$$\bar{F} = \bar{J}_\phi \times \bar{B}_v$$

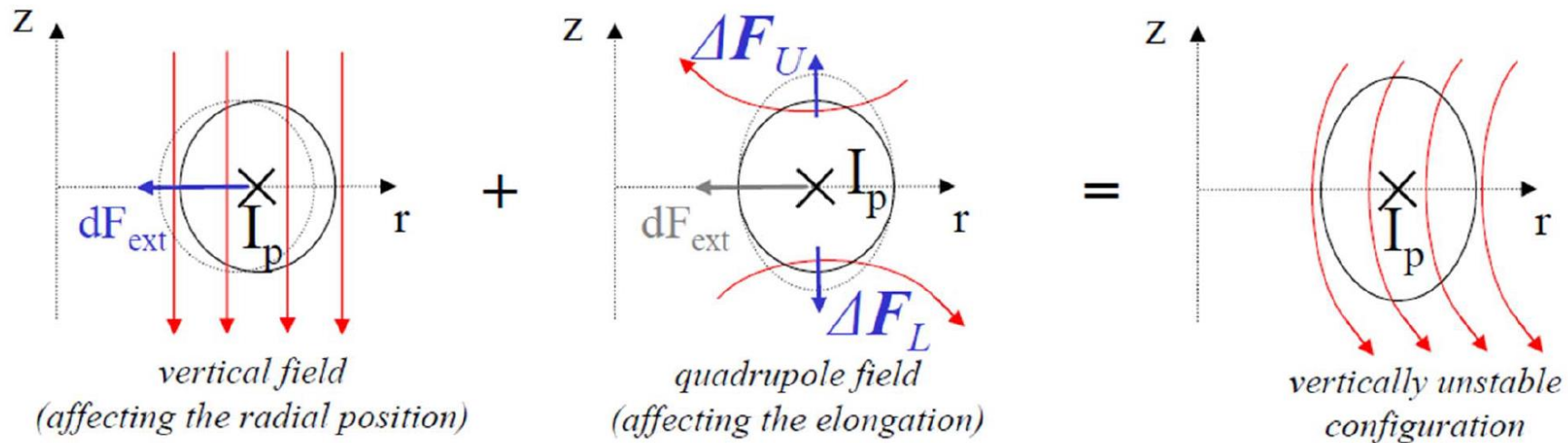
can be produced to establish the toroidal force balance.



# Elongated plasma

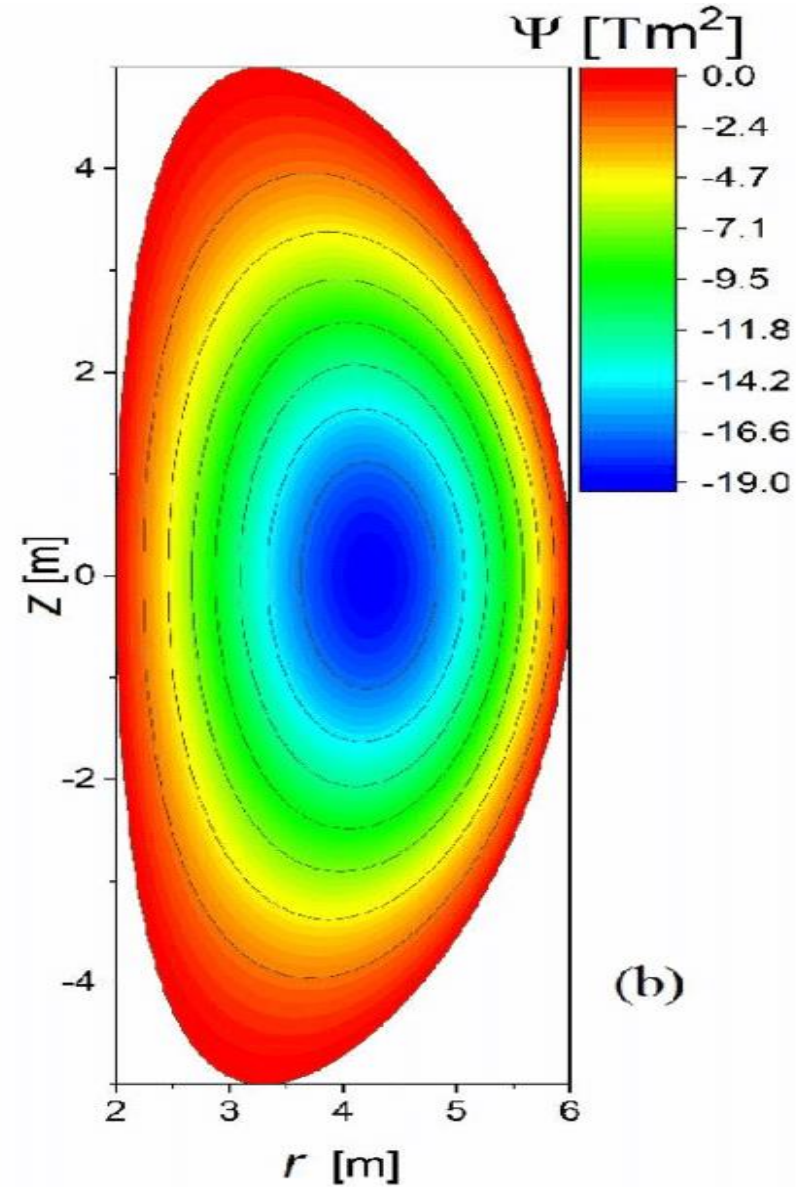
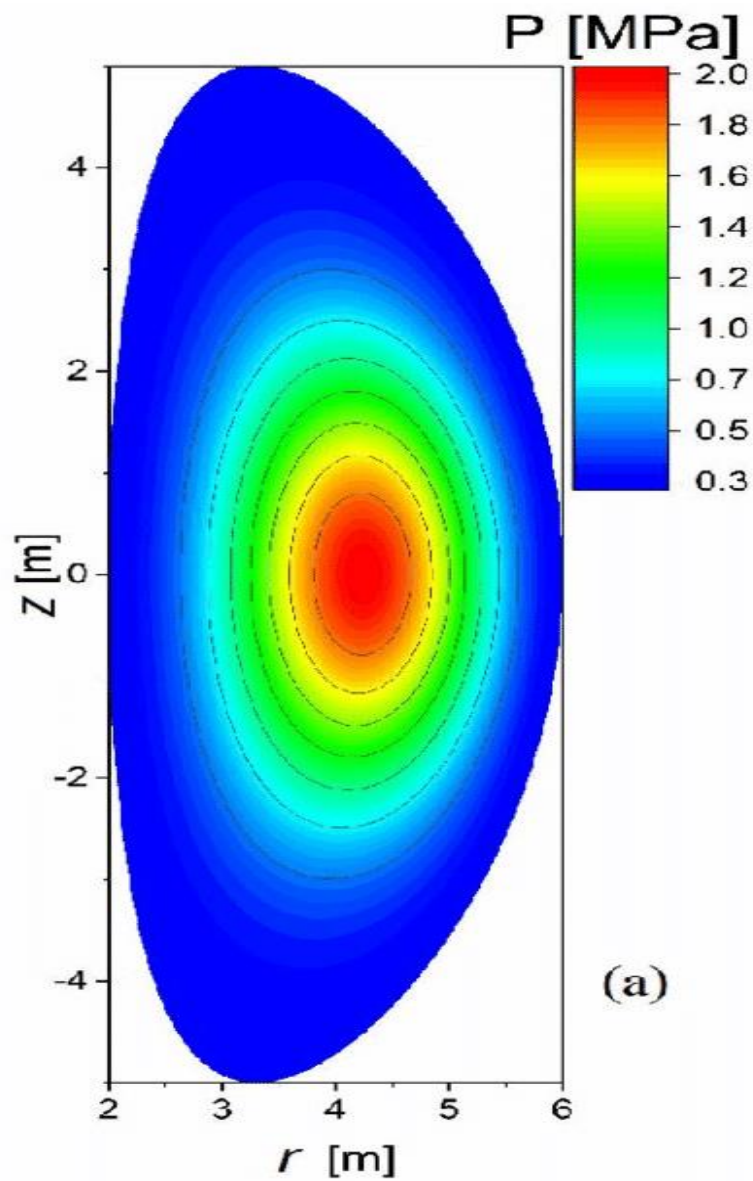
Vertically elongated plasma allow to maximize the performance-cost ratio. In particular, D-shape plasma improves the stability with regards to a number of different types of instabilities.

The elongation of a plasma is due to current in external conductors, which create additional forces (with zero total force ).



Elongated plasmas are vertically unstable and are kept in the center of the vessel by an active vertical stabilization system

# Elongated plasma

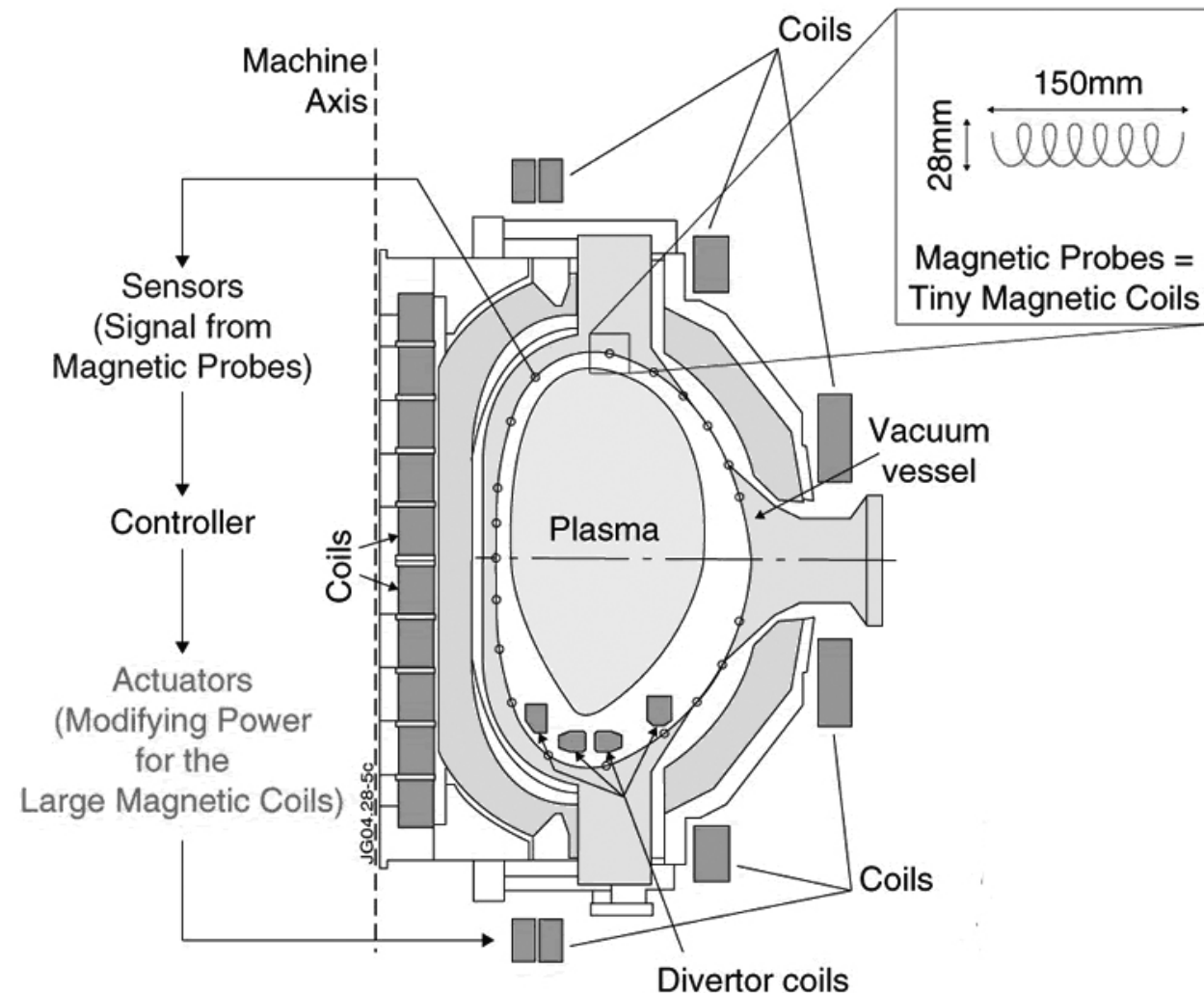


# Magnetic feed back control

*If the plasma is displaced from its equilibrium position, the resultant force is such as to increase the displacement. In addition, to make the best use of the available volume and to ensure good passive stabilization in large, highly elongated tokamaks, the plasma must be maintained as close as possible to nearby components such as the first wall, limiter, and baffles.*

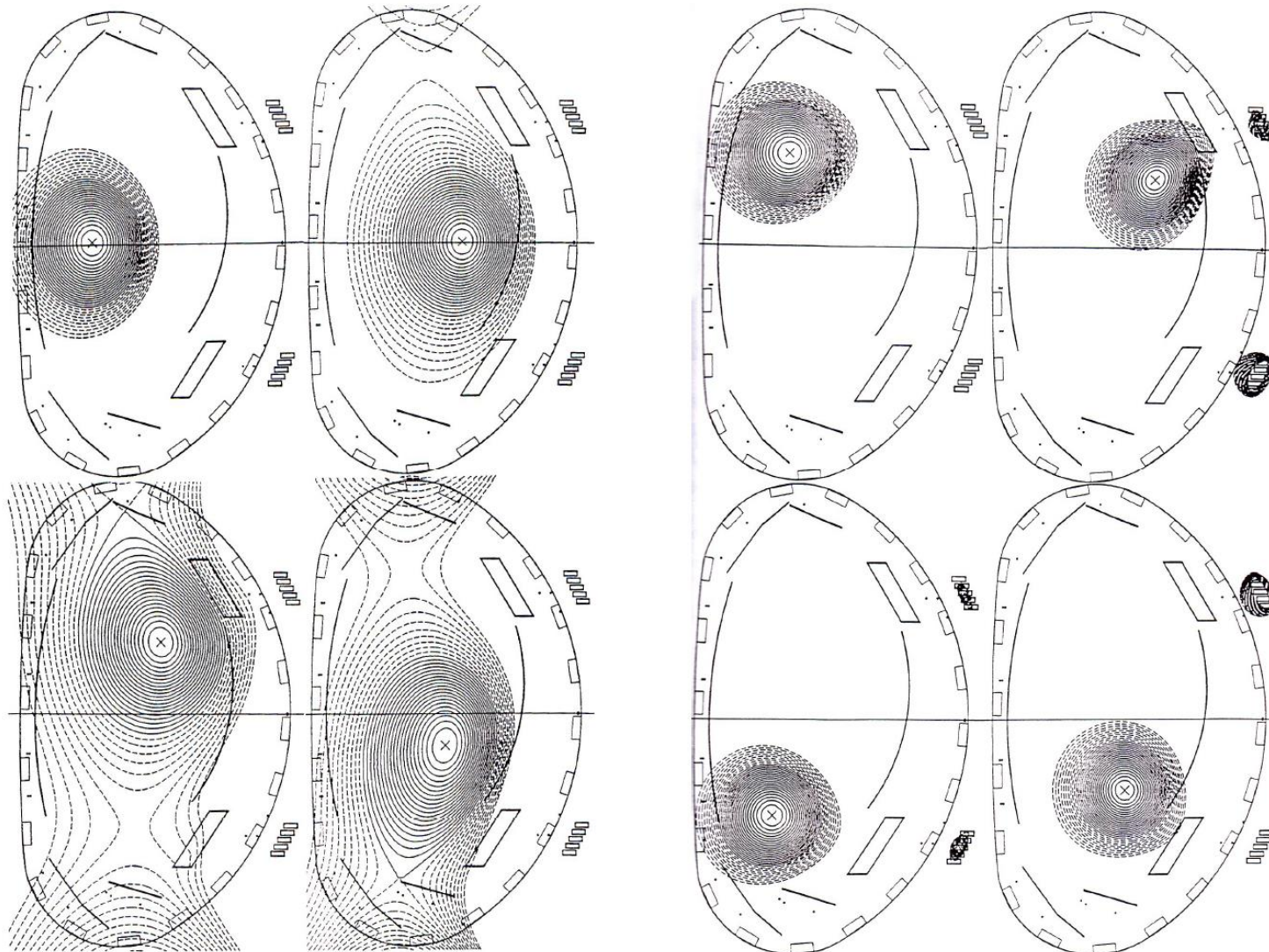
Active Magnetic feed back control system:

- plasma current control*
- radial and vertical position of the current centroid control*
- Magnetic flux control
- Gap control



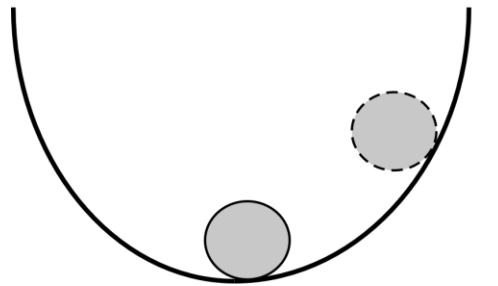
# Magnetic feed back control

Plasma position and shape feedback control is necessary to assure the stability of the discharge



# MHD stability in ideal plasmas

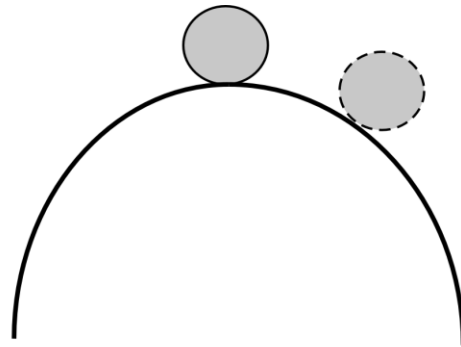
stable equilibrium



shift or displacement  $\xi$   
 resulting force  $F$

$$\delta W = W_1 - W_0 > 0$$

unstable equilibrium



shift or displacement  $\xi$   
 resulting force  $F$

$$\delta W = W_1 - W_0 < 0$$

unstable only if  $\delta W < 0$

$$\delta W = \frac{1}{2} \int \vec{\xi} \cdot \vec{F} d\tau$$

$$F = (\vec{J} \times \vec{B}) - \nabla p$$

Magnetic force

Pressure force

$$\delta W = \frac{1}{2} \int_{\text{plasma}} \left( \underbrace{\gamma p_0 (\nabla \cdot \vec{\xi})^2}_{>0} + \underbrace{(\vec{\xi} \cdot \nabla p_0)}_{\text{pressure driven instabilities}} \nabla \cdot \vec{\xi} + \underbrace{\frac{B_1^2}{\mu_0}}_{>0} - \underbrace{\vec{j}_0 \cdot (\vec{B}_1 \times \vec{\xi})}_{\text{current driven instabilities}} \right) d\tau + \underbrace{\int_{\text{vacuum}} \frac{B_{\text{vac}}^2}{2\mu_0} d\tau}_{>0}$$

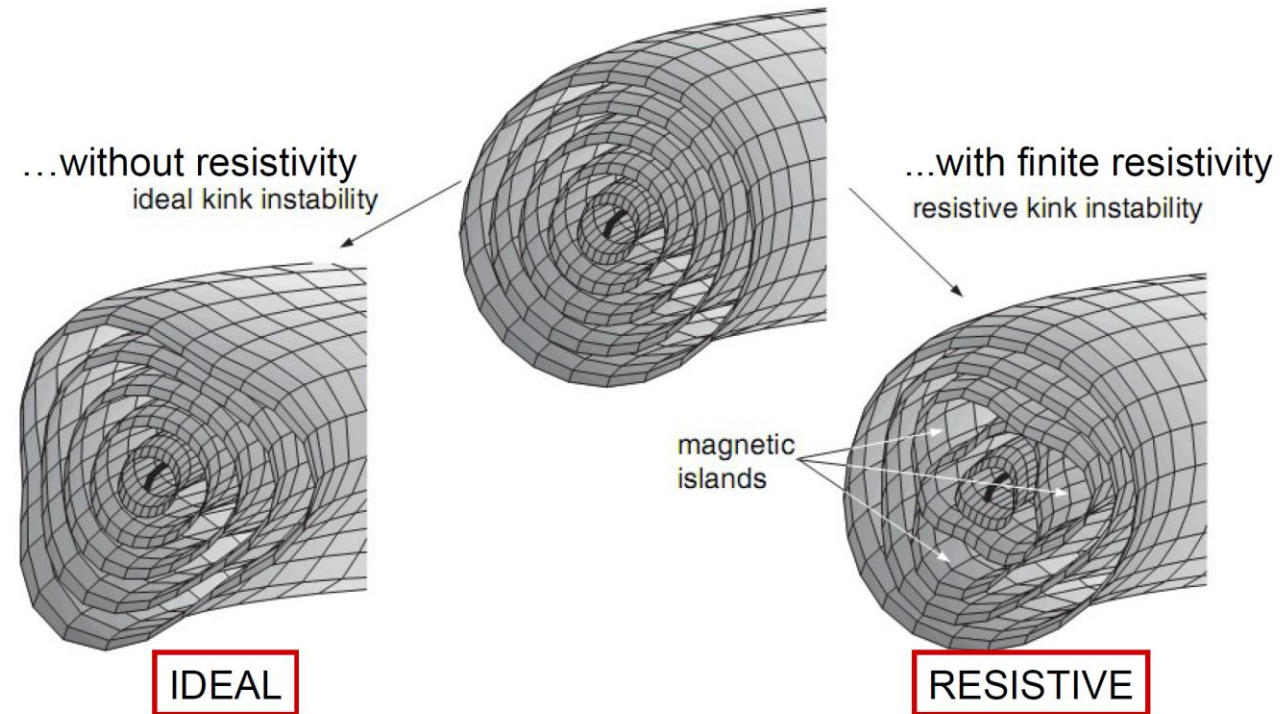
# MHD activity in tokamaks

MHD instability can be *resistive* (if reconnection of the magnetic field lines are necessary) or *ideal* (simple distortion of the magnetic surfaces)

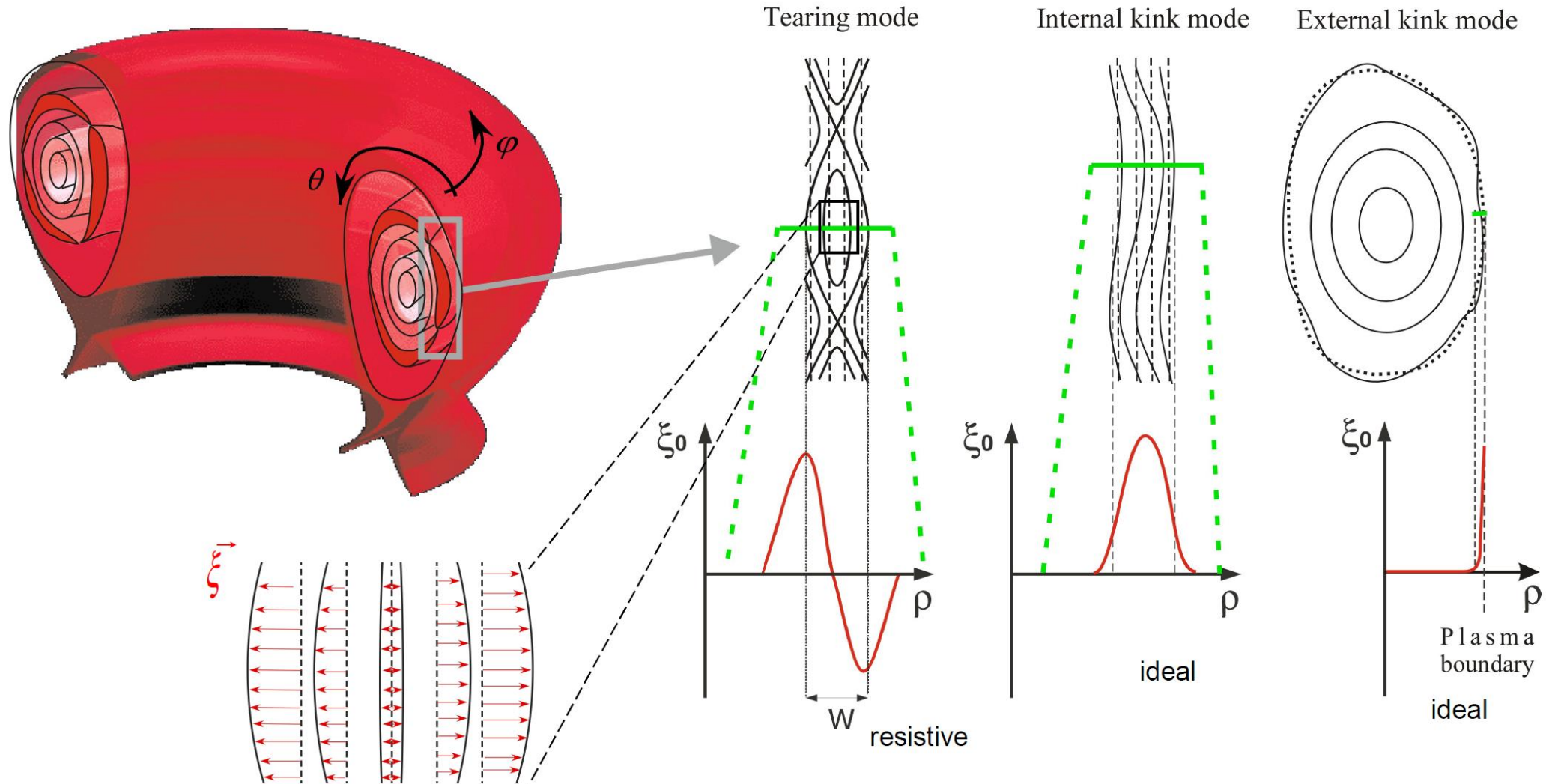
MHD instabilities can develop at the rational surfaces (integer poloidal ( $m$ ) and toroidal ( $n$ ) mode numbers)

The energy sources are gradient of current profile and/or pressure profile. Thus, they can be pressure-driven or current driven, according to the term dominating the energy variation

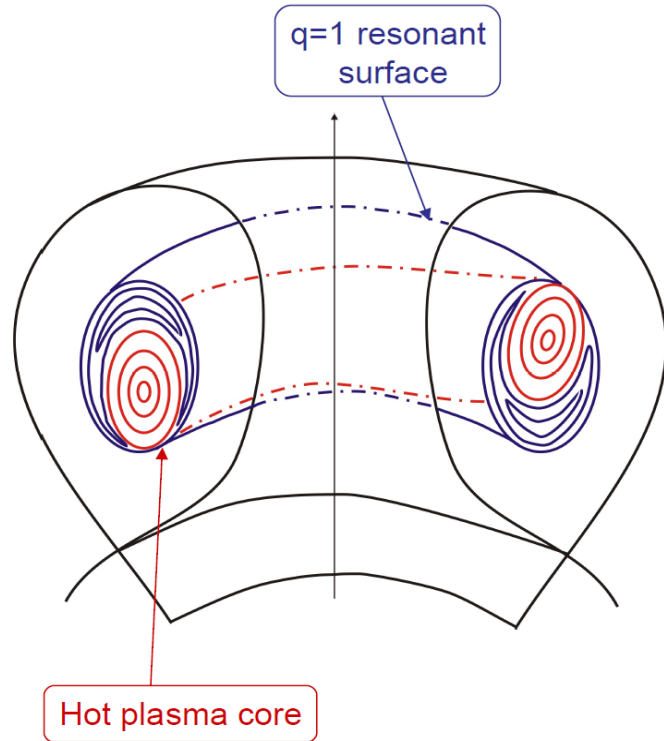
MHD instabilities can develop at rational surfaces



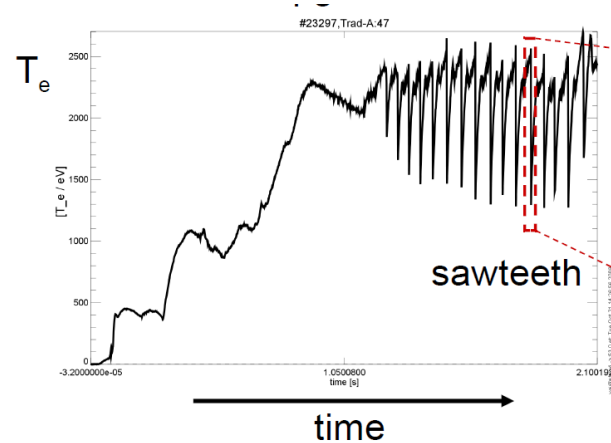
# MHD activity in tokamaks



# Internal kink mode (or Sawtooth)

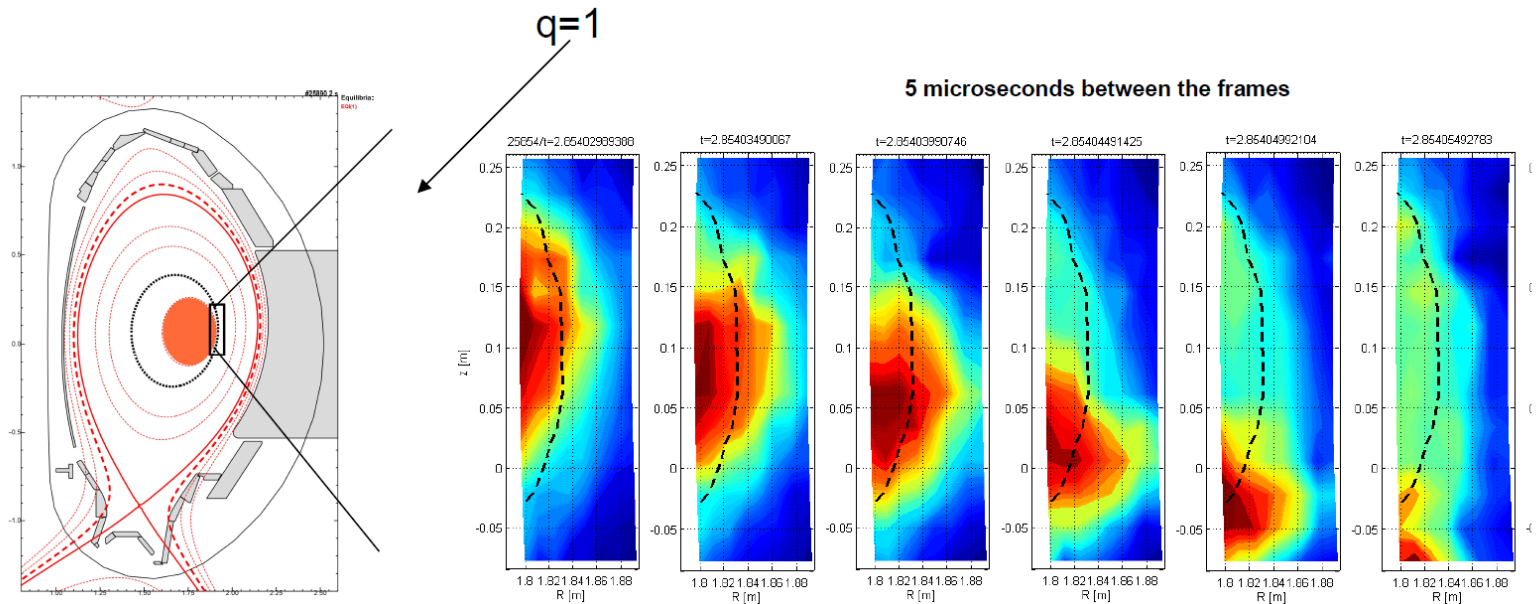


It is possible to modify the current profile by launching electromagnetic waves in plasma. By this technique one can constantly destabilize (1,1) mode and as a result get small and frequent sawteeth



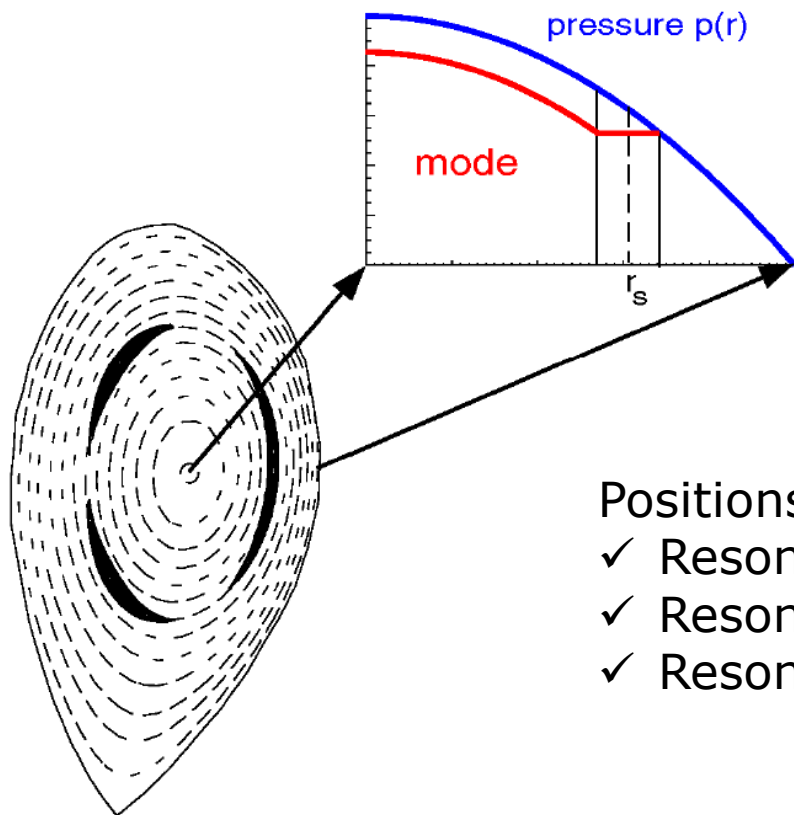
Rotation of the mode

During the sawtooth drop, heat flows out of  $q < 1$  region



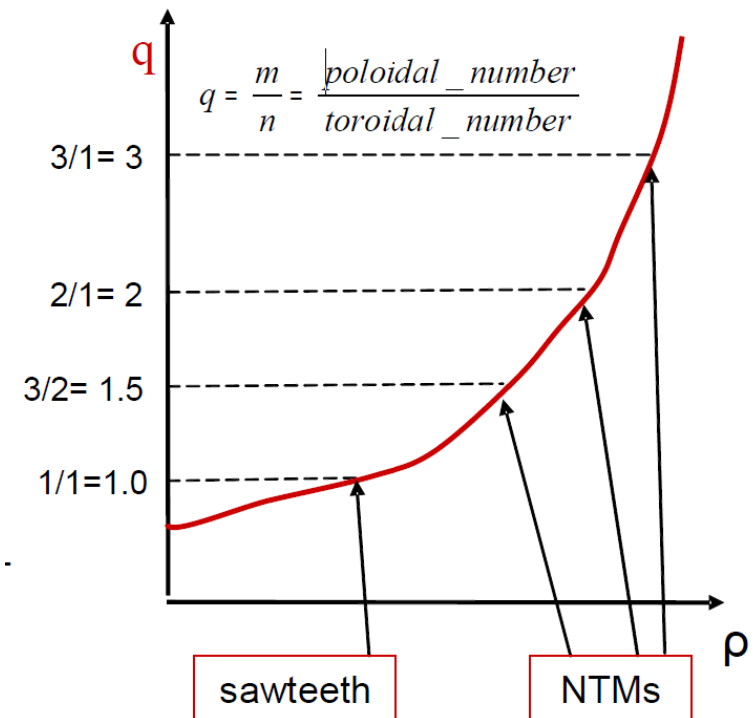
# Neoclassical Tearing Mode (NTM)

Neoclassical Tearing Mode *flattens pressure and temperature profile* and reduces global confinement properties of the plasma (smaller  $\beta$ ), thus smaller fusion power.



This process requires finite resistivity for island creation (resistive instability).

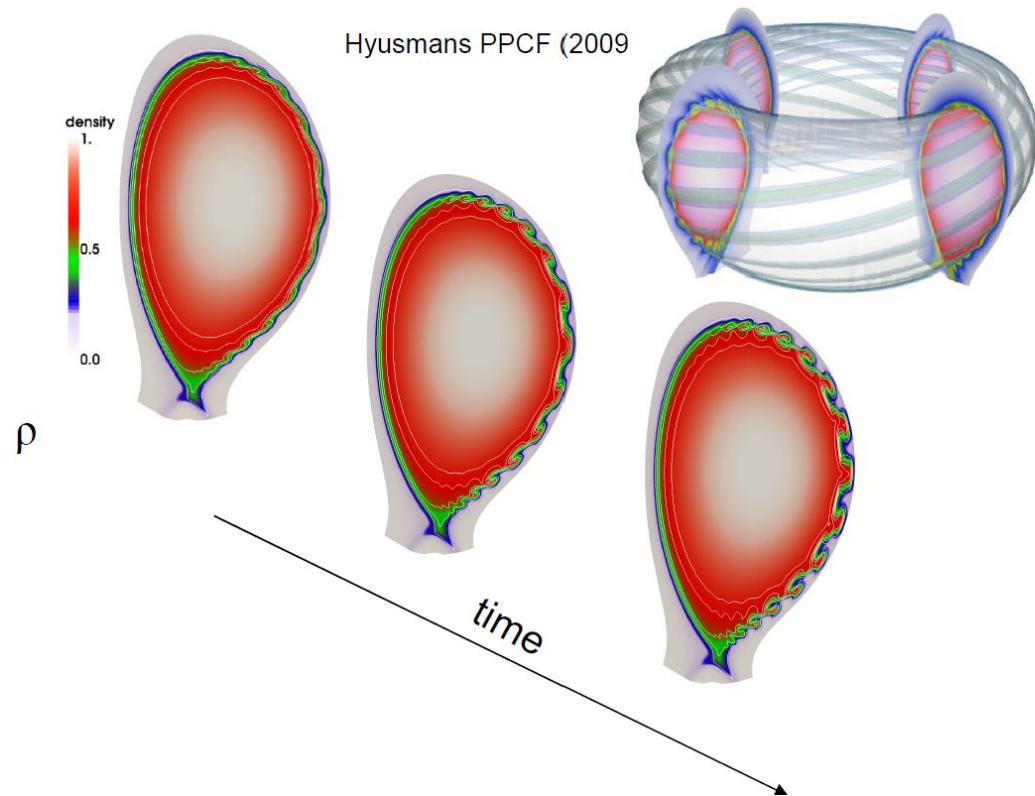
- Positions of most dangerous NTMs:
- ✓ Resonant surface for (3,2) mode
  - ✓ Resonant surface for (2,1) mode
  - ✓ Resonant surface for (3,1) mode



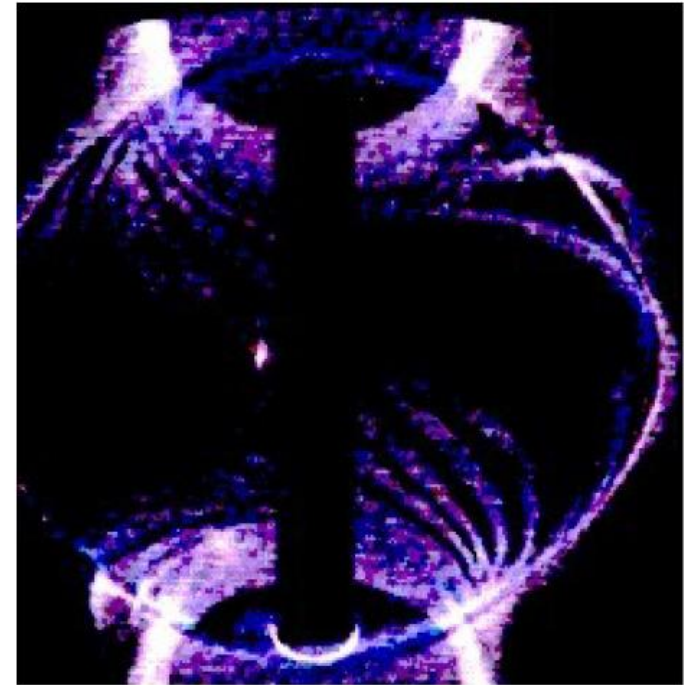
One can suppress neoclassical tearing mode with the same current drive system as it was made for sawteeth.

# Edge Localised Mode (ELM)

ELM are *pressure driven instability*, it consists of many harmonics localized at the plasma edge



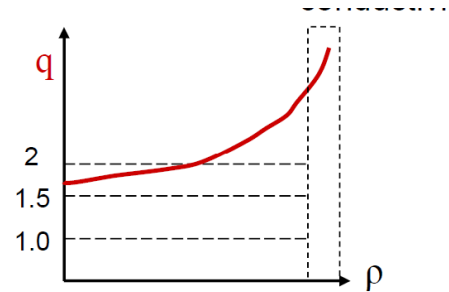
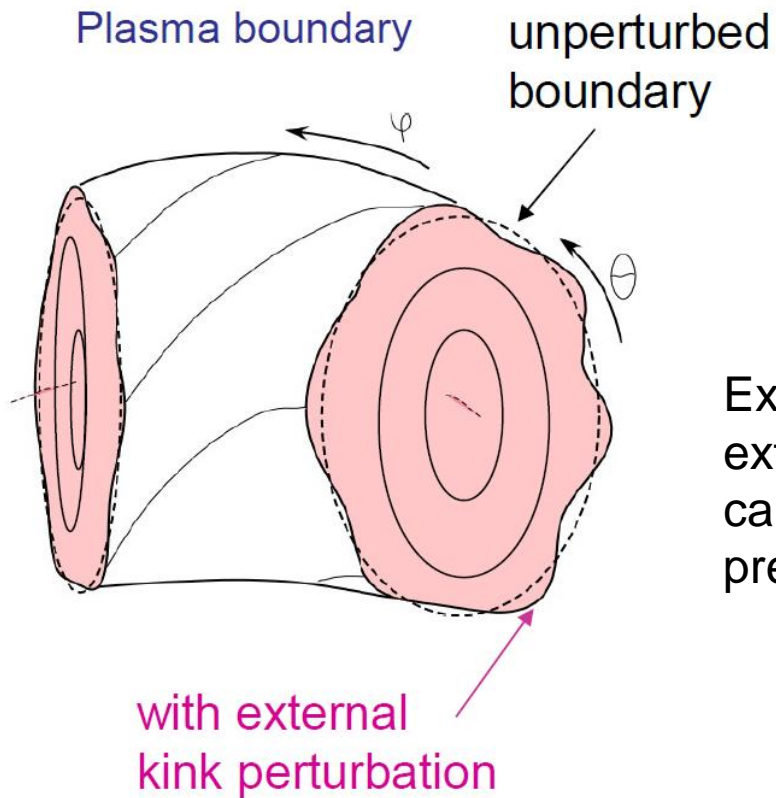
Filaments moving radially outward



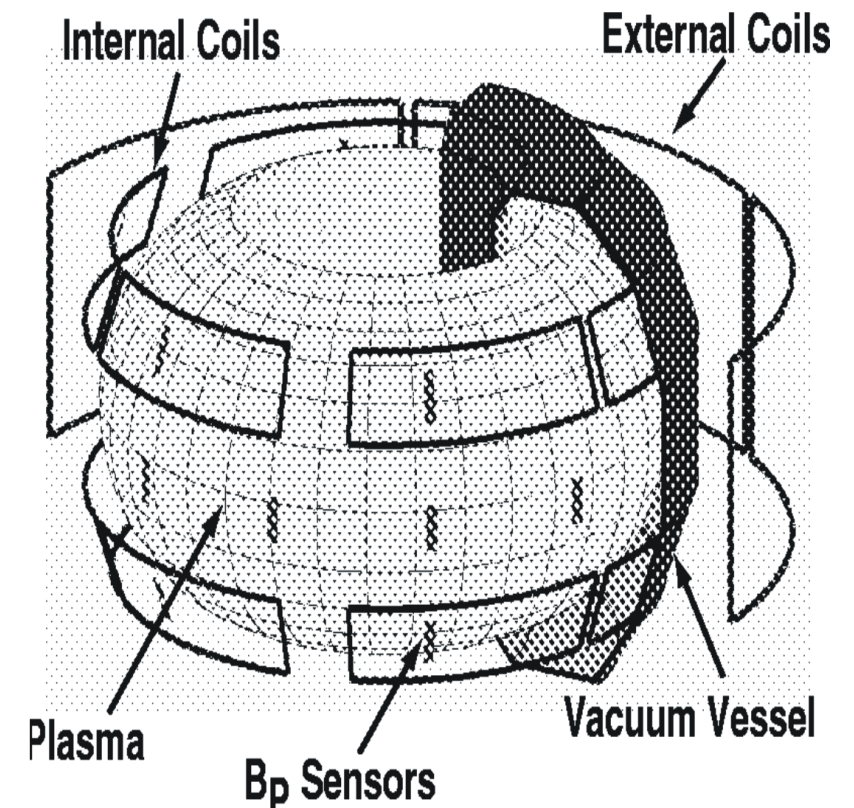
The main problem with Edge Localized Modes (ELMs) is large heat loads on the plasma facing components if the ELM is big

# Resistive Wall Mode (RWM)

Resistive wall mode is a current drive instability, it is an external kink mode which interacts with vacuum vessel. The mode will be stable in case of an ideally conducting wall. But real wall has finite conductivity and the mode grows.

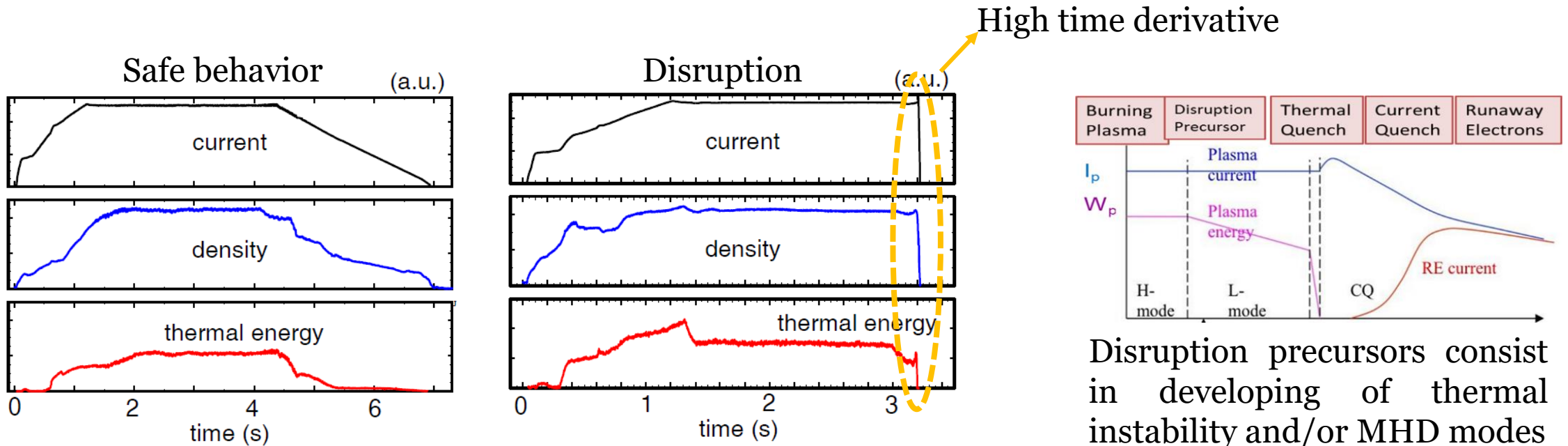


External coils create the external magnetic fields to cancel the perturbed field and prevent this penetration.



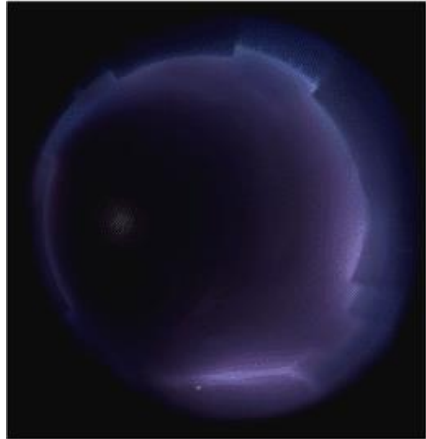
# Disruptions

The disruptions end the discharge abruptly. Disruptions are sudden losses of the thermal and magnetic energy stored within the plasma, which occur when operating near plasma stability limits or when systems malfunction and plasma control is lost.

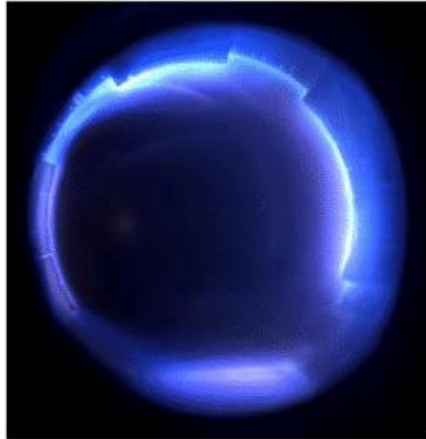


Disruption evolves in two phases: thermal quench (TQ) and current quench (CQ). In the first phase, a large fraction of the thermal energy ( $\int nT dV$ ) is lost to plasma-facing components, and in the second one, all the magnetic energies ( $LI_p^2/2$ ) are dissipated.

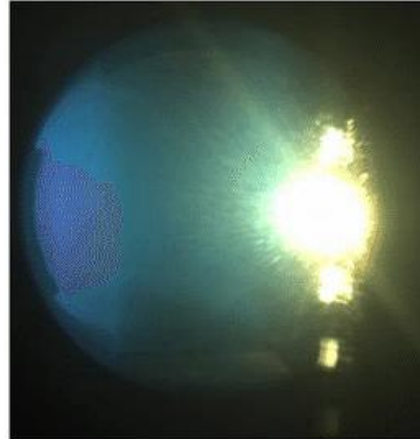
# Disruptions



a



b



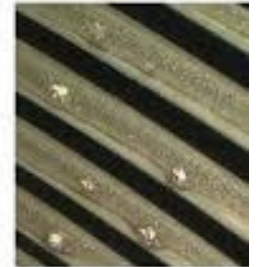
c



a



b



c

Disruptions consequences:

- ❖ **High power fluxes**, when the plasma touches the wall after the loss of confinement, then the high and localized heat flux can cause the melting or evaporation of its components.
- ❖ **Electromagnetic forces**, *eddy currents* flow in the tokamak structure during the CQ, it can result in  $\vec{J} \times \vec{B}$  forces which can damage vessel components
- ❖ **Runaway electron** generation by the intense electric field developing during a disruption. Their impact on plasma face components leads to the activation of the materials which complicate the maintenance operations
- ❖ **Halo current** occur when the plasma undergoes large shifts within the VV. Can have significant toroidal asymmetries, when their *poloidal component is crossed with the toroidal field*, it can lead to large asymmetric sideways forces on the vacuum vessel and other components