Introduction to Nuclear Fusion

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Tokamak stability

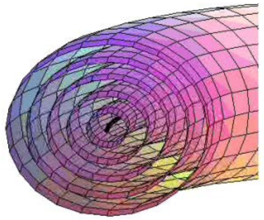
Tokamak Stability

- Considering plasma states which are not in perfect thermodynamic equilibrium (no exact Maxwellian distribution, e.g. non-uniform density), even though they represent equilibrium states in the sense that the force balance is equal to 0 and a stationary solution exists, means their entropy is not at the maximum possible and hence free energy appears available which can excite perturbations to grow: unstable equilibrium state
- The gradients of plasma current magnitude and pressure are the destabilising forces in connection with the bad magnetic field curvature: The ratio of these two free energies turns out to be β_p

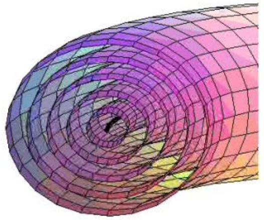
Tokamak Stability

- **Ideal MHD instabilities**

- current driven (kink) instabilities
  internal modes
  external modes
- pressure driven instabilities
  interchange modes
  ballooning modes
- current+pressure driven: Edge Localised Modes (ELMs)
- vertical instability



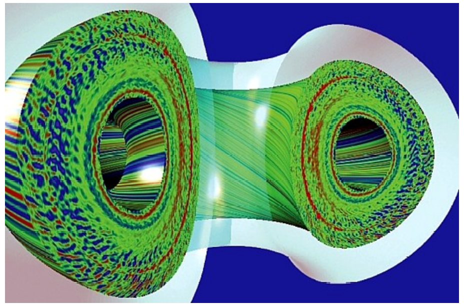
Flux conservation
Topology unchanged



Reconnection of field lines
Topology changed

- **Resistive MHD instabilities**

- current driven instabilities
  tearing modes
  neoclassical tearing modes (NTMs)
- nonlinear modes
  sawtooth
  disruption



- **Microinstabilities - Turbulence**

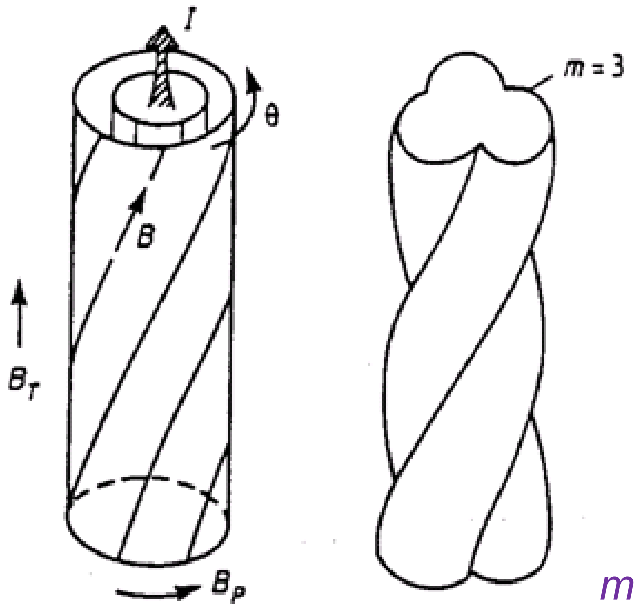
Ideal MHD instabilities in a Tokamak

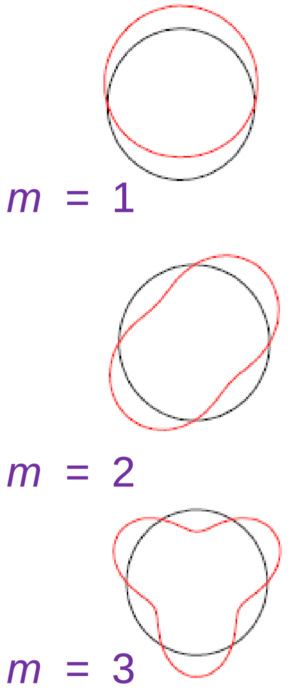
Ideal MHD Instabilities

- **The most Virulent Instabilities**
  - fast growth (microseconds)
  - the possible extension over the entire plasma

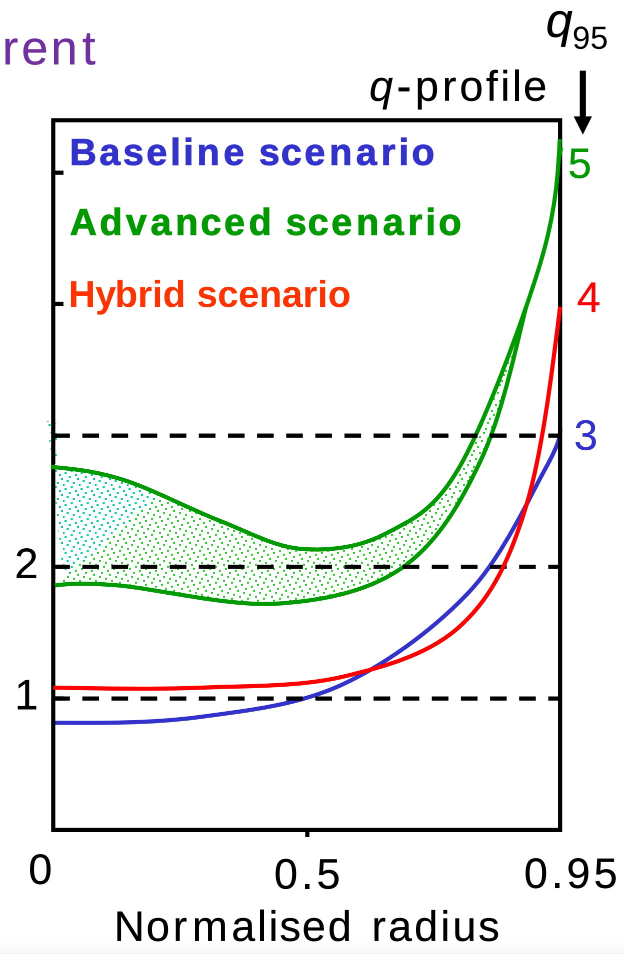
Ideal MHD Instabilities

- **Kink modes**
  - Causing a contortion of the helical plasma column
  - Driven by the radial gradient of the toroidal current
  - External kind modes:
    Fastest and most dangerous
    Arising mainly when $q_a < 2$



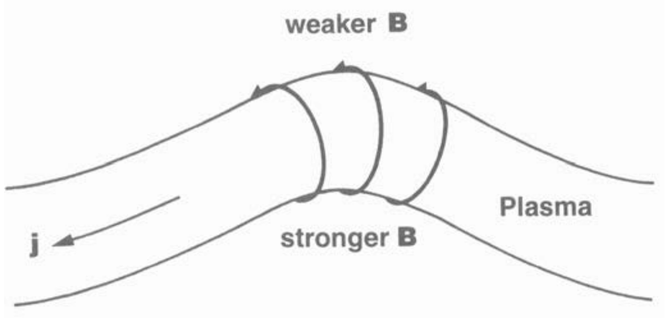


m: poloidal mode number



http://www.maysville-online.com/news/local/tollesboro-home-destroyed-in-fire/article_a5e0eb4e-235b-5c7d-afee-74bf98c4e738.html

Ideal MHD Instabilities



- **Kink modes**
  - Stabilising effect by the conducting wall and strong toroidal magnetic field

$$q_a = \frac{aB_\phi}{R_0 B_\theta} = \frac{aB_\phi}{R_0 \mu_0 I_P / 2\pi a} \propto \frac{B_\phi}{I_p}$$

B_ϕ ↗ stabilising

I_p ↘ destabilising

Determining plasma current limit set by kink instabilities → **safety** factor

$$q_a > 1$$

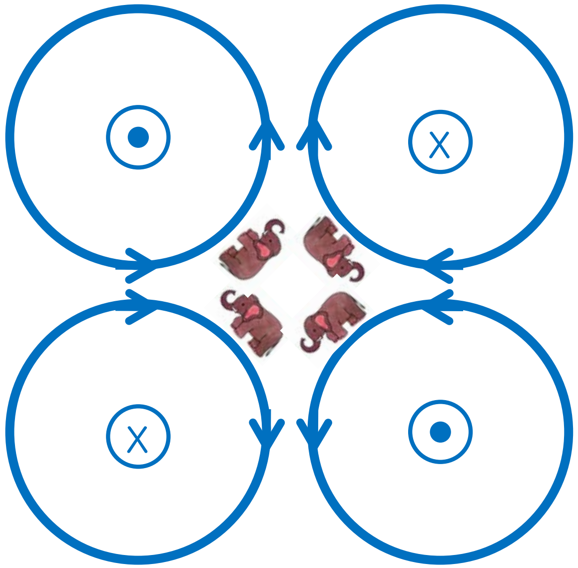
Kruskal-Shafranov criterion:
stability condition for external kink mode for the worst case

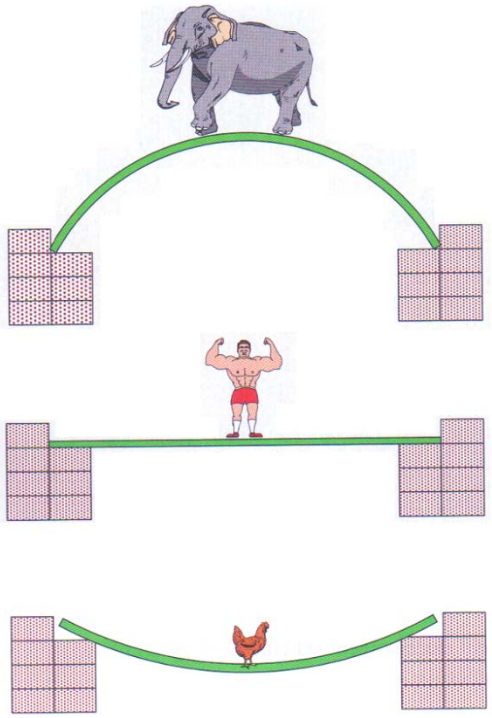
Imposing an important constraint on tokamak operation:
toroidal current upper limit: Kruskal-Shafranov current ($I < I_{KS}$)

$$q_a = \frac{aB_\phi}{R_0 B_p} = \frac{2\pi a^2 B_\phi}{\mu_0 R_0 I_{KS}} = 1 \qquad I_{KS} \equiv 2\pi a^2 B_\phi / \mu_0 R_0 = 5a^2 B_\phi / R_0 \text{ [MA]}$$

Ideal MHD Instabilities

- **Interchange modes**
  - A toroidally confined plasma sees 'bad' convex curvature of the helical magnetic field lines on the outboard side of the torus.



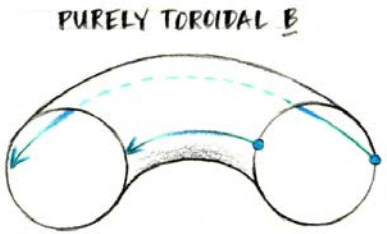


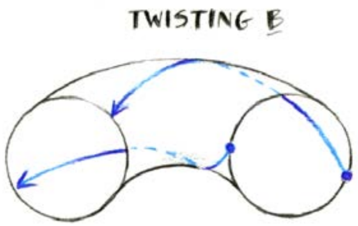
F. F. Chen, "An Indispensable Truth", Springer (2011)

http://blog.naver.com/PostView.nhn?blogId=ray0620&logNo=150112423635&parentCategoryNo=1&viewDate=&currentPage=1&listtype=0
http://en.wikipedia.org/wiki/File:St_Louis_Gateway_Arch.jpg

Ideal MHD Instabilities

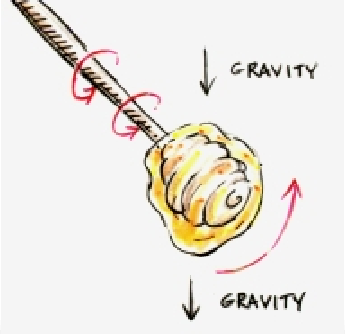
- **Interchange modes**
  - A toroidally confined plasma sees ‘bad’ convex curvature of the helical magnetic field lines on the outboard side of the torus.
  - The average curvature of **B**-field lines over a full poloidal rotation is ‘good’ for windings with a rotational transform $\iota \leq 2\pi$, i.e., $q \geq 1$.
  - Interchange perturbations do not grow in normal tokamaks if $q \geq 1$.





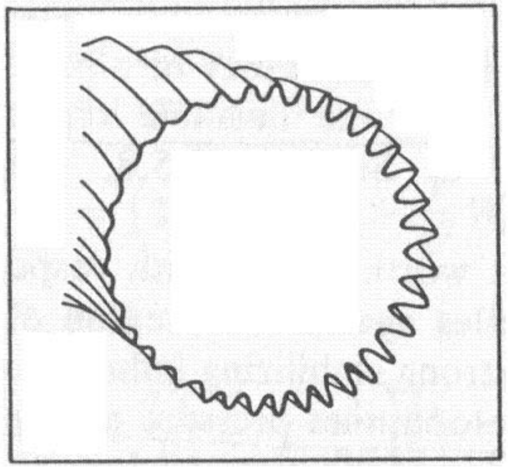
Unstable

Stable



Ideal MHD Instabilities

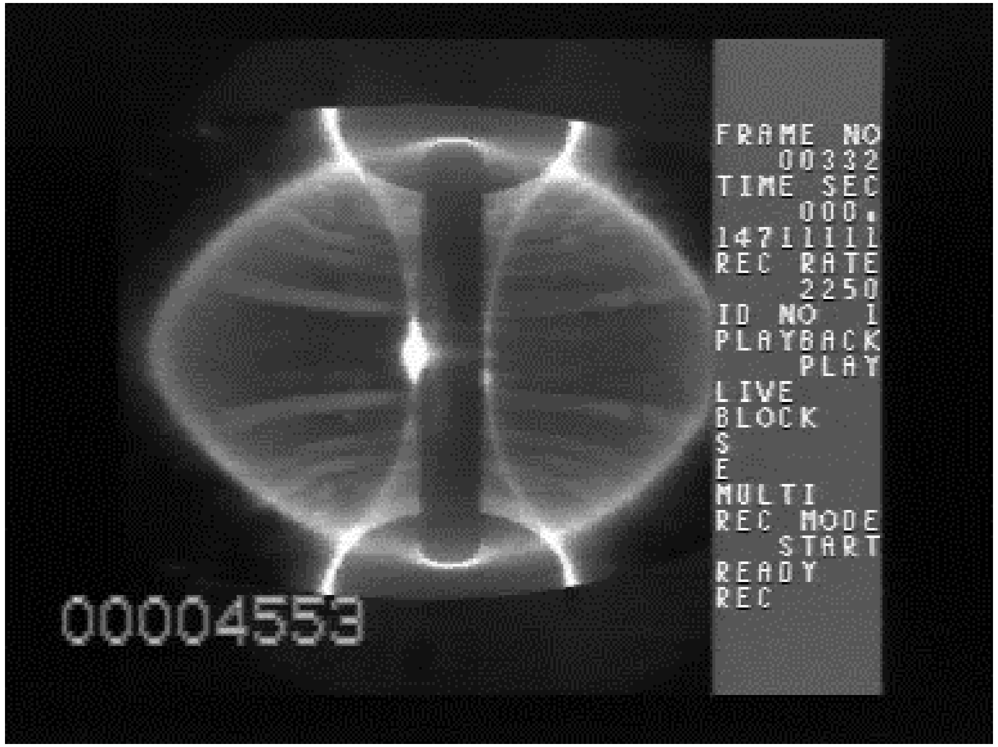
- **Ballooning modes**
  - locally grow in the outboard bad curvature region: ballooning modes
  - A high local pressure gradient is responsible for driving the ballooning instability.
  - Can be suppressed almost everywhere in the plasma by establishing appropriate pressure profiles and appropriate magnetic field line windings.



J.P. Freidberg, "Ideal Magneto-Hydro-Dynamics", lecture note

Ideal MHD Instabilities

- **Edge Localised Modes (ELMs)**
  - current driven (peeling mode) and pressure driven (ballooning mode) combined instability



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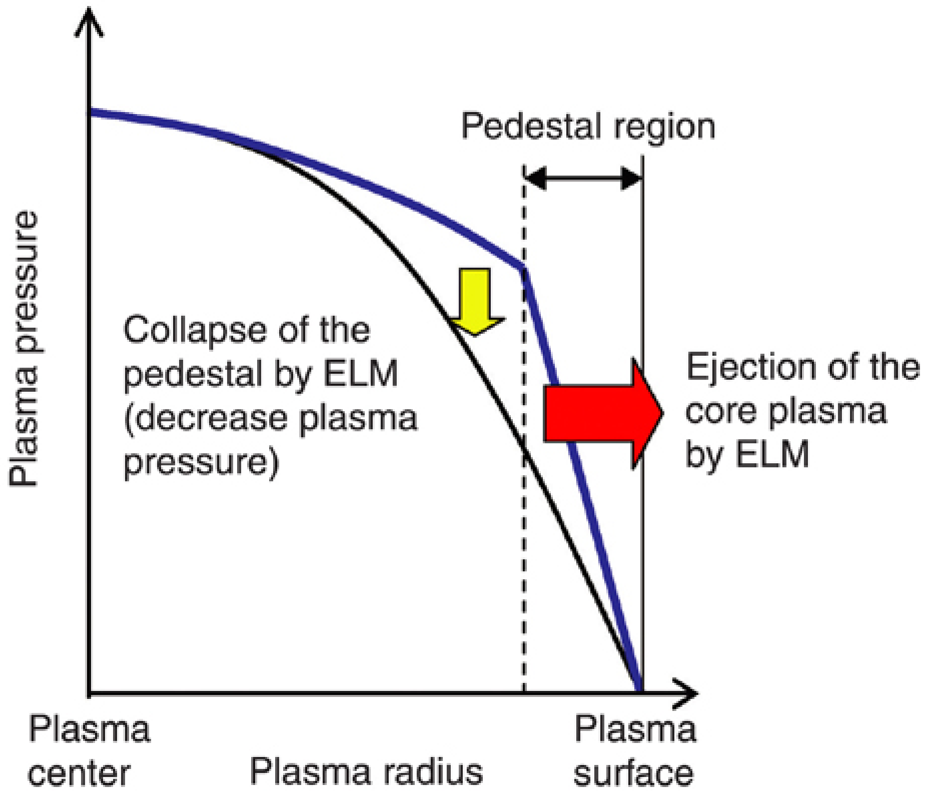
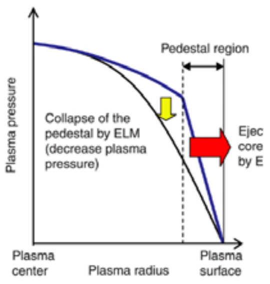
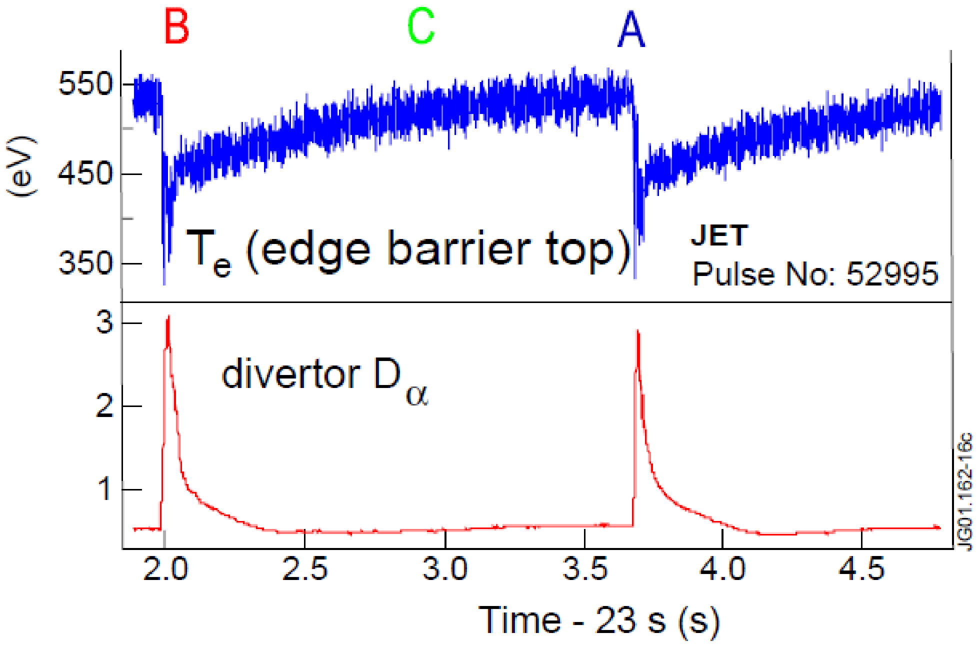


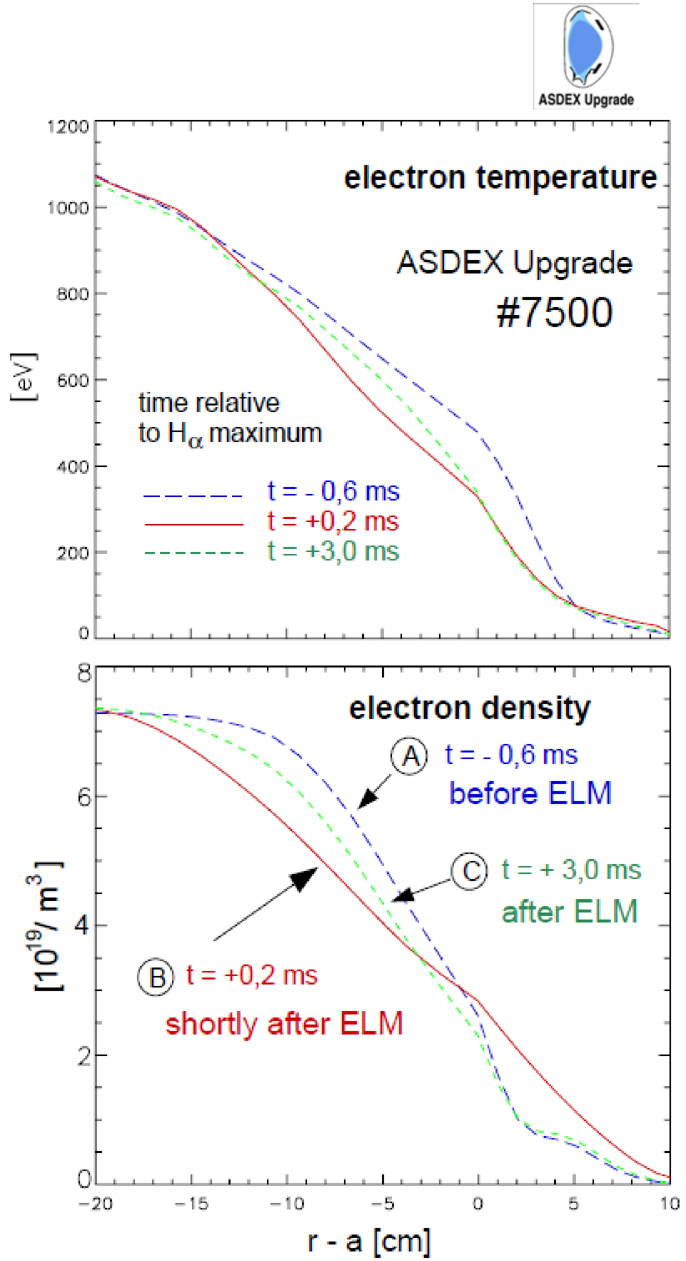
Ideal MHD Instabilities

- **Edge Localised Modes (ELMs)**

  A. Critical ∇p in H-mode barrier region reached → short unstable phase (ELM event)
  B. Energy and particle loss reduces gradients.
  C. Gradients build up during reheat/refuelling phase.







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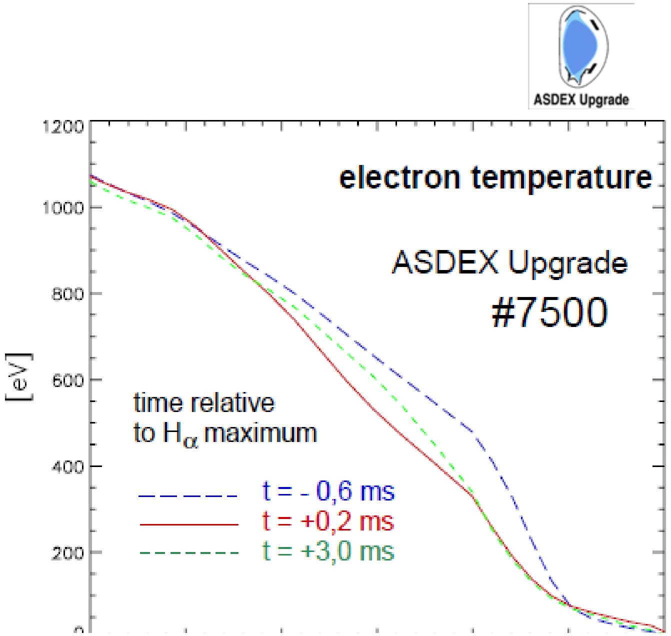
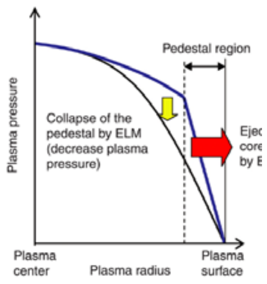
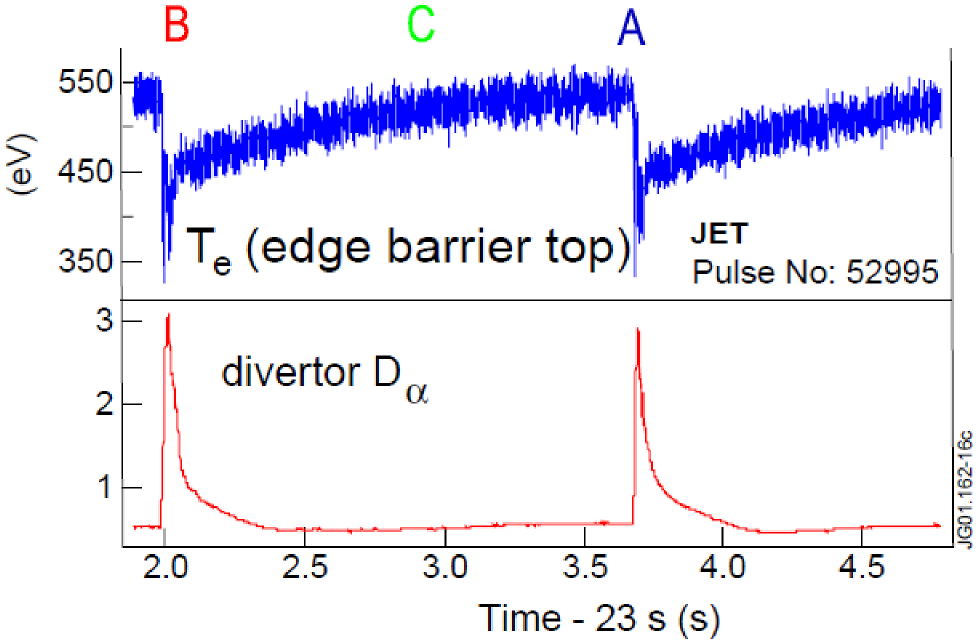
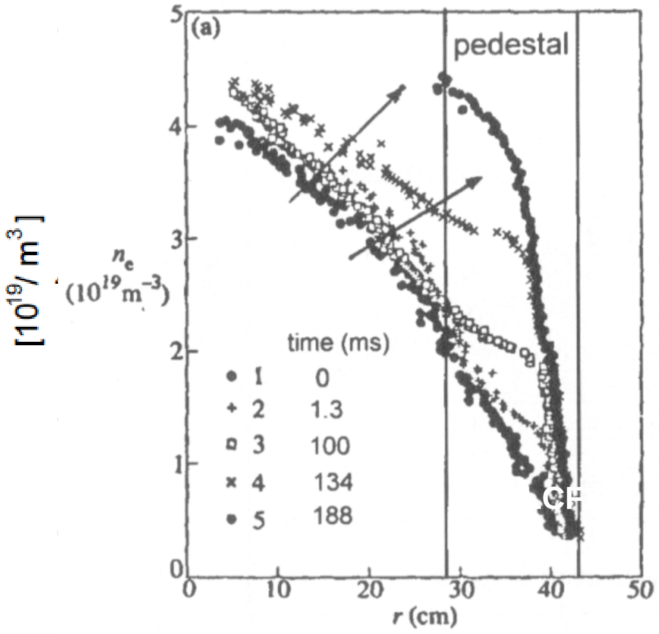


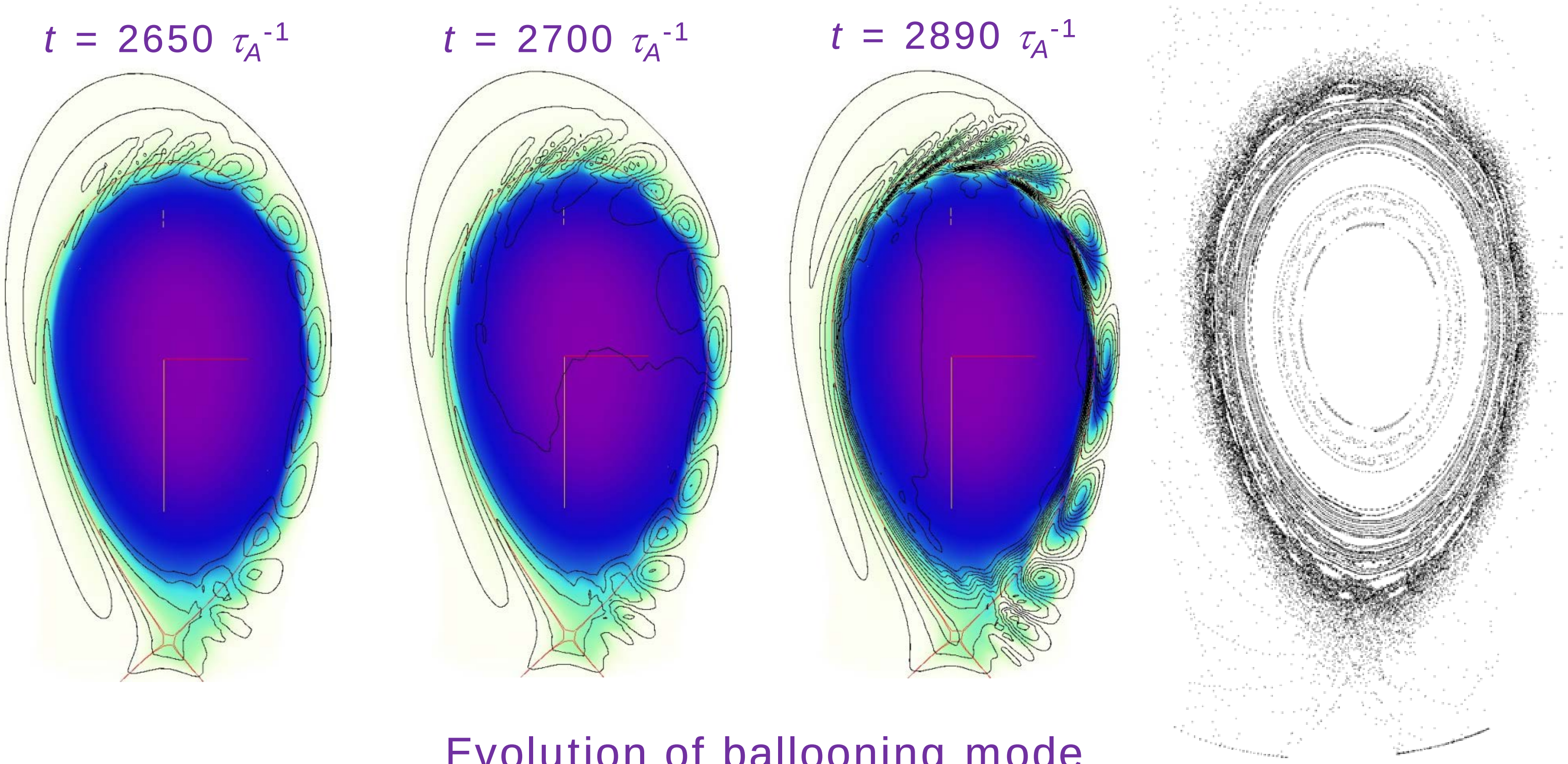






Ideal MHD Instabilities

- **Edge Localised Modes (ELMs)**
  - Non-linear MHD simulations with JOREK

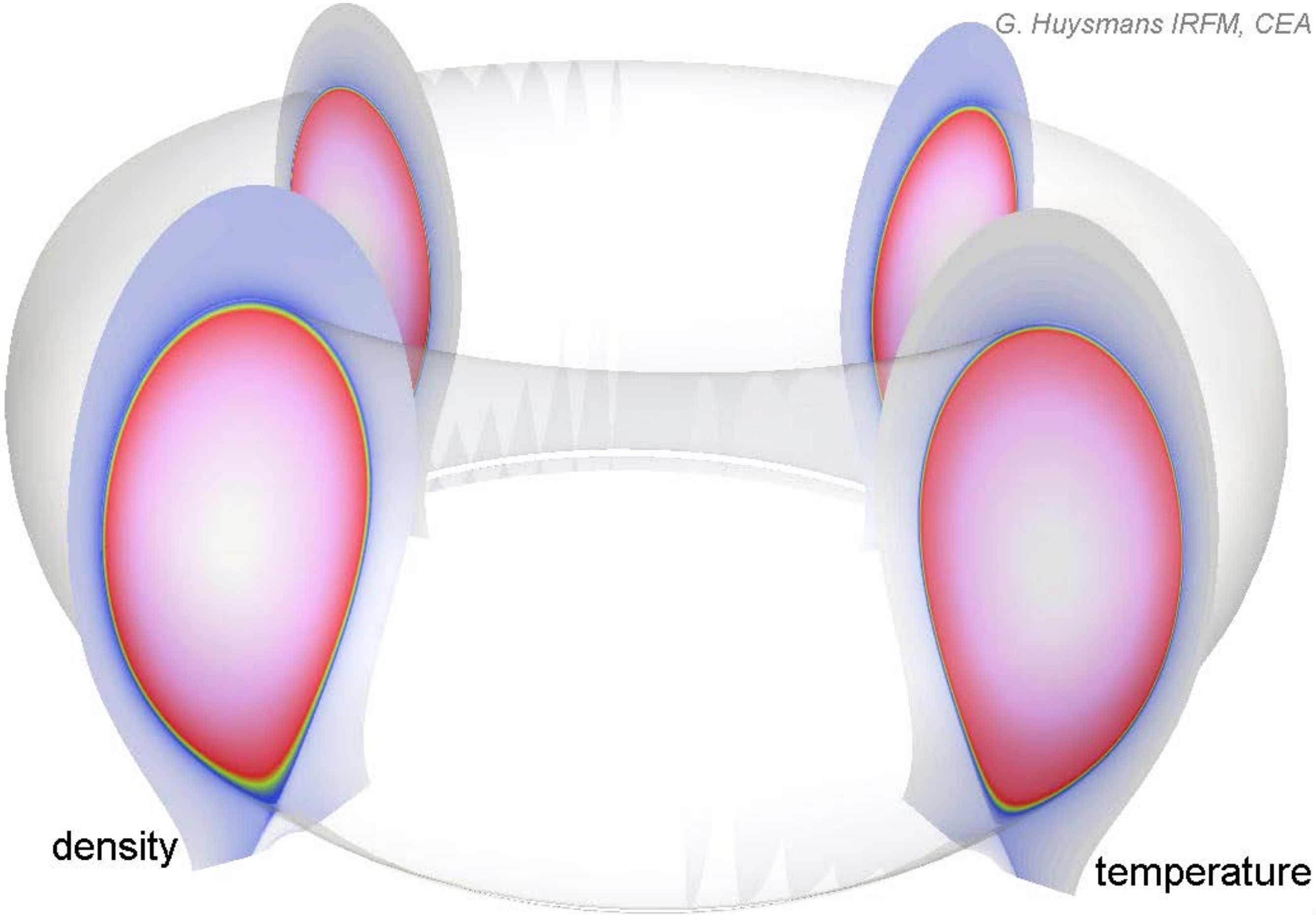


Evolution of ballooning mode

Huysmans, Czarny, NF ***47*** *659 (2007)*

Ideal MHD Instabilities

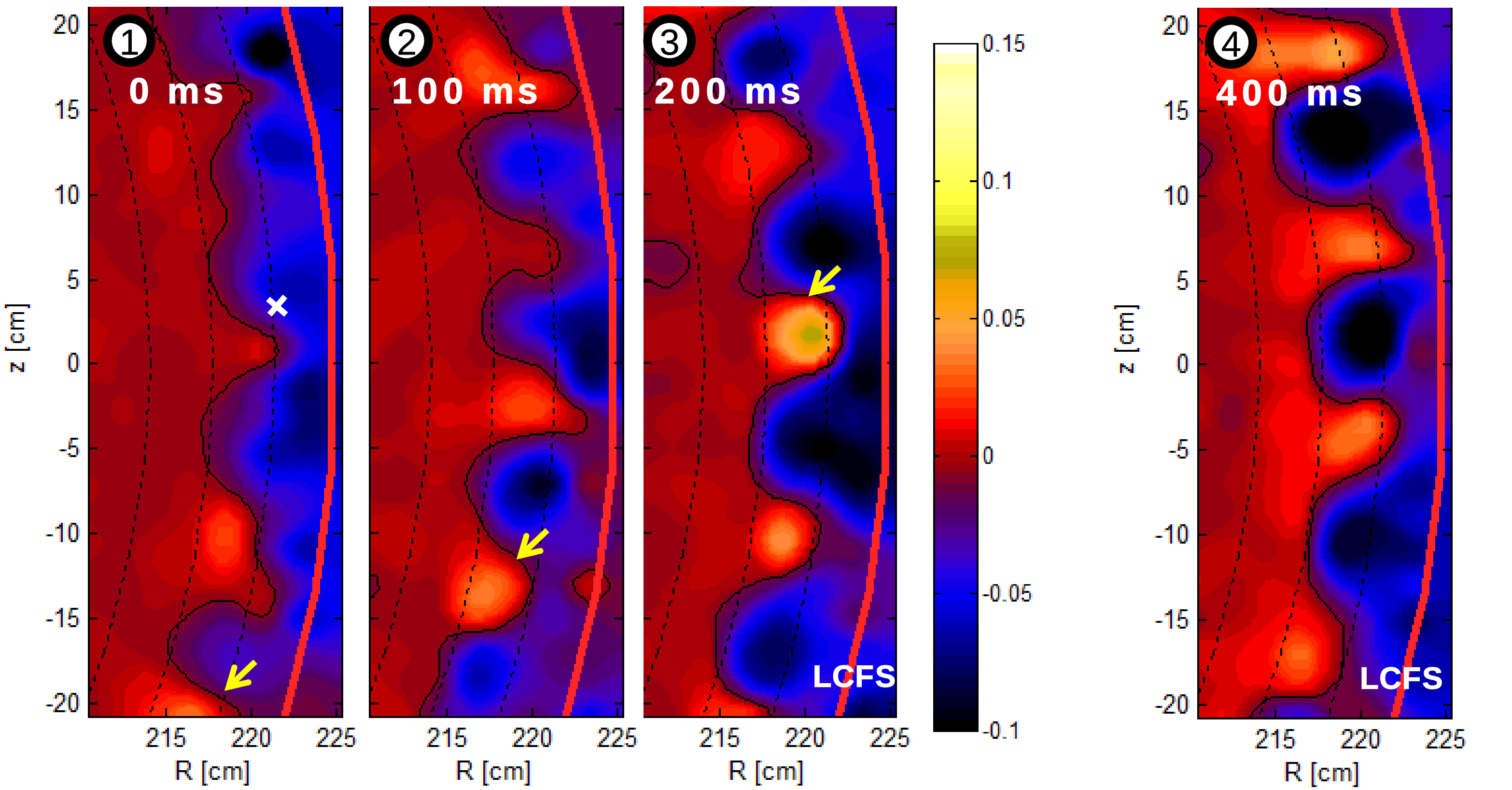
- **Edge Localised Modes (ELMs)**
  - Non-linear MHD simulations with JOREK



Ideal MHD Instabilities

- **Edge Localised Modes (ELMs)**
  - Standard ELM dynamics in the KSTAR visualized by ECEI

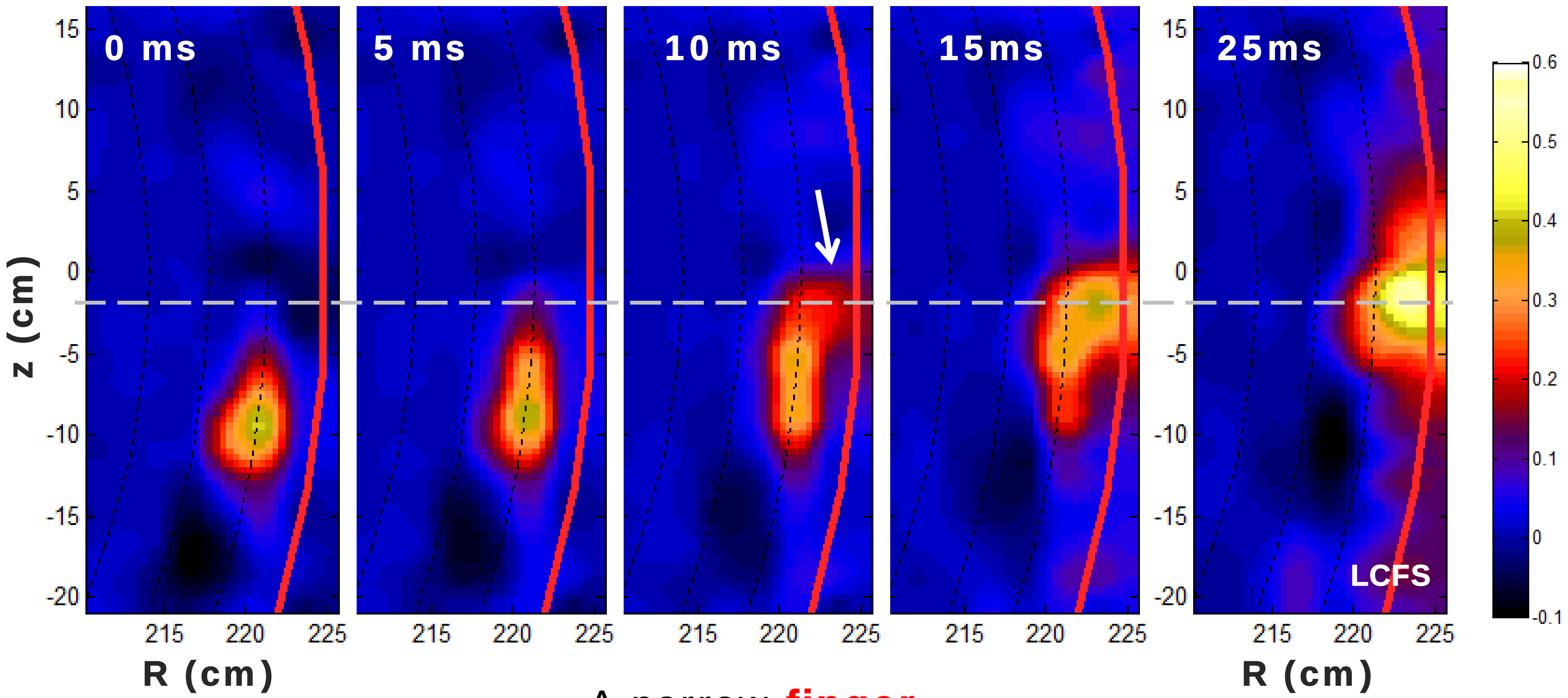
(1) Initial Growth (2) Saturation



G.S. Yun et al., PRL (2011)

Ideal MHD Instabilities

- **Edge Localised Modes (ELMs)**
  - Standard ELM dynamics in the KSTAR visualized by ECEI
    - (3) ELM crash



Filaments elongate poloidally ⇨ A narrow **finger**-like structure develops ⇨ Particles/heat transport through the finger

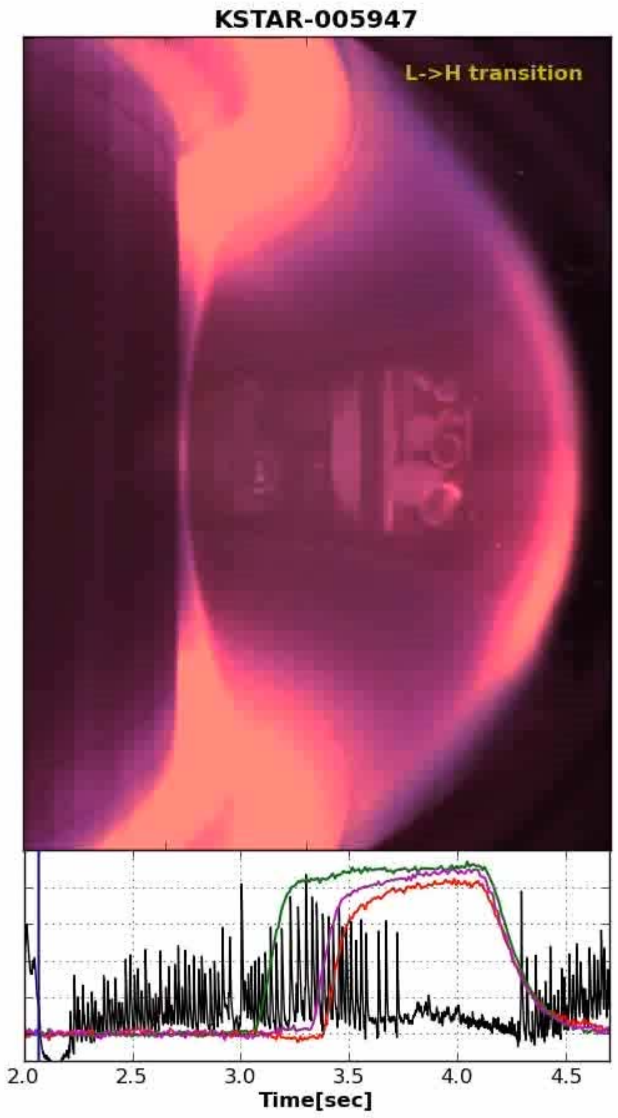
G.S. Yun et al., PRL (2011)

Ideal MHD Instabilities

- **Edge Localised Modes (ELMs)**

  - Mitigation by 3D magnetic perturbation

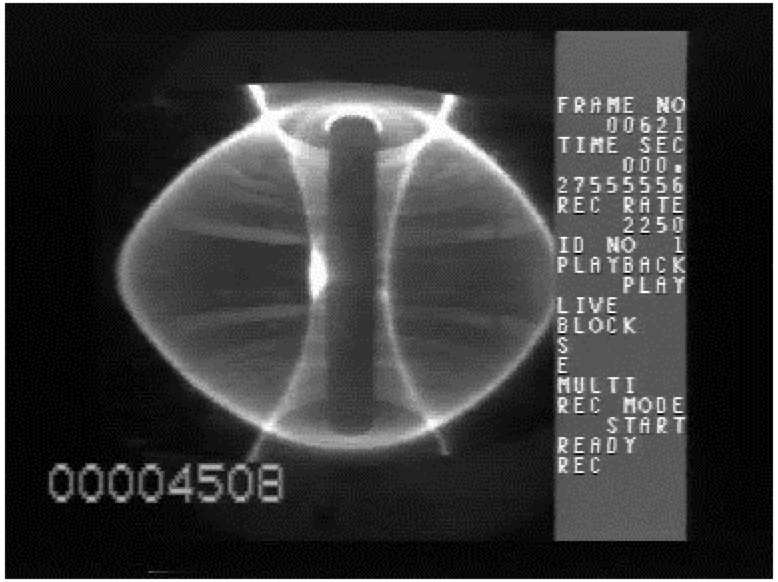
  - COMPASS-D (n = 1): triggered (2001)
  - DIII-D (n = 3): suppressed (2004)
  - JET (n = 1 or 2): mitigated (2007)
  - NSTX (n = 3): triggered (2010)
  - MAST (n = 3): mitigated (2011)
  - ASDEX Upgrade (n = 2): mitigated/suppressed (2011)
  - KSTAR (n = 1): ELMs suppressed (2011)



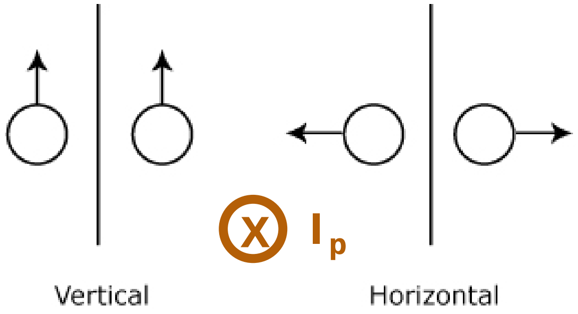
Courtesy of Y. M. Jeon (NFRI)

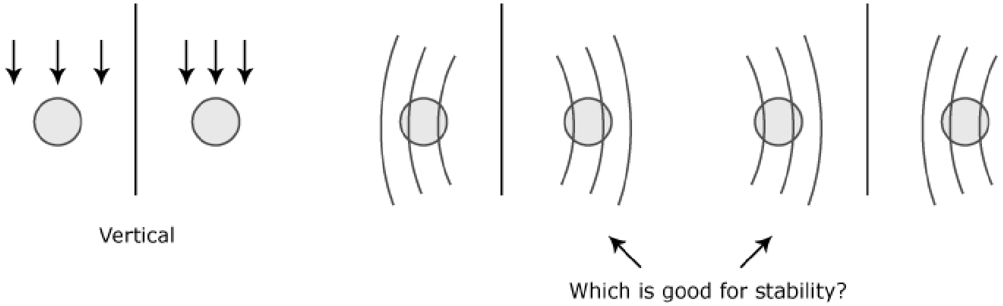
Ideal MHD Instabilities

- **Vertical Instability**
  - Macroscopic vertical motion of the plasma towards the wall



MAST
MEGA-AMPERE SPHERICAL TOKAMAK

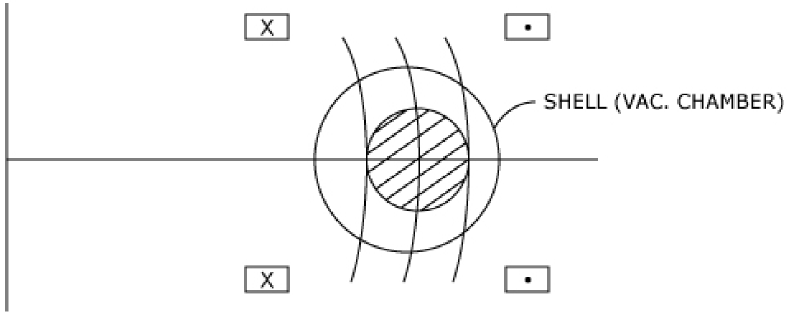


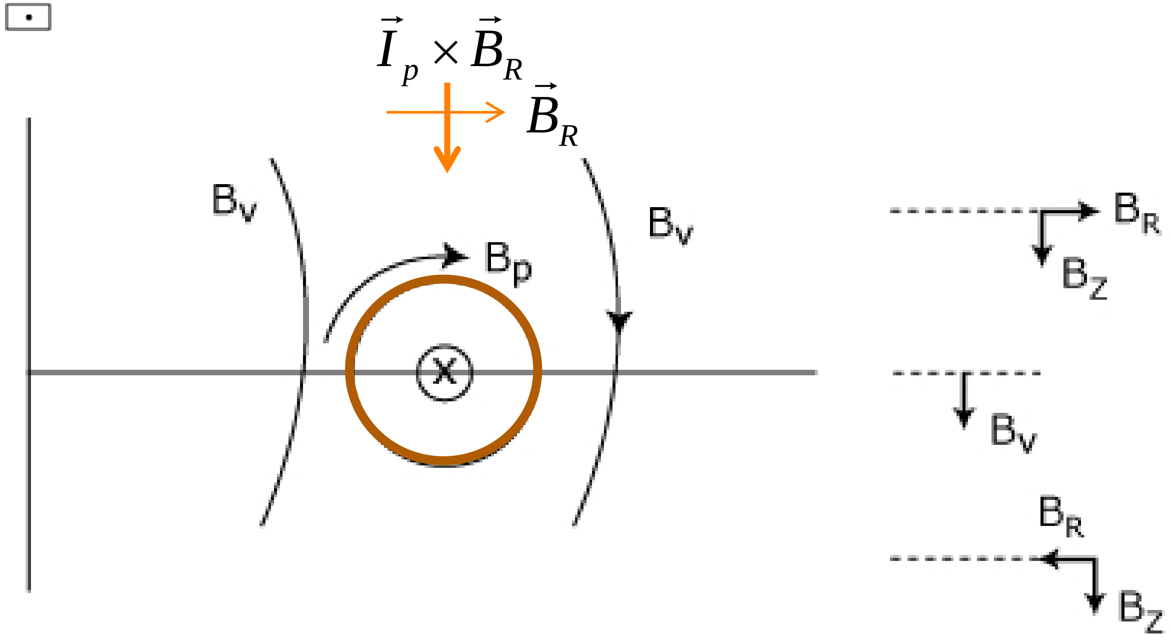


J.P. Freidberg, “Ideal Magneto-Hydro-Dynamics”, lecture note

Ideal MHD Instabilities

- **Vertical Instability**





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Ideal MHD Instabilities

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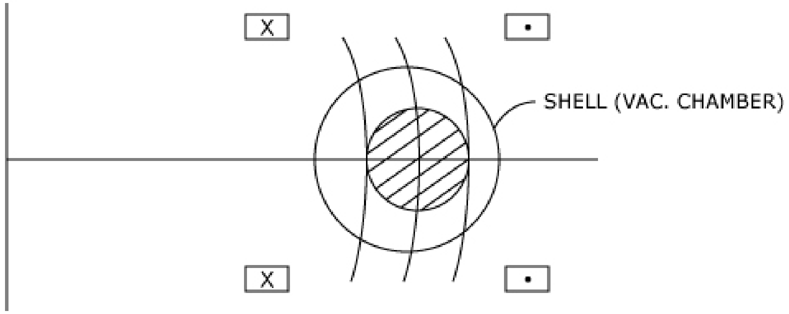

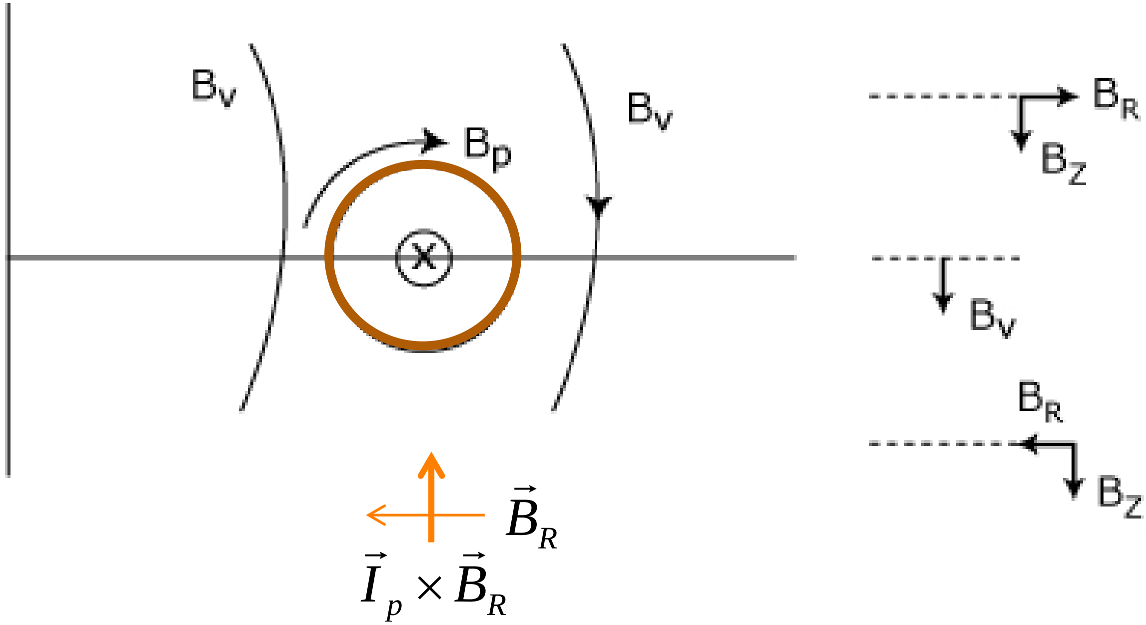

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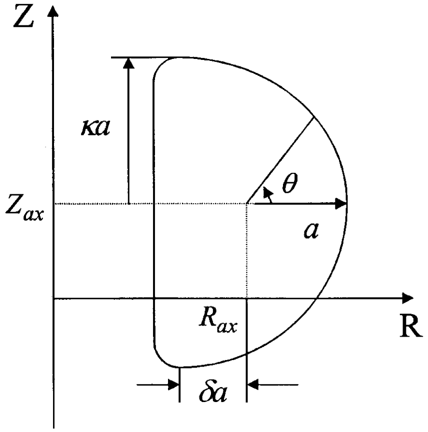
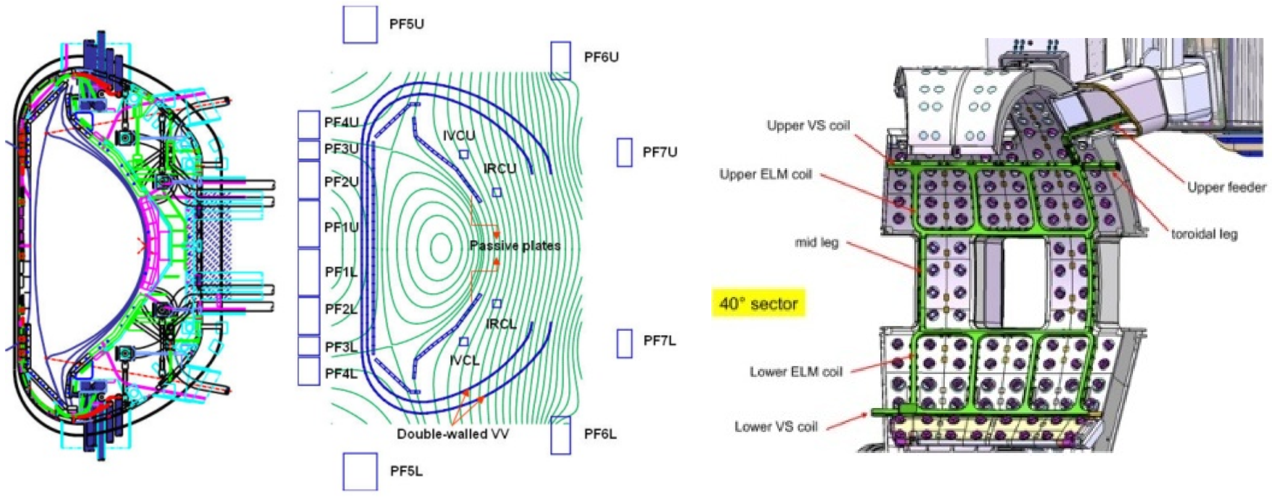
Ideal MHD Instabilities

- **Vertical Instability**
  - For a circular cross sections a moderate shaping of the vertical field should provide stability.
  - For noncircular tokamaks, vertical instabilities produce important limitations on the maximum achievable elongations.
  - Even moderate elongations require a conducting wall or a feedback system for vertical stability.





KSTAR & ITER

J.P. Freidberg, “Ideal Magneto-Hydro-Dynamics”, lecture note