Hard and soft MHD stability limit in LHD: sawtooth like events, internal disruptions and core density collapse.

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Presentation

- PhD. Plasma Physics and controlled Fusion.
  - University Carlos III (Spain) and NIFS (Japan).
  - L. Garcia, K. Watanabe, S. Ohdachi, R. Sanchez, Y. Narushima.
- Quantemol Ltd. / University College of London
  - Plasma etching (semiconductors) and medical plasmas.
- Observatory of Paris – Meudon.
  - Astrophysical plasmas: solar wind and Hermean magnetosphere
  - F. Pantellini and M. Moncuquet.
- CEA Saclay - LIMSI.
  - Project VKS and stellar dynamos.
  - S. Brun, C. Nore, D. Berengere.

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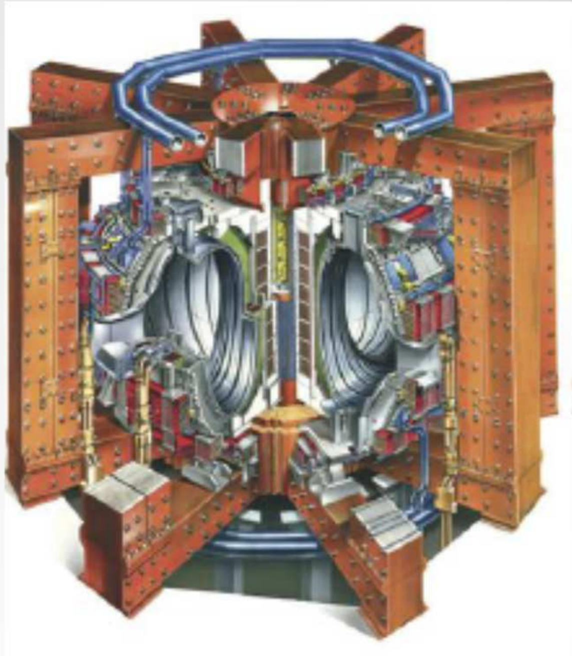
3- Sawtooth like activity in LHD inward configurations and MHD soft-hard transition.

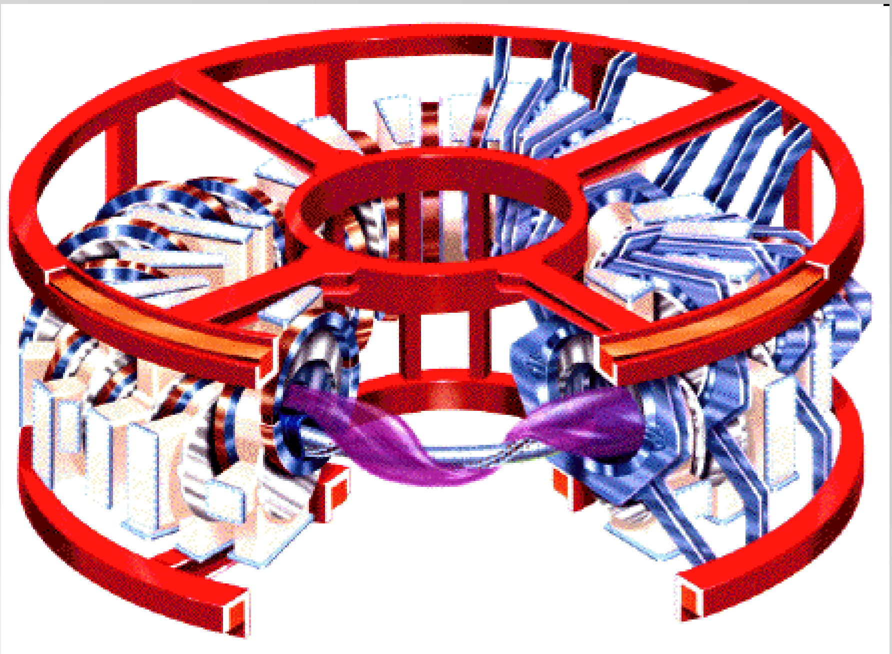
4- Internal disruptions in LHD inward configurations.

5- MHD soft - hard limit transition in LHD: internal disruptions.

Thermonuclear Fusion by magnetic confinement

Two different devices:

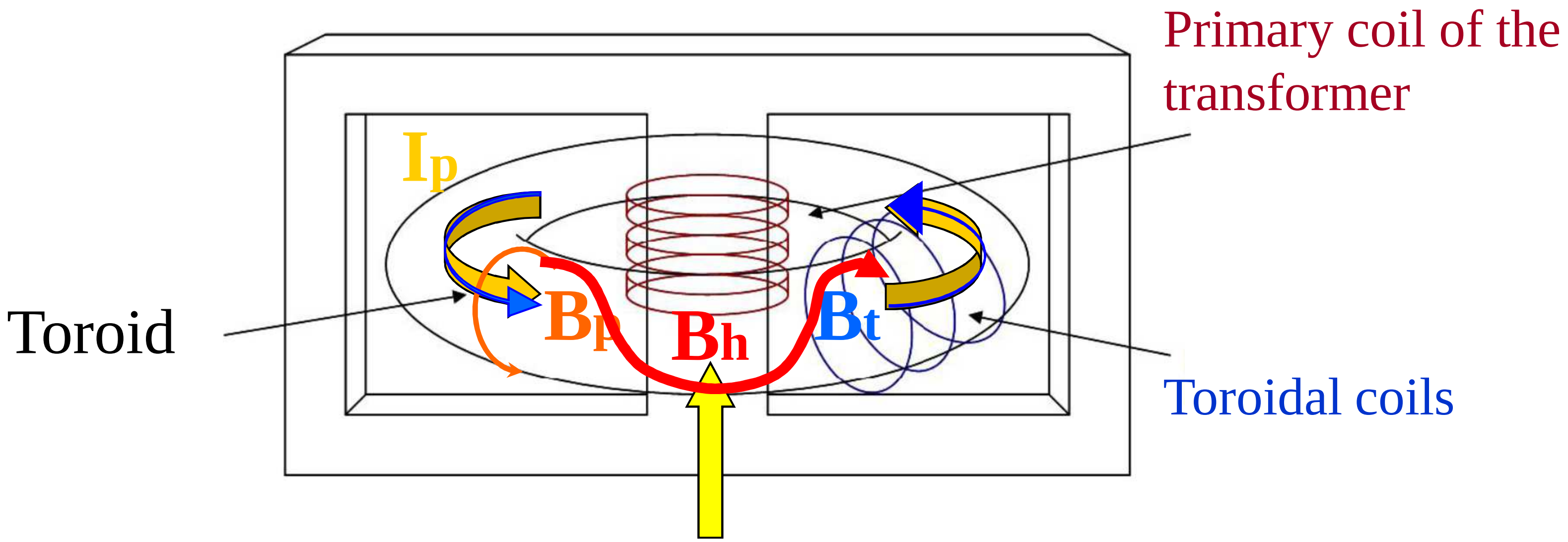




TOKAMAK **STELLARATOR**

Thermonuclear Fusion by magnetic confinement

Two different devices:



The current is induced in the plasma by transformer effect.

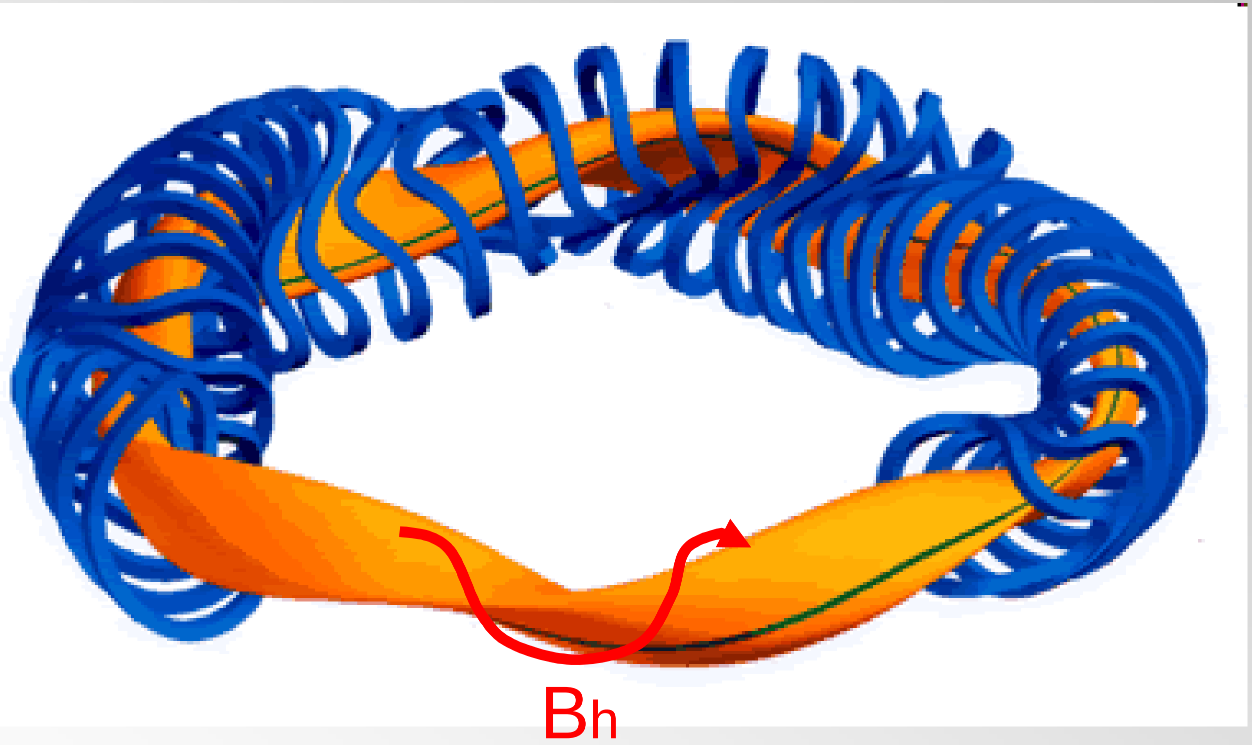
The induced current generates the poloidal magnetic field.

The combination of the toroidal and poloidal magnetic field creates the helical magnetic field.

Thermonuclear Fusion by magnetic confinement

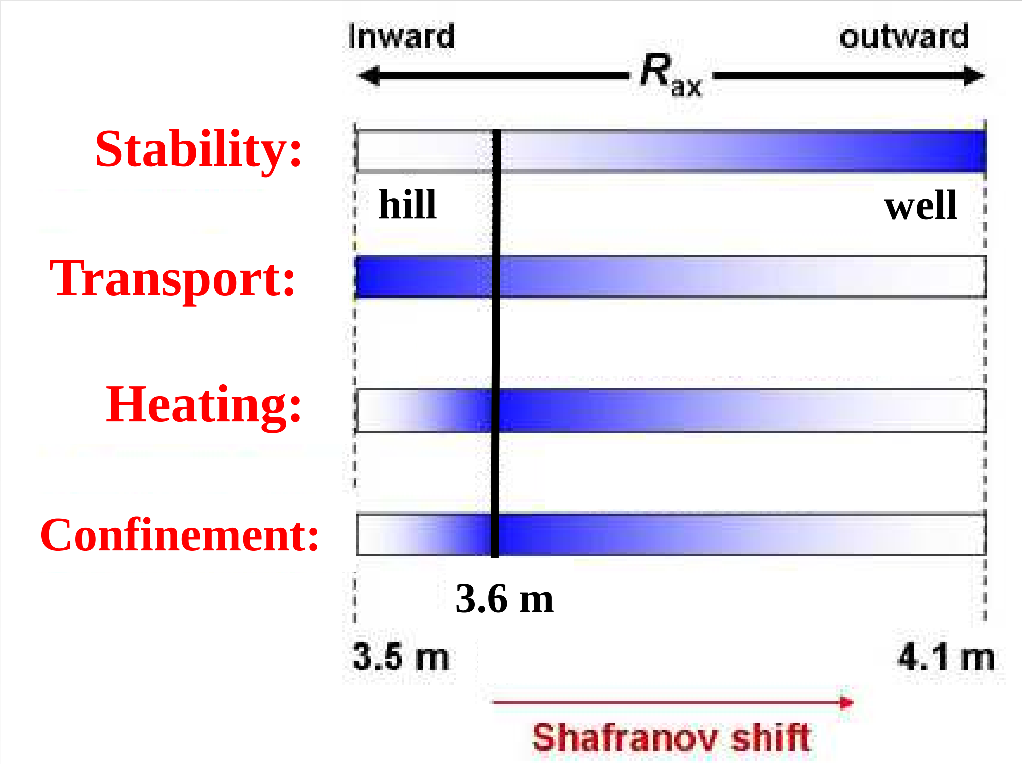
Two different devices:

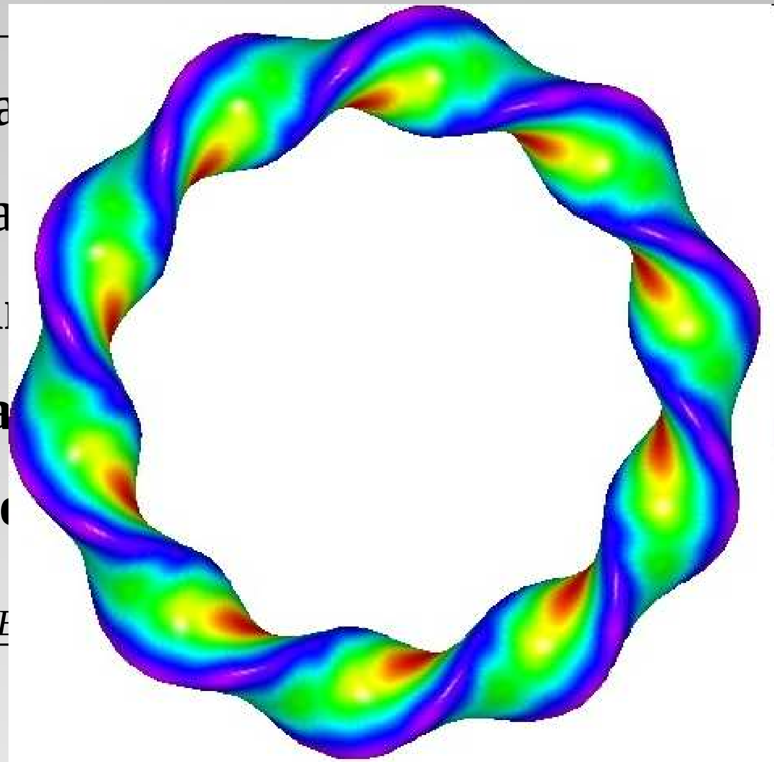
STELLARATOR



The helicoidal magnetic field is generated by the current in the coils, no induced currents in the plasma to avoid the new sources of instability.

Stellarator: Heliotron Large Helical Device

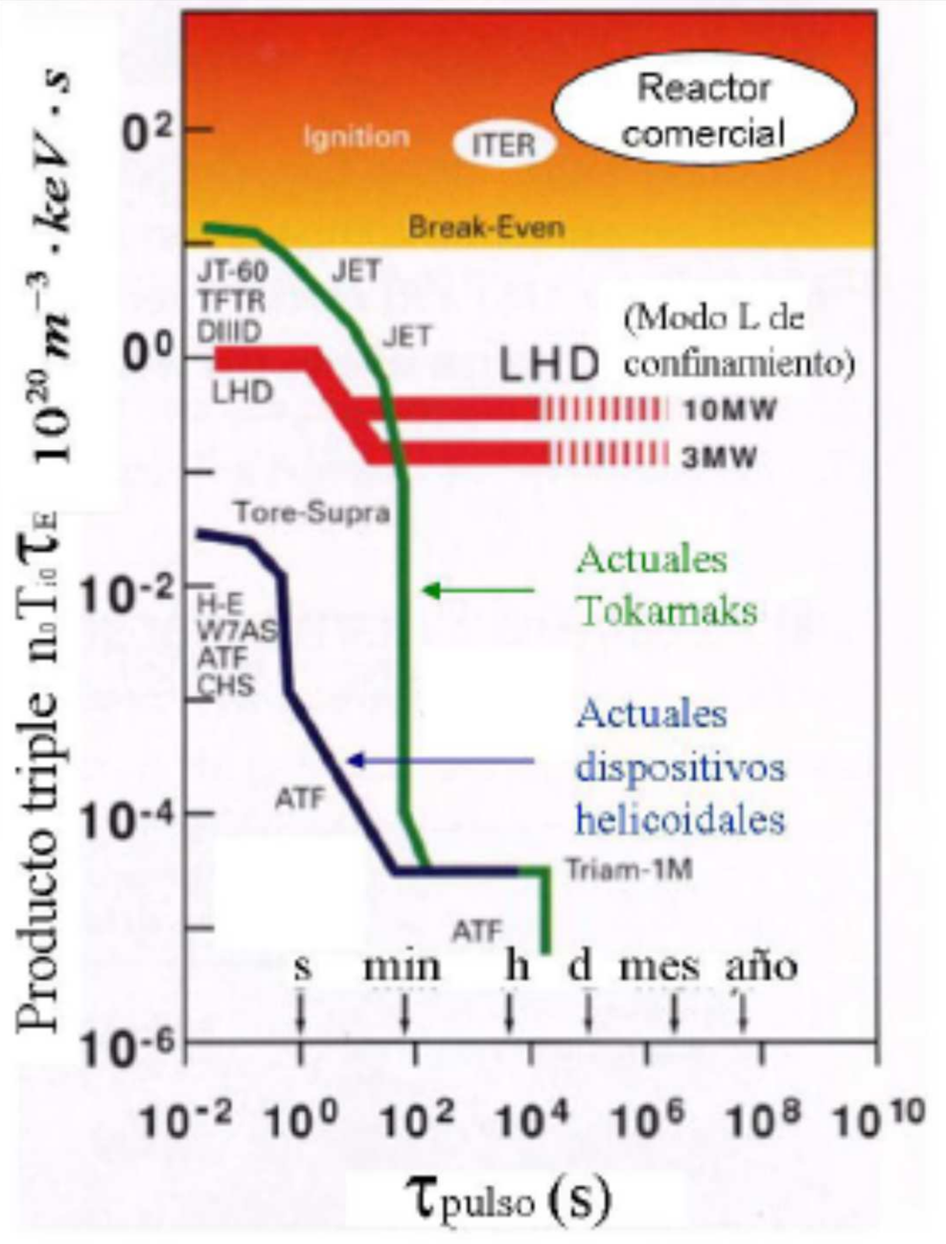




Main targets:

- **Foresee steady state operation.**
- **Plasmas free of net toroidal currents.**
- **Improved confinement and advance operation scenarios.**

LHD: optimization



- **Efficiency; reach the highest beta value before strong instabilities are driven inside the plasma.**

$$\beta = \frac{p_{plasma}}{p_{magnetica}}$$

- **Triple product.**

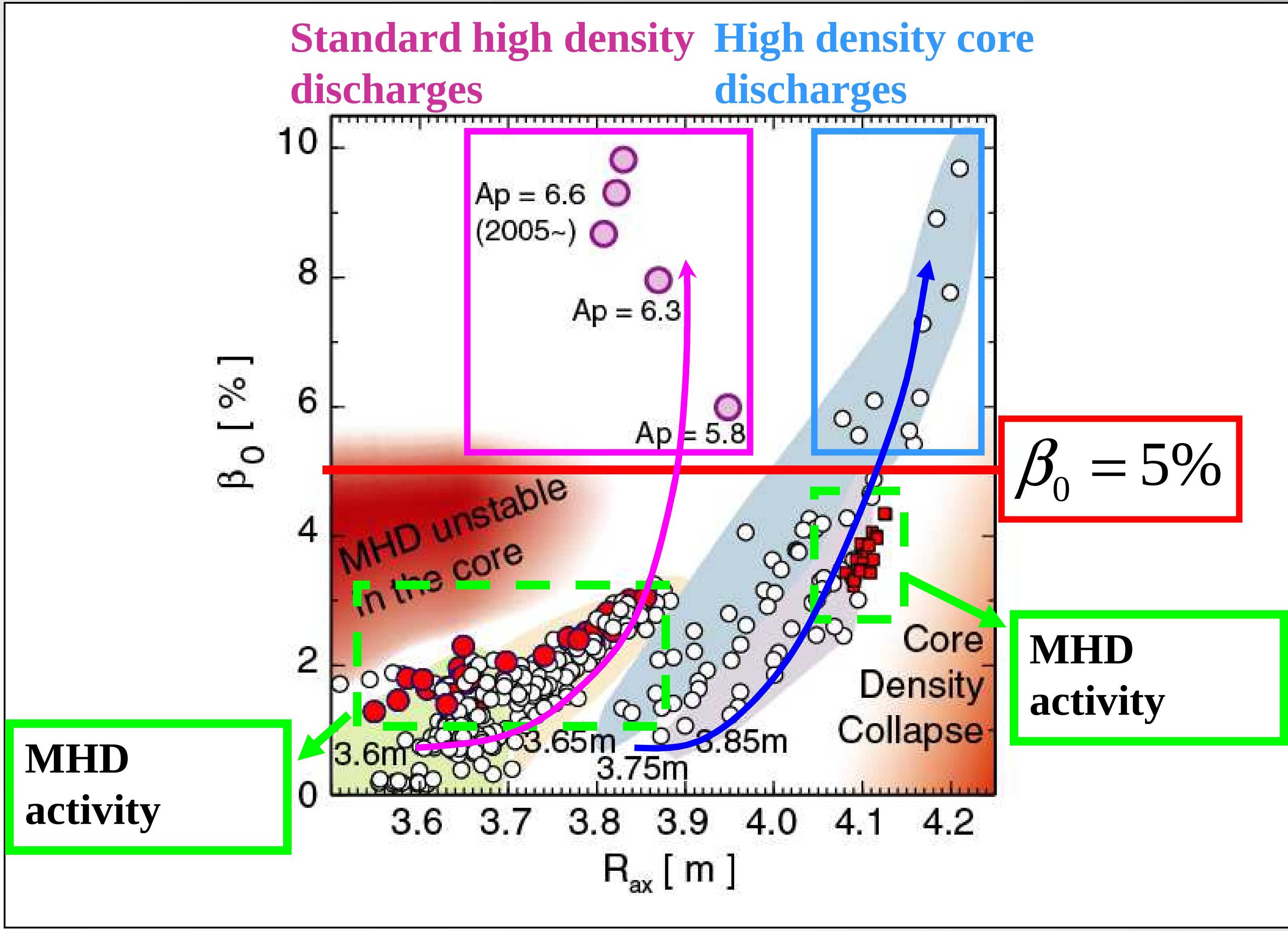
$$n\tau_E T_i \uparrow$$

n : **increase the density**
no Greenwald limit

τ_E : **confinement time**
Magnetic trap

T_i : **ionic temperature**
Heating is expensive !!

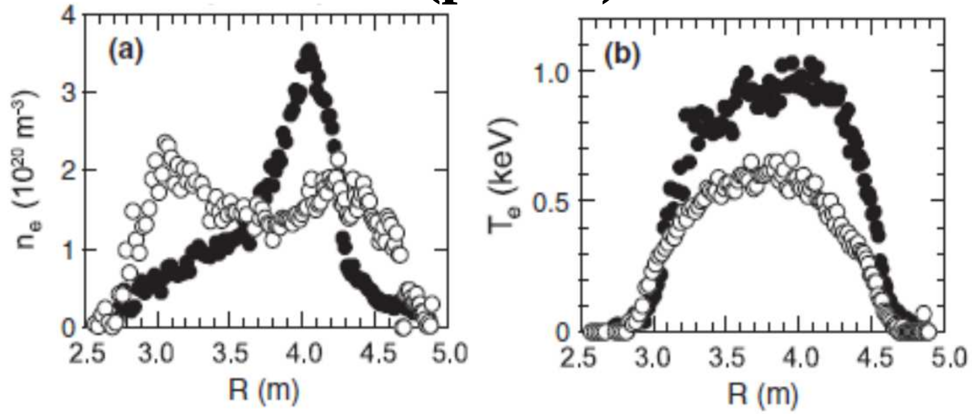
MHD stability operation limit in LHD



Advance operation scenario in LHD

1. **High density core discharge:**
   - **Outward configuration.**
   - **Strong MHD activity:**
     - ➢ **Core density collapse (CDC).**

◦ **Normal (gas puff)**
• **IDB (pellets)**



- ➢ **IDB**
- ➢ **Peaked pressure profiles**

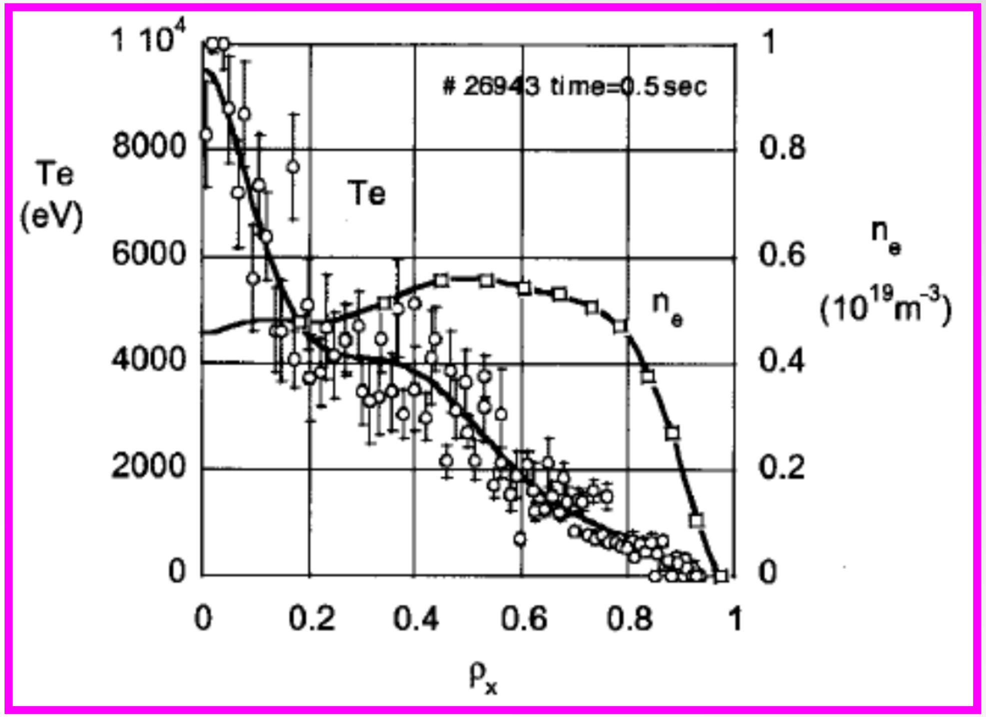
$$\langle \beta \rangle \approx 2\% \quad \beta_0 \approx 10\%$$

Advance operation scenario in LHD

2. Standard high density discharge:

- **Inward configuration.**
- **MHD instability:**

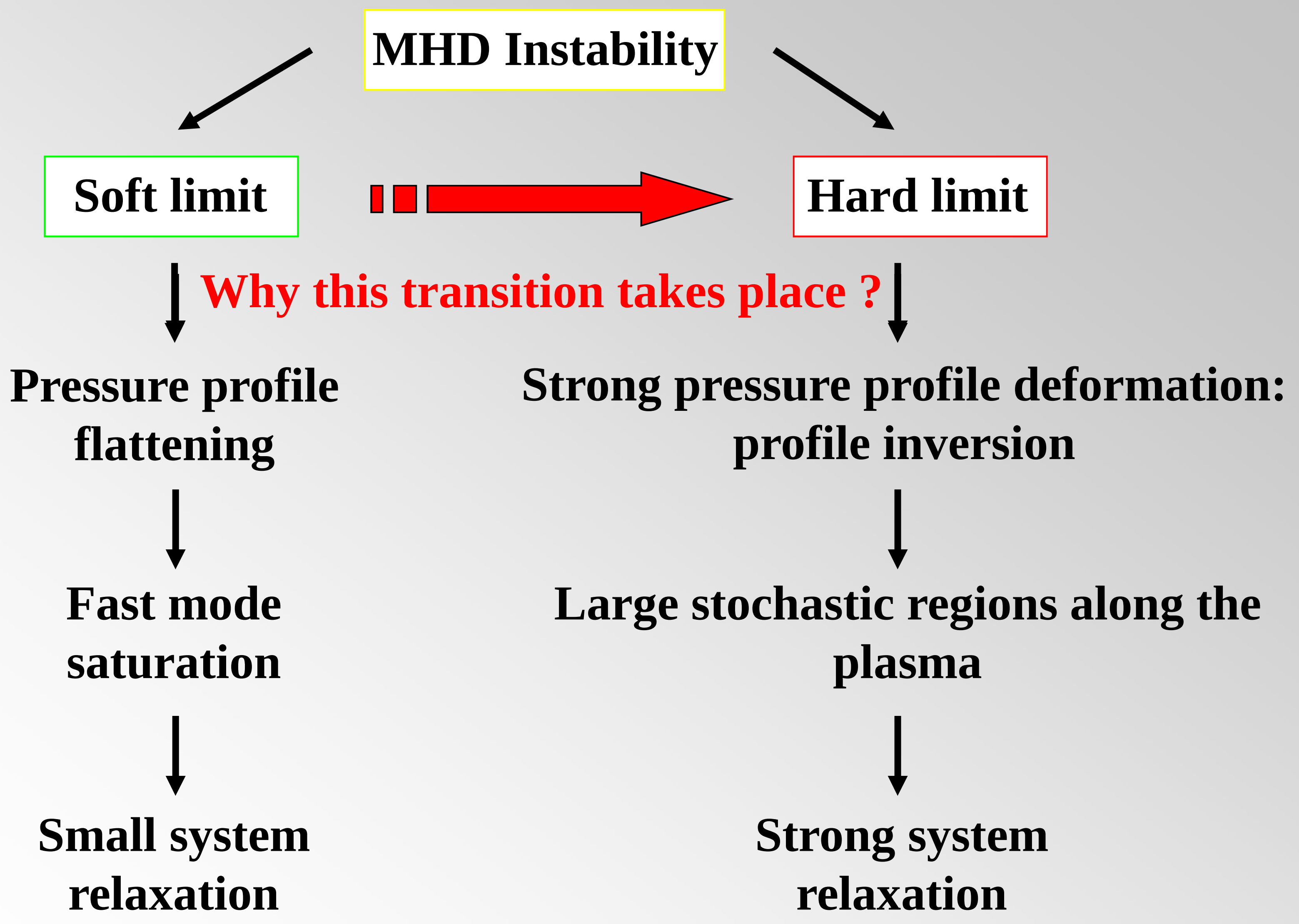
  - ➢ **Sawtooth like events.**
  - ➢ **Internal disruption.**



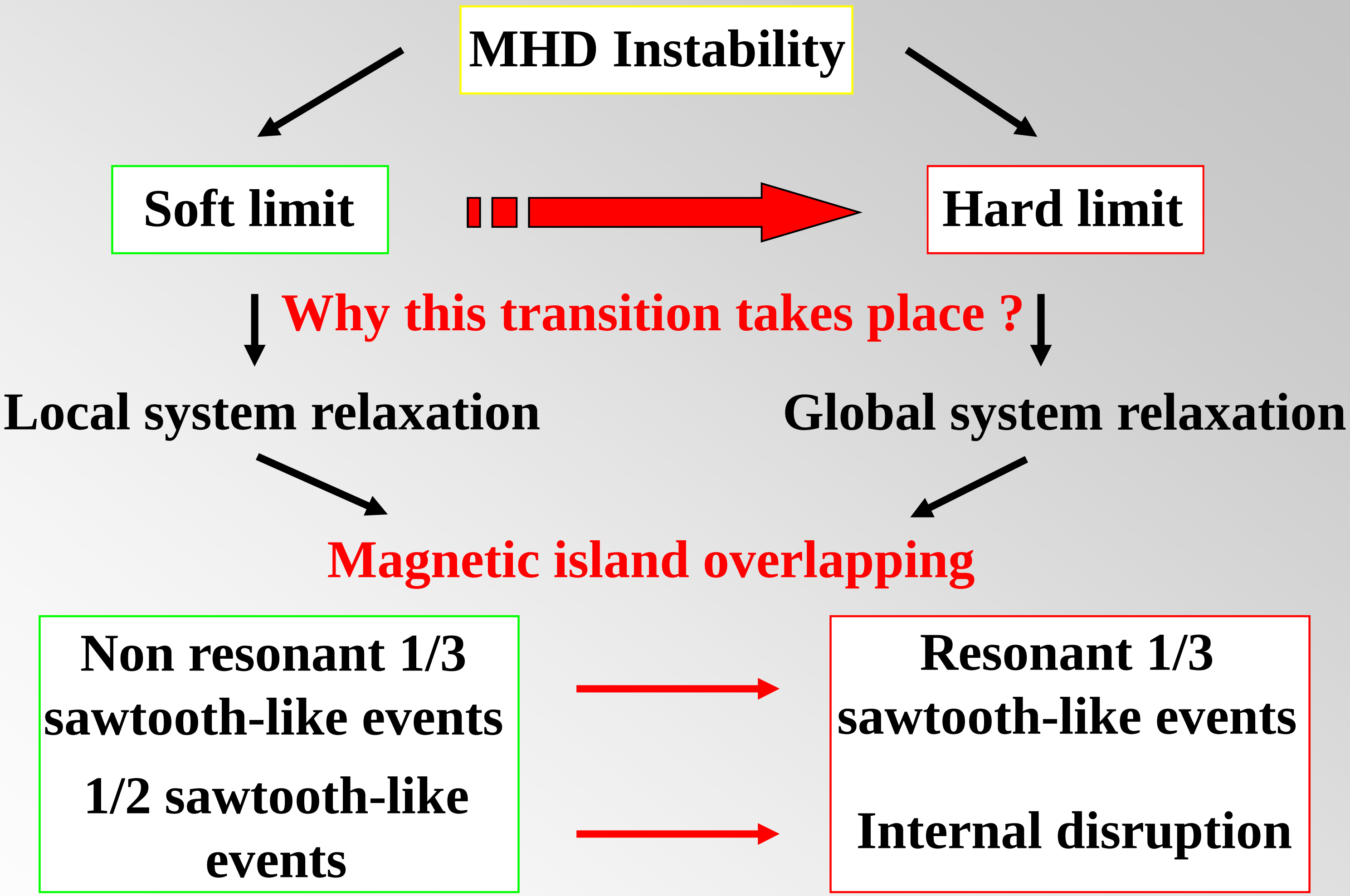
- ➢ **ITB**
- ➢ **Broad pressure profiles**
- ➢ **Aspect ratio increases**

$$\langle \beta \rangle \approx 5\% \quad \beta_0 \approx 10\%$$

MHD stability and operation limit of LHD



MHD stability and operation limit of LHD



Pressure gradient driven instabilities

Eigenvalues: $$A(r,\theta,\zeta) = B(r)\sum_{n}^{m} \text{sen}(m\theta + n\zeta)$$

- n: toroidal number
- m: poloidal number

Interchange modes: low n modes

⇒ Unstable if global curvature is unfavorable

Ballooning modes:
- Tokamak like (middle n modes)
- Helical (high n modes)

⇒ Unstable if local curvature is unfavorable

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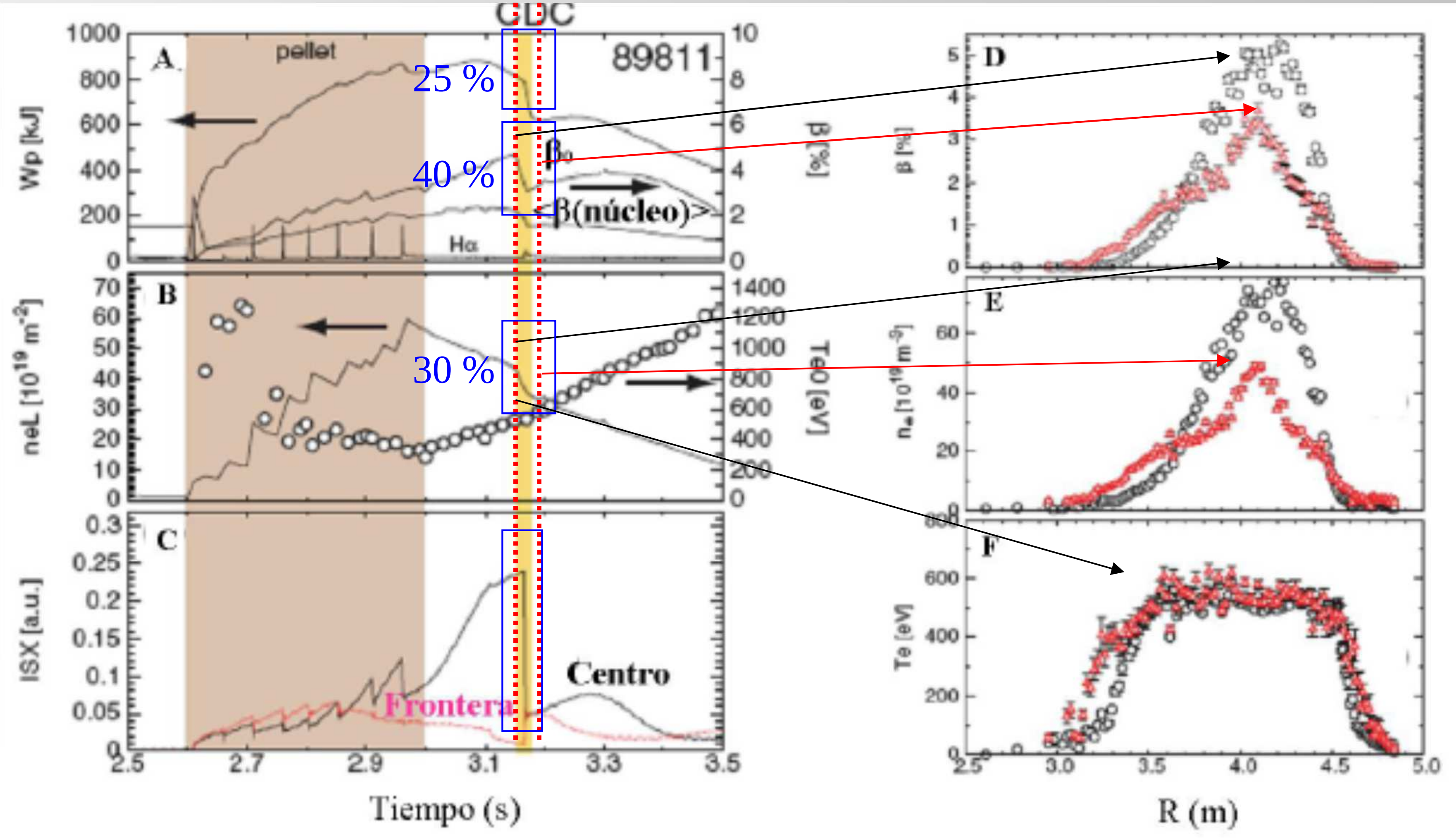
IDB/SDC Operation: Core Density Collapse

IDB/SDC discharge with a CDC event:



Ballooning modes, IDB/SDC and core density collapse

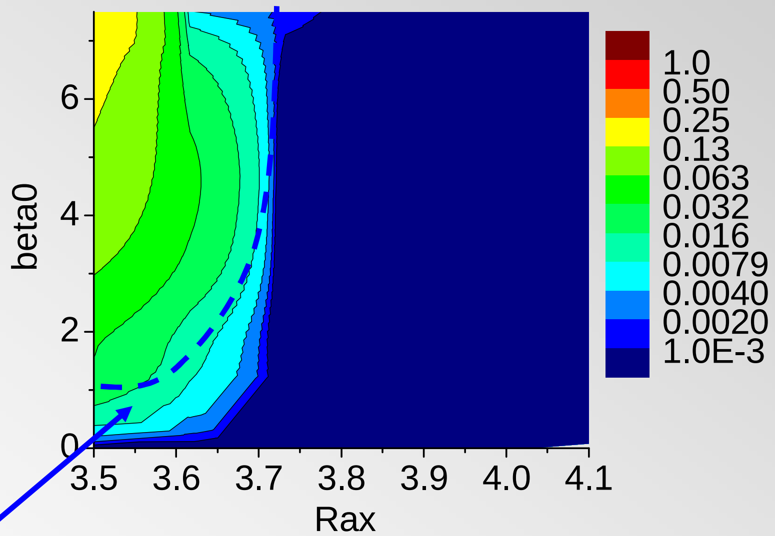
• Ideal ballooning modes stability by the code Hn-Bal for several VMEC fixed boundary equilibria:

- Broad pressure profiles $p(\psi_N) = p_0\left(1-\psi_N^2\right)^2$

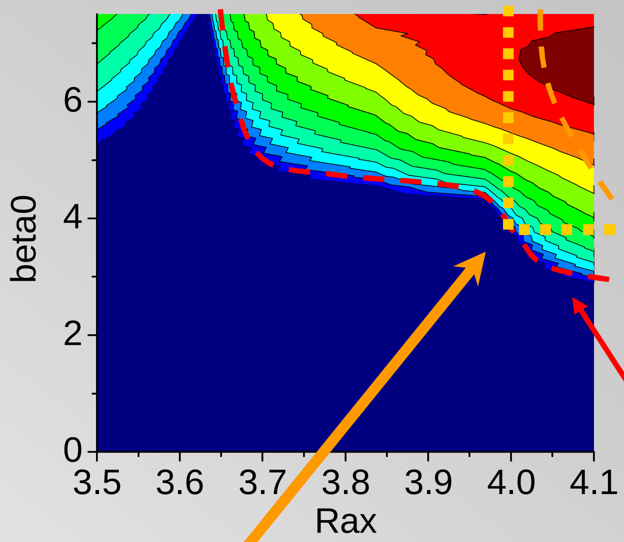
  and peaked $p(\psi_N) = p_0\left(1-\psi_N^2\right)$.
- β_0 values: 0.5 – 7.5 %.
- Vacuum magnetic axis location $R_{ax} = 3.5 - 4.1\, m$.
- Good and bad magnetic curvature lines.
- Mercier parameter; interchange modes stability.
- Main rational surfaces.

Ballooning modes, IDB/SDC and core density collapse

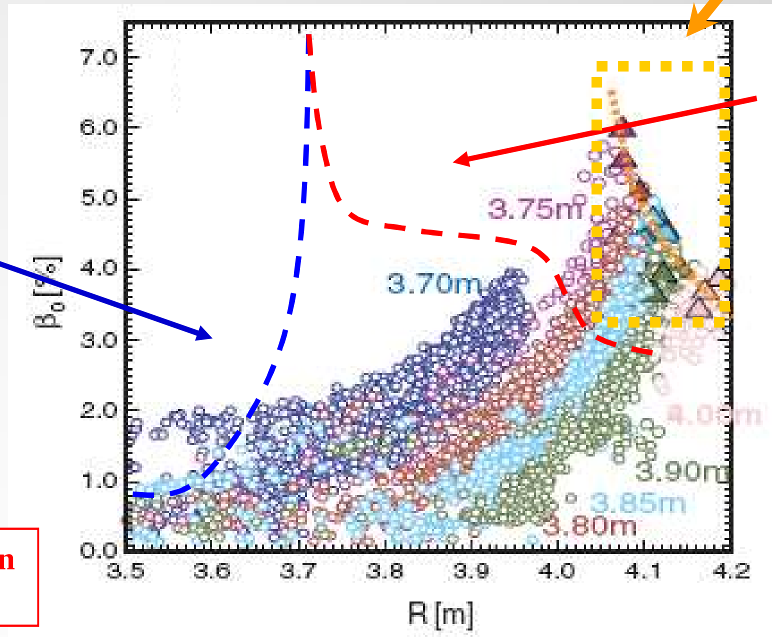
Growth rate $\rho = 0.3$



Growth rate $\rho = 0.8$



Interchange modes



Ballooning modes

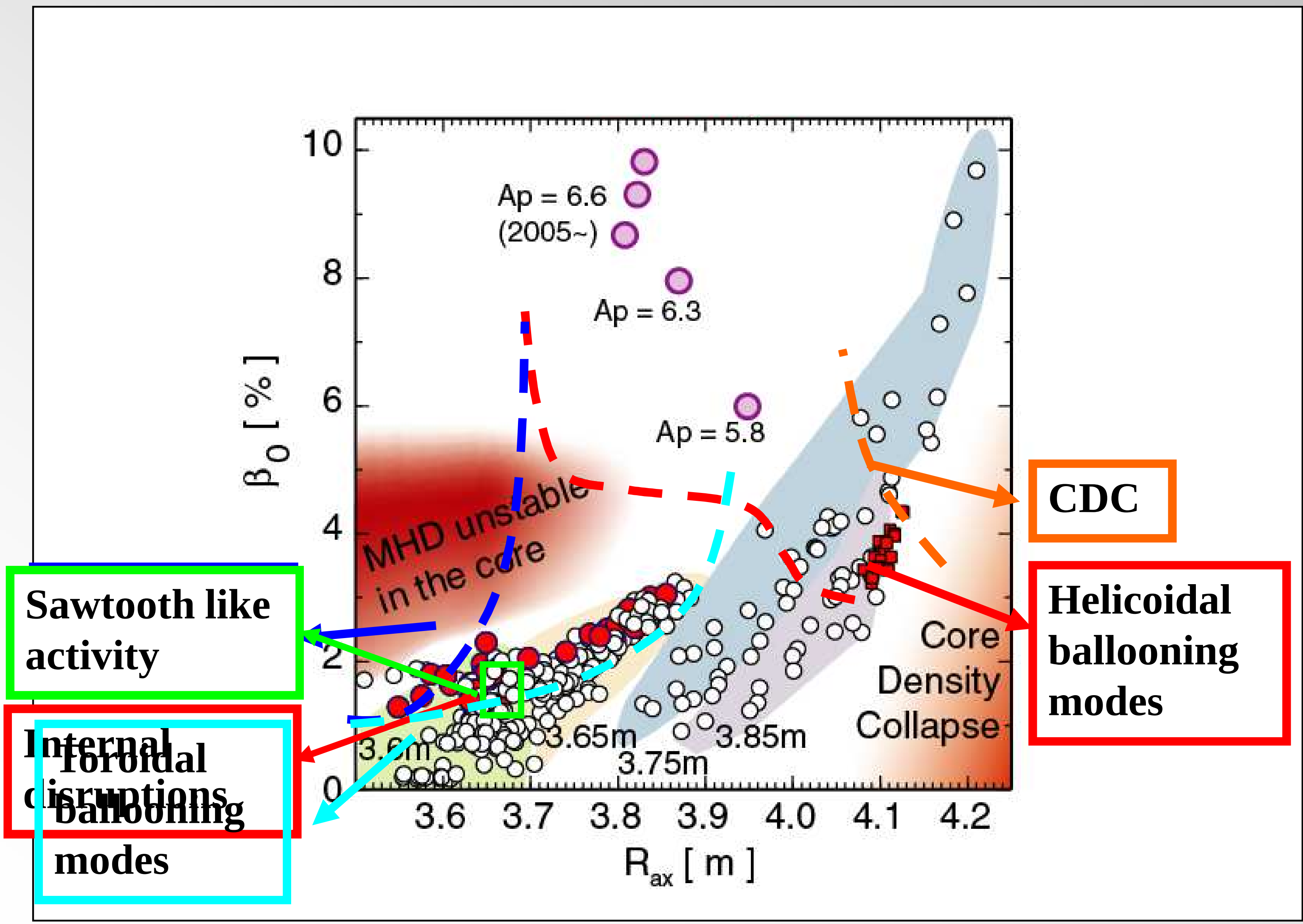
Transition soft – hard MHD limit: magnetic field line curvature

Helicoidal ballooning modes as main driver of CDC

J. Varela et al, Plasma and Fusion Research, 6, 1403013, 2011.

S. Ohdachi et al, Contri. Plasma Phys., 50, 552, 2010

Internal disruptions and sawtooth like activity in LHD



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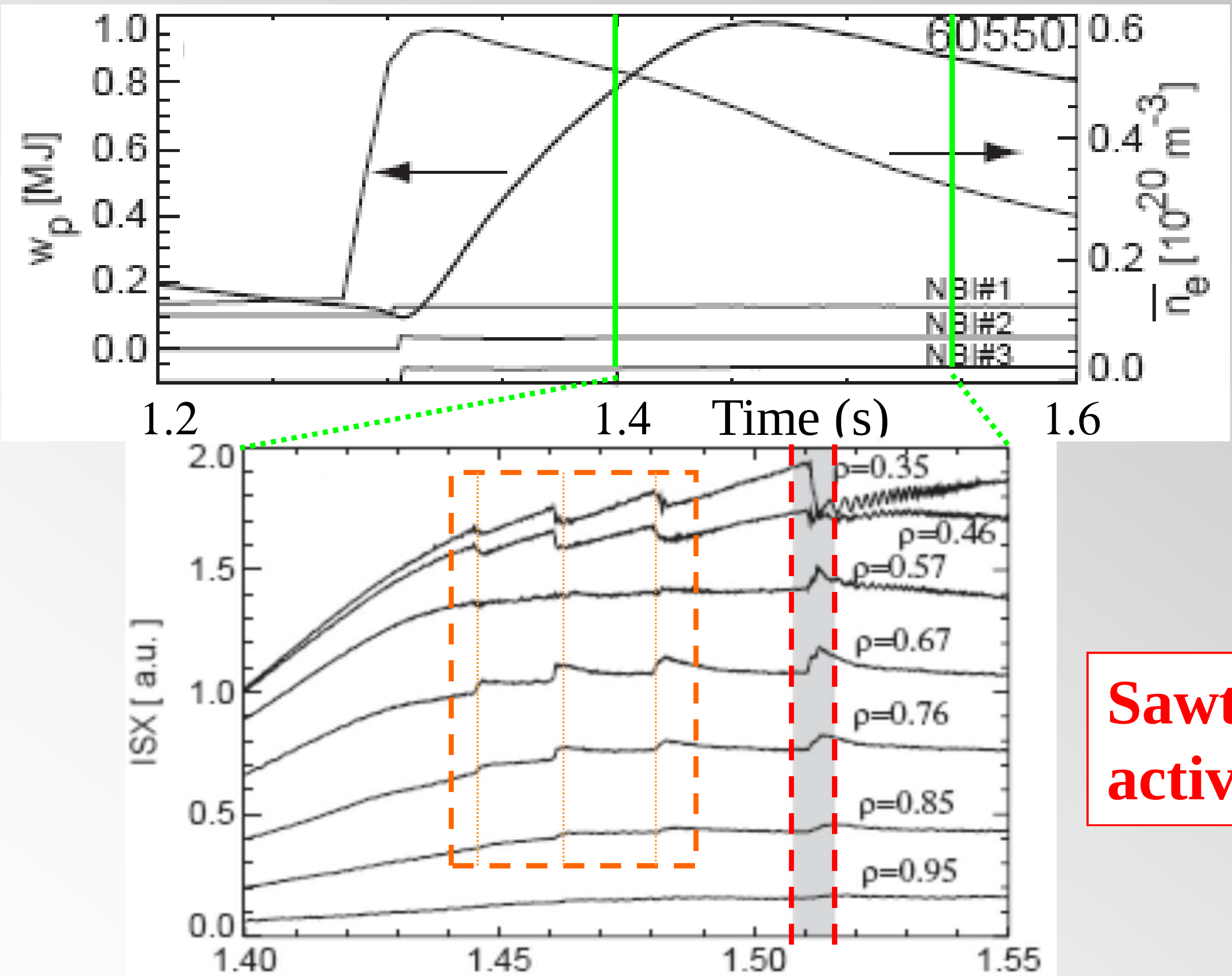
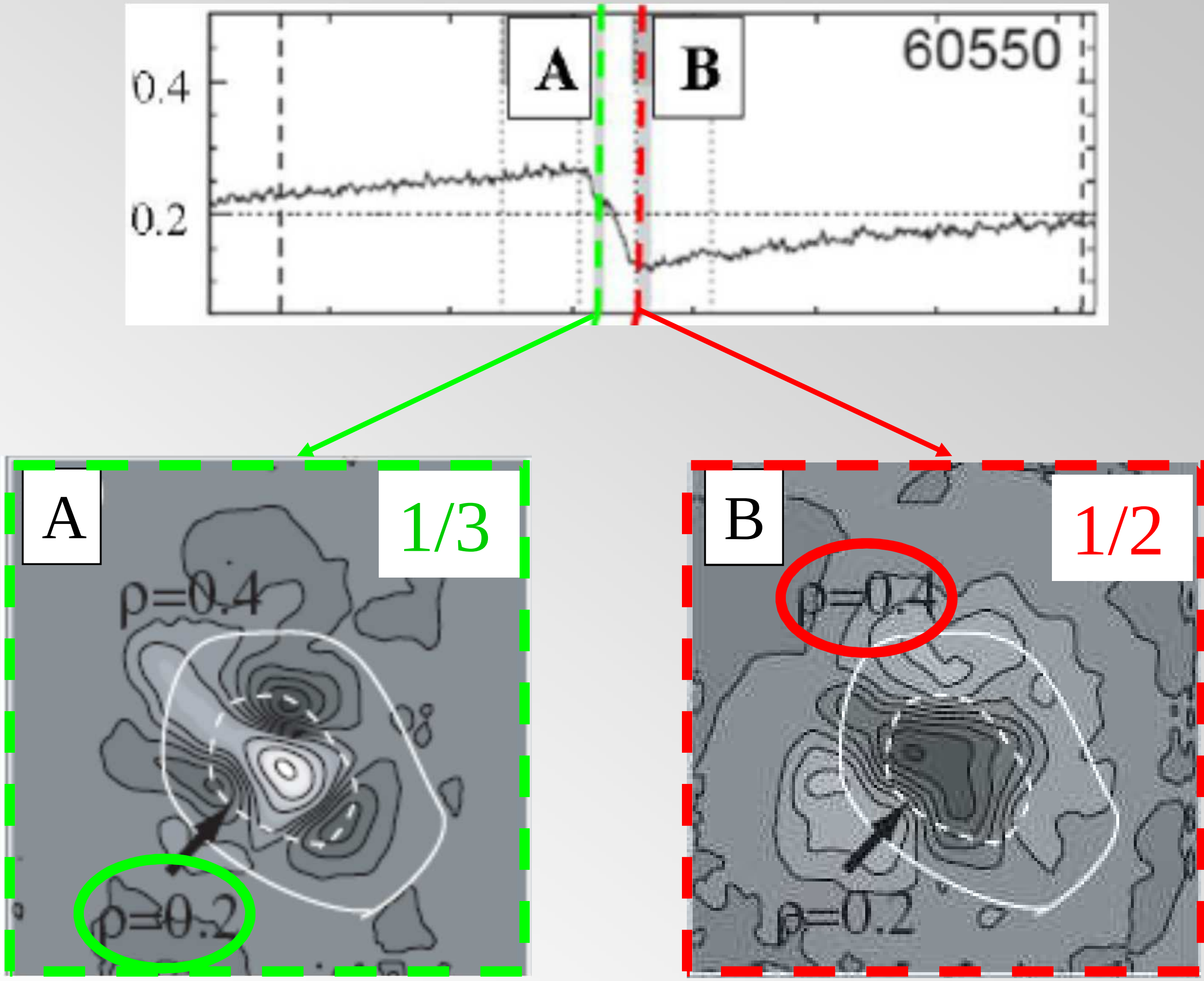
Sawtooth-like activity in the LHD



Sawtooth like activity

Sawtooth-like activity in the LHD



Tangential soft X ray Camera

MHD model

$$\frac{\partial \psi}{\partial t} = \nabla_{||}\Phi + \eta B_{\zeta}^{eq} J_{\zeta}$$

Toroidal Flow ψ

$$\frac{\partial U}{\partial t} = -\vec{v}\cdot\vec{\nabla}U + S^2\left[\frac{\beta_0}{2\epsilon^2}\left(\frac{1}{\rho}\frac{\partial\sqrt{g}}{\partial\theta}\frac{\partial p}{\partial\rho} - \frac{\partial\sqrt{g}}{\partial\rho}\frac{1}{\rho}\frac{\partial p}{\partial\theta}\right)\right.$$
$$\left. + \nabla_{||}J^{\zeta} - \frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho J_{eq}^{\zeta})\frac{1}{\rho}\frac{\partial\psi}{\partial\theta} + \frac{1}{\rho}\frac{\partial J_{eq}^{\zeta}}{\partial\zeta}\frac{\partial\psi}{\partial\rho}\right]$$

Vorticity U

$$\frac{\partial p}{\partial t} = -\vec{v}\cdot\vec{\nabla}p + \frac{dp_{eq}}{\rho}\frac{1}{\rho}\frac{\partial\Phi}{\partial\theta}$$

Pressure p

MHD model

Far-3D code

Resistive non linear code

Reduced equations

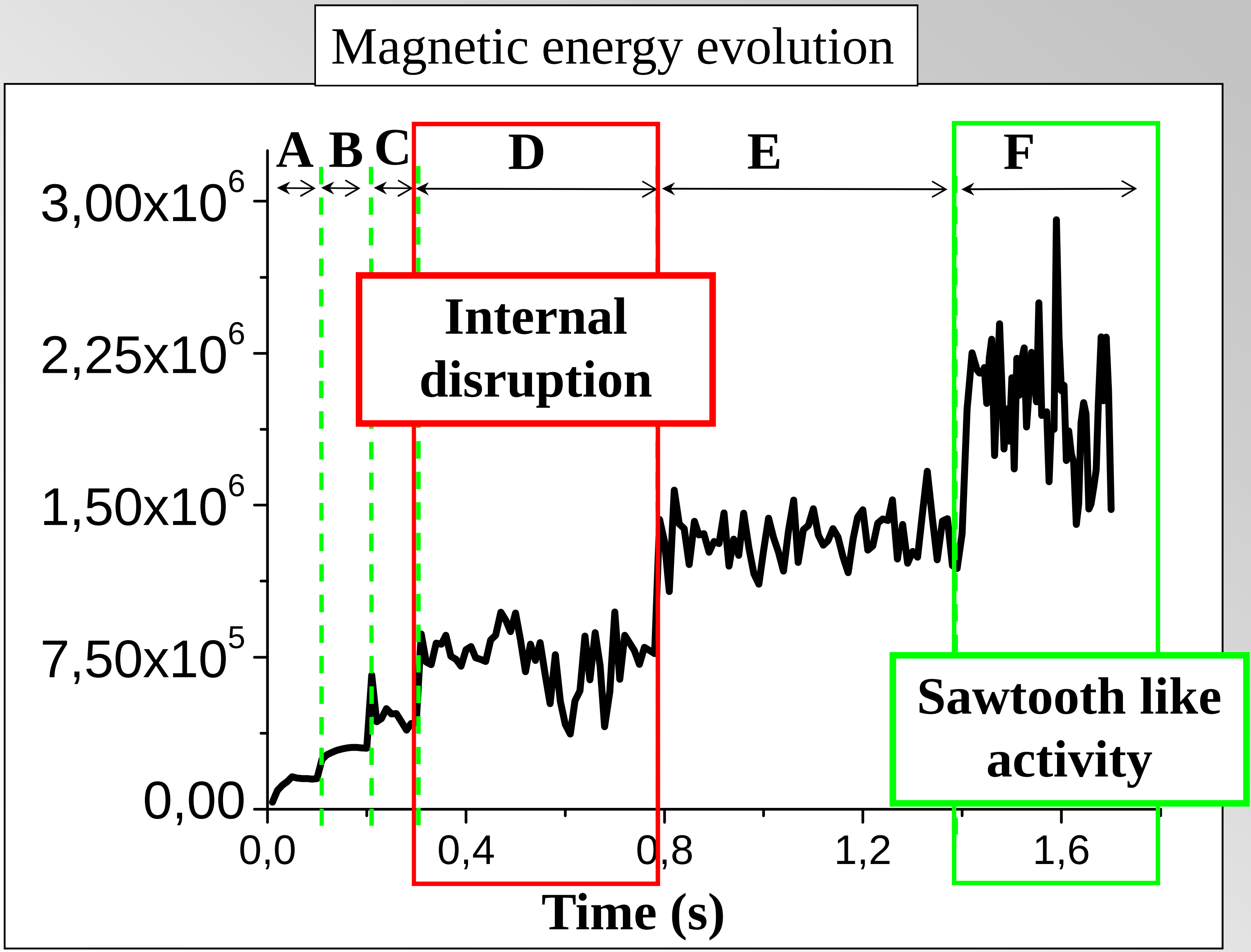
Perturvative model

3D system

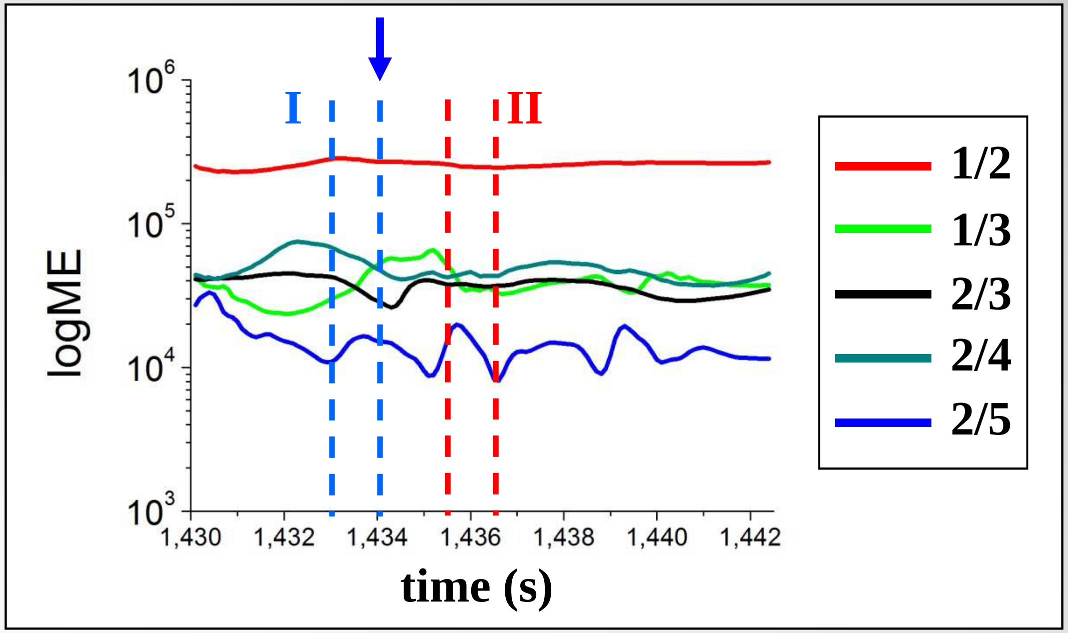
Global modes

Toroidal coupling

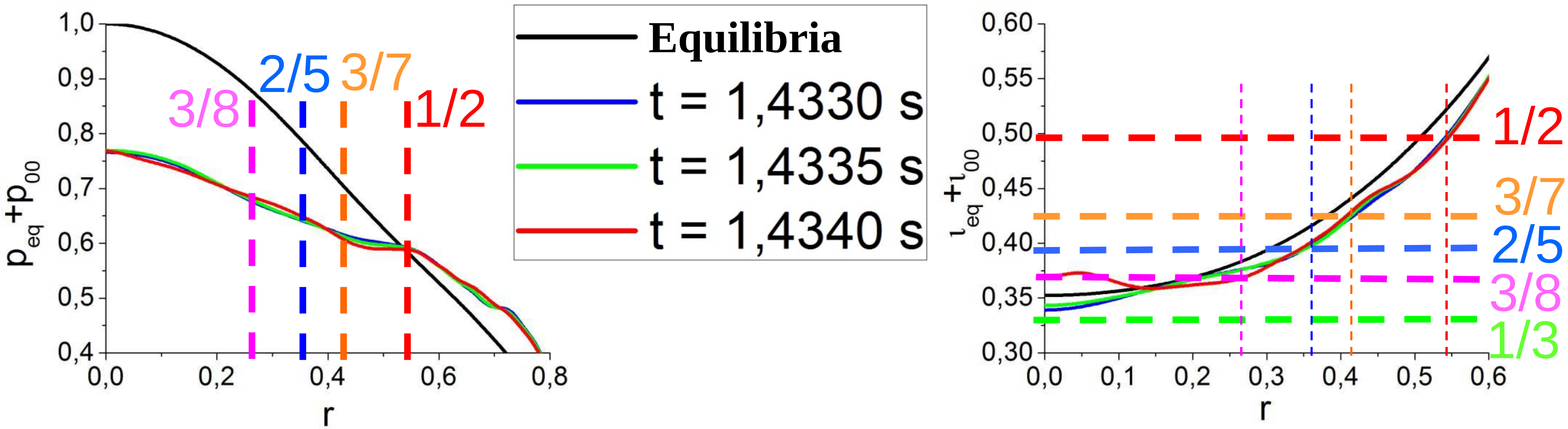
Simulation properties



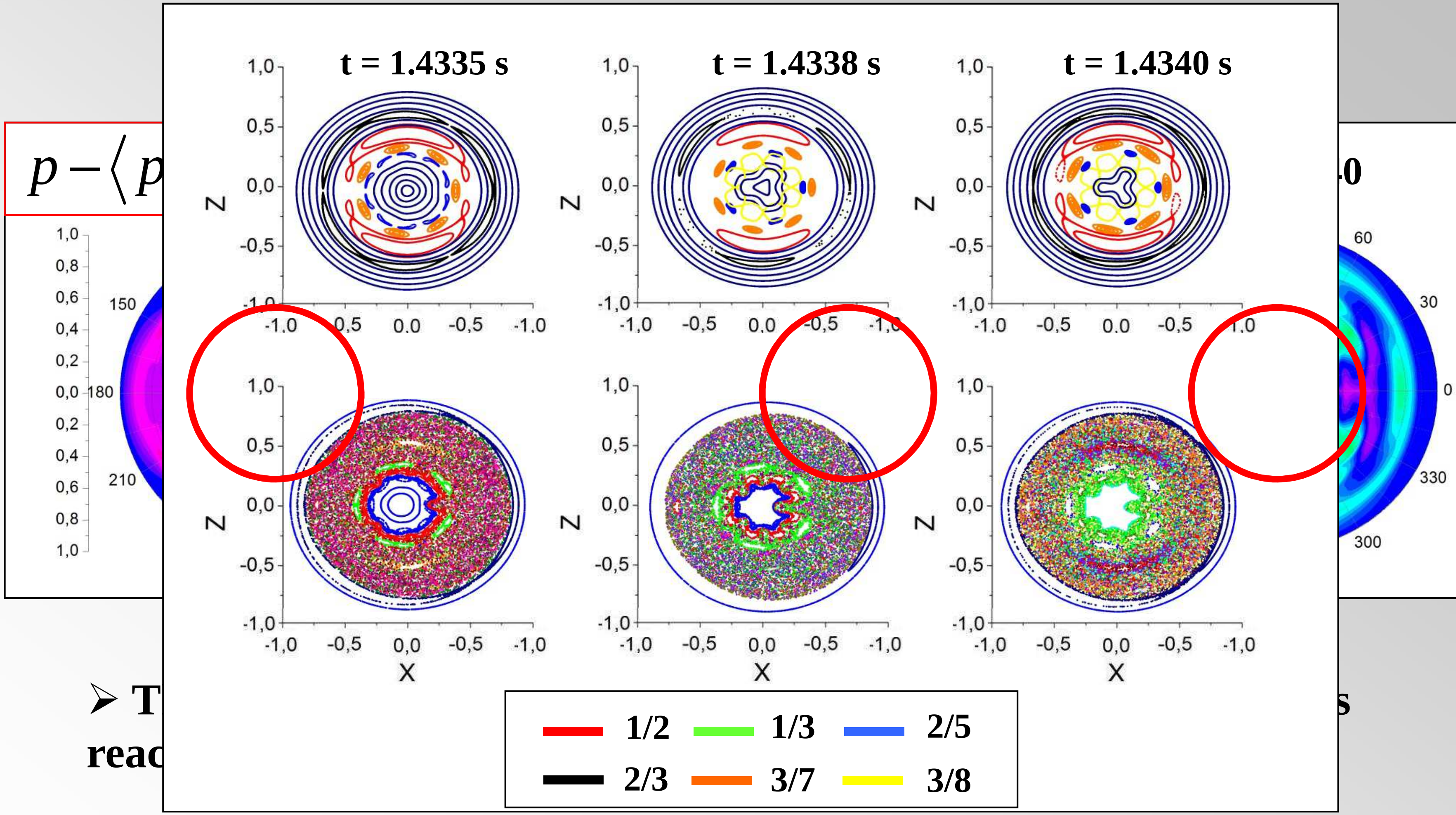
Analysis results: events selection



- Event **I**: non resonant
- Event **II**: resonant
  - ➢ 1/3 energy increases.
  - ➢ Pressure profile deformation slightly increase in middle region.
  - ➢ Iota profile broader near the magnetic axis.



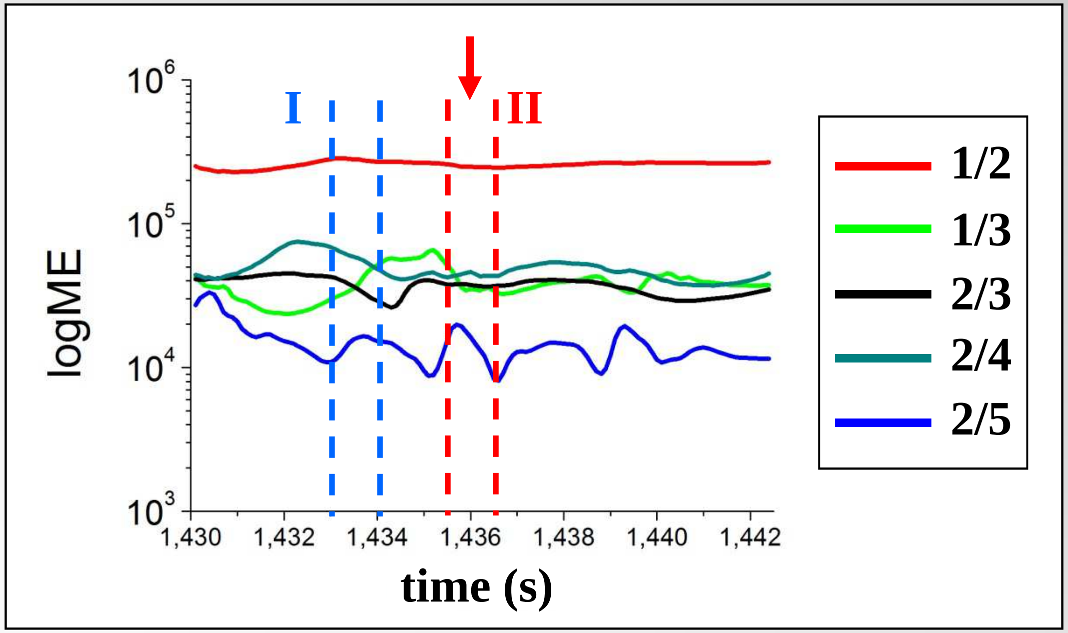
Analysis results: non resonant event



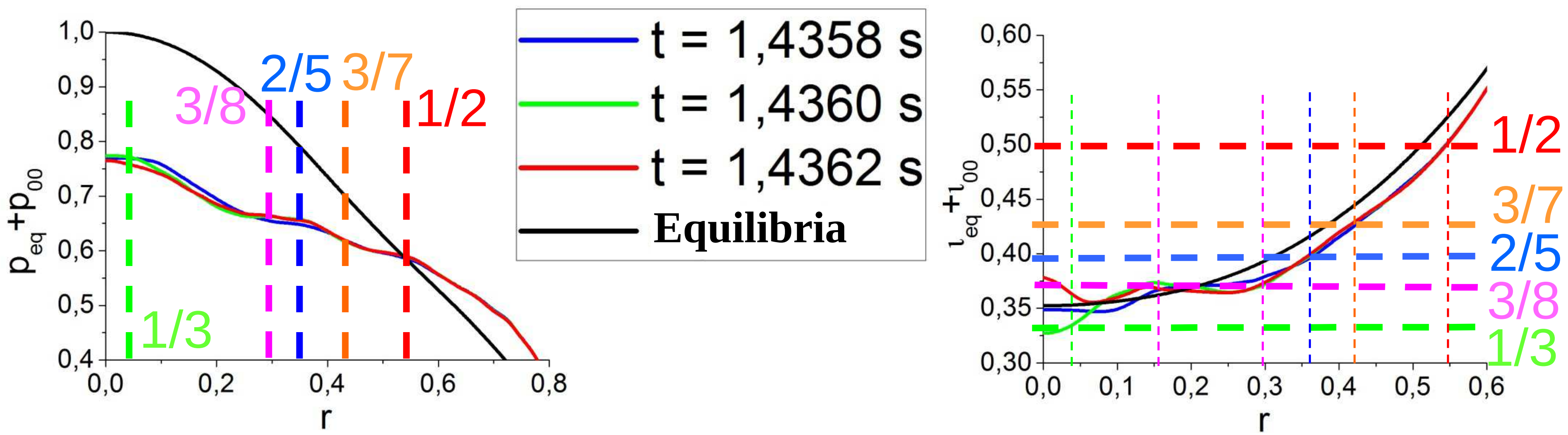
➢ T ... s
reac

➢ **Magnetic flux surfaces are deformed and the stochastic region increase in the inner plasma region.**

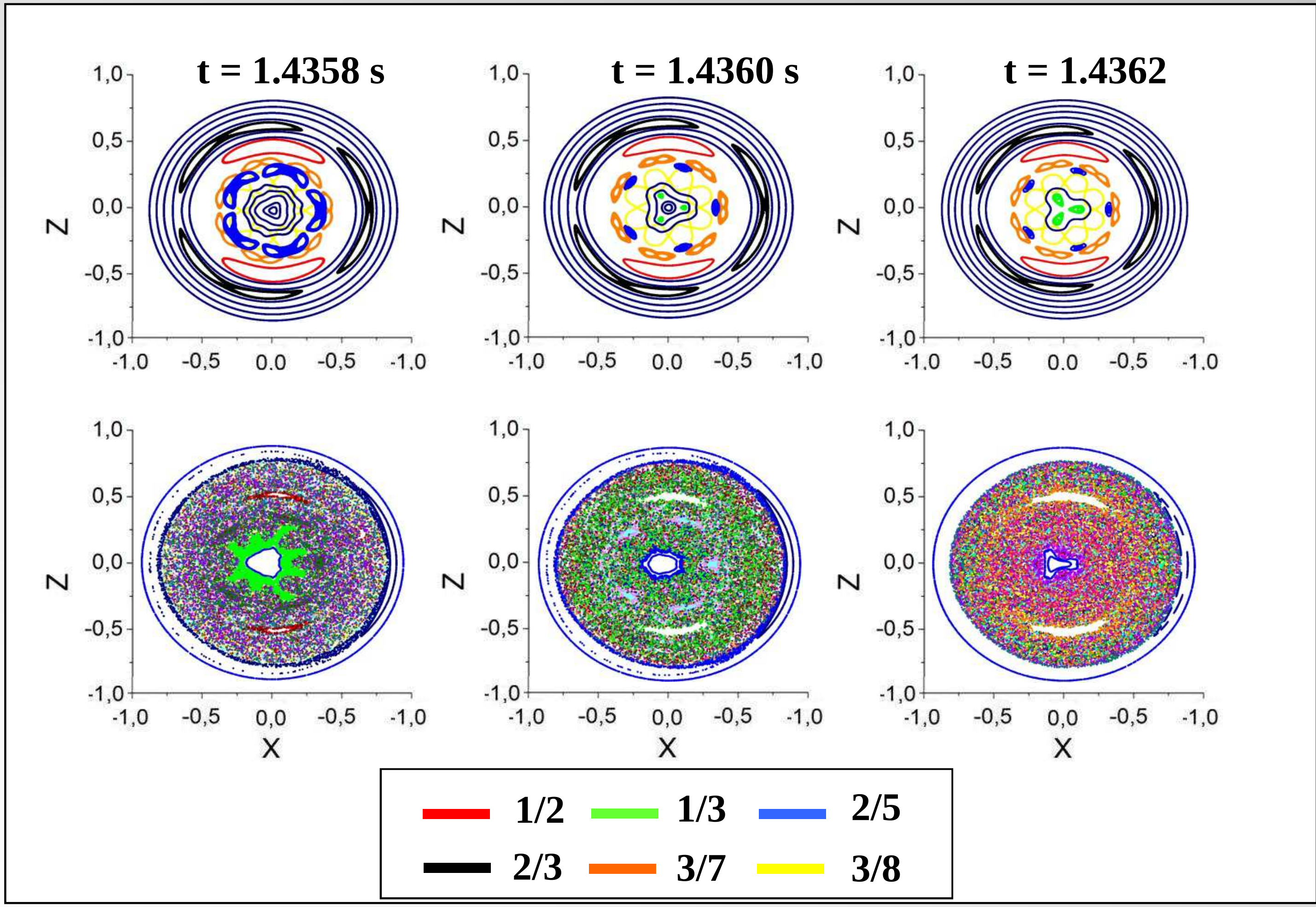
Analysis results: events selection



- Event **II**: resonant
  - **1/3** and **2/5** reach maximum.
  - Pressure profile is flat near the magnetic axis.
  - Iota profile falls below **1/3** value at t = 1.4360 s.

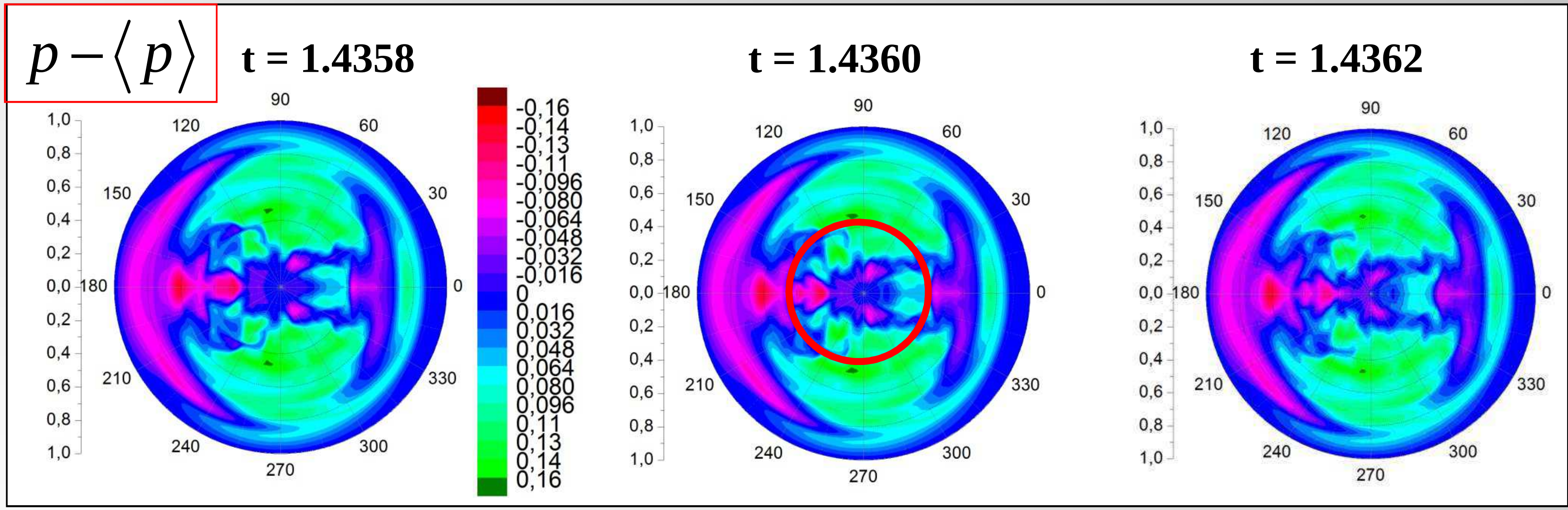


Analysis results: resonant event



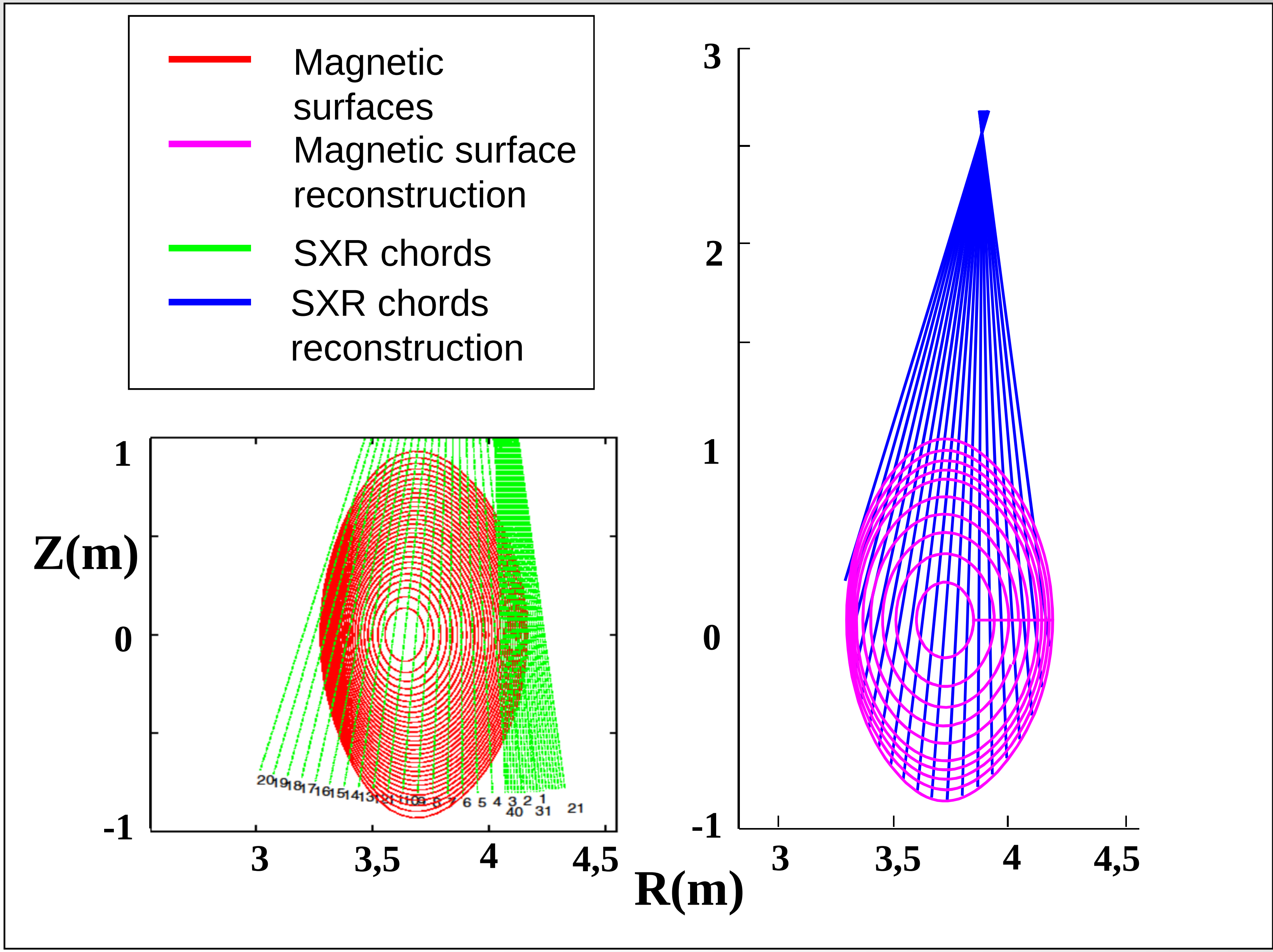
➢ **The mode 1/3 is located in the plasma core at t = 1.4360 – 1.4362 s and the stochastic region reaches the plasma core.**

Analysis results: resonant event



➢ **In the plasma core three islands, three islands are observed near the magnetic axis.**

Plasma Emissivity reconstruction



Plasma Emissivity reconstruction

Plasma Emissivity

$$I \propto \int dl p^2$$

$$dl = \sqrt{dR^2 + dZ^2}$$

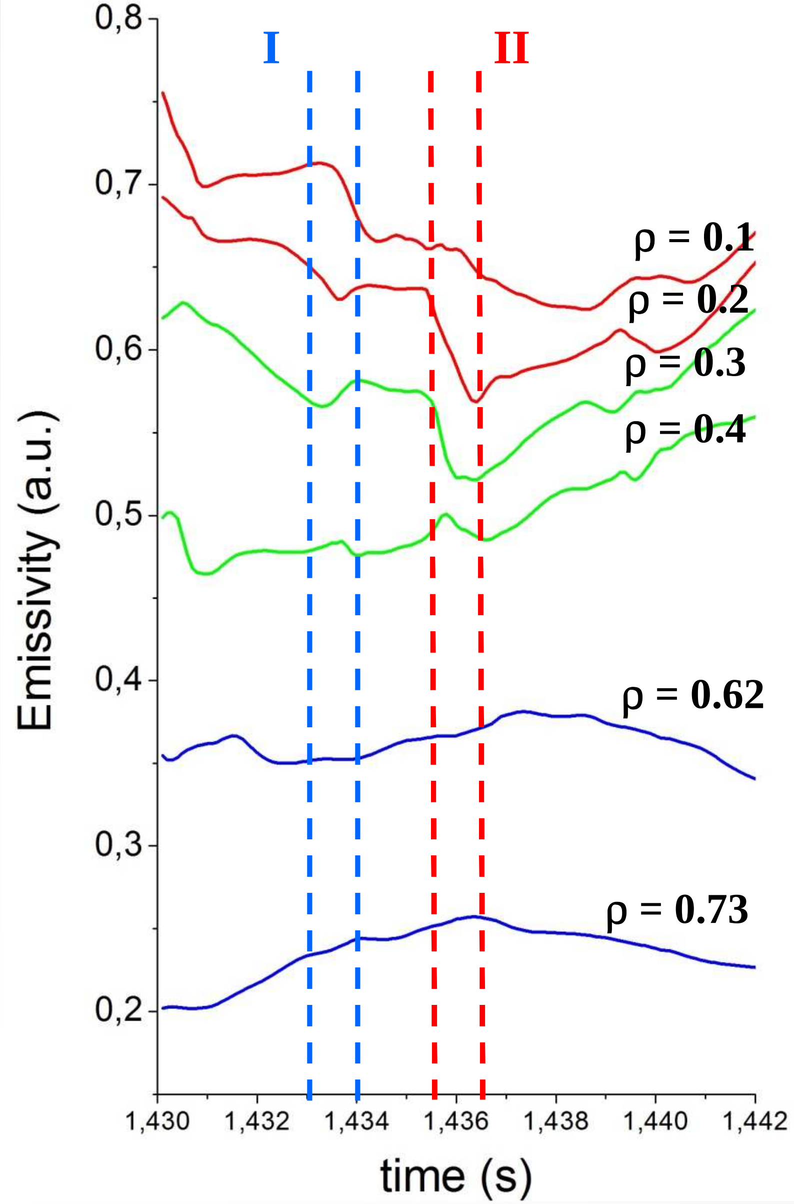
Poloidal rotation

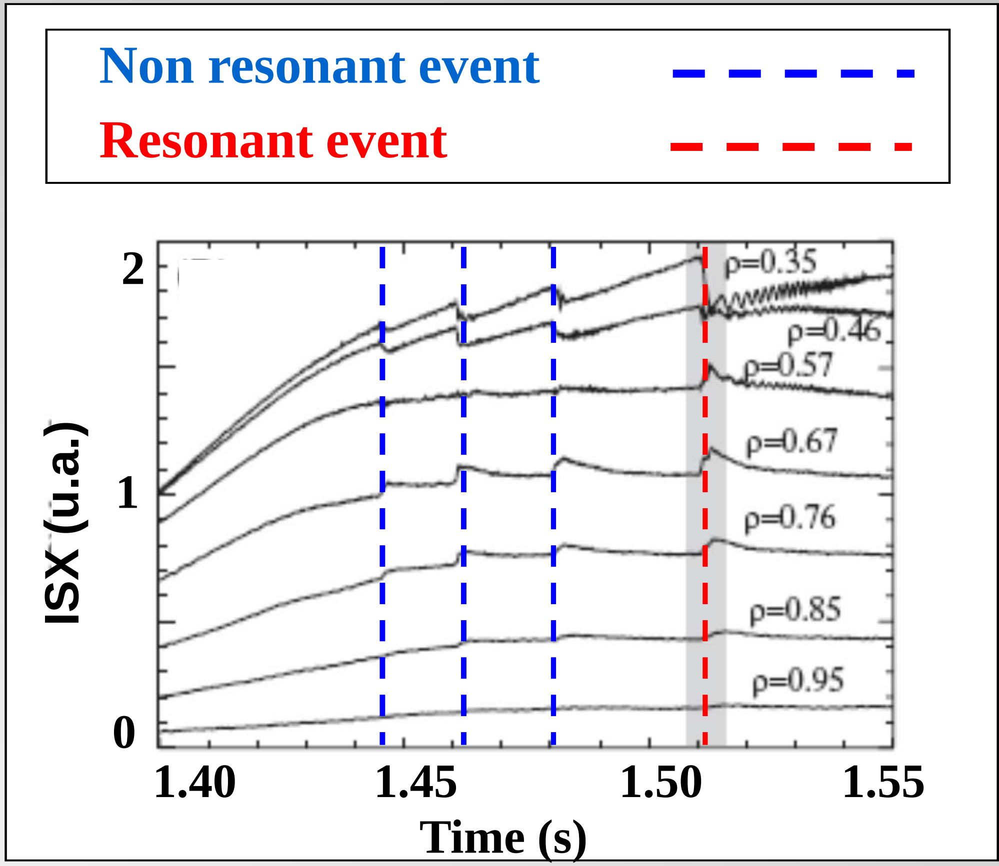
$$\vec{v} = \frac{\vec{E} \wedge \vec{B}}{B^2} - \frac{\vec{\nabla} p}{nq} \wedge \frac{\vec{B}}{B^2}$$

Electron diamagnetic direction

$$v_\theta = 0.75 km / h$$

Experiment data versus theoretical diagnostic





Transition soft – hard MHD limit: large iota profile deformation in the plasma core

J. Varela et al, Phys. Plasmas 19, 082501, 2012

J. Varela et al, Phys. Plasmas, 21, 032501, 2014

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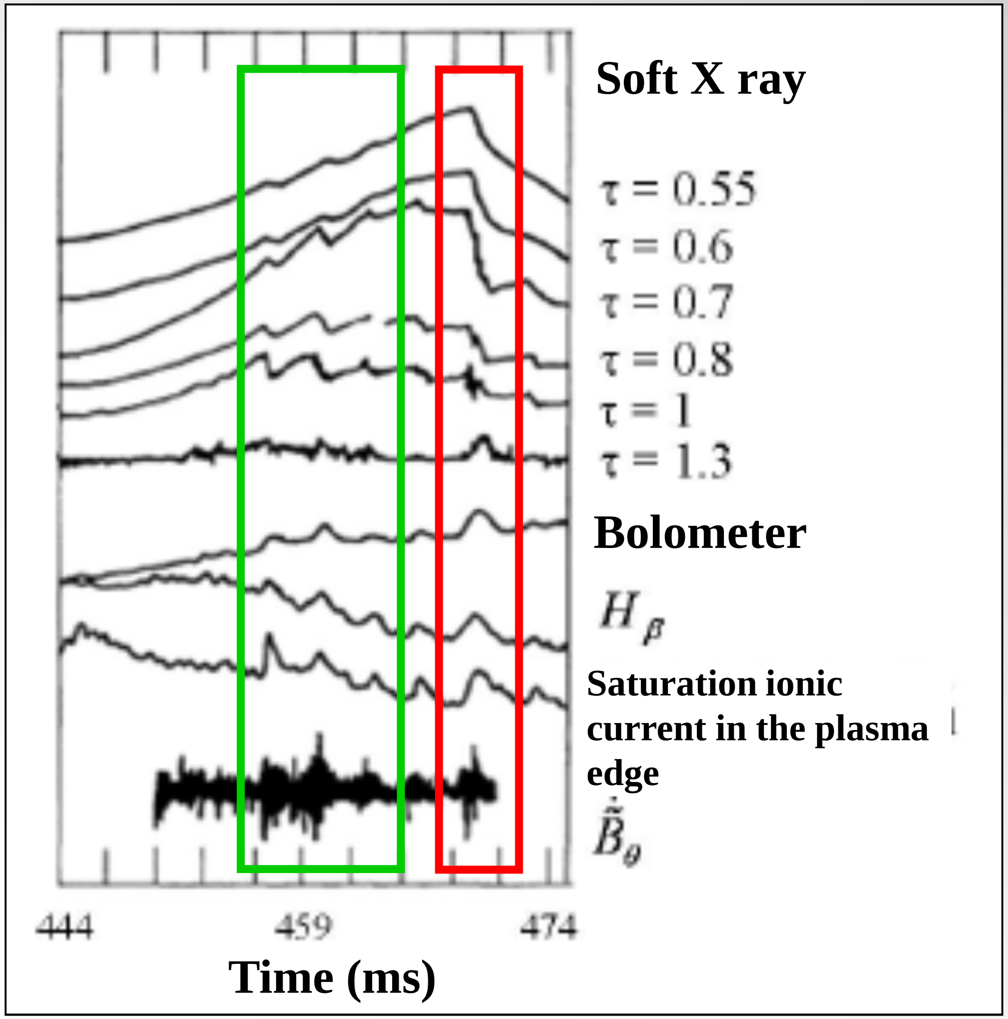
Internal disruption in Stellarator

Heliotron E



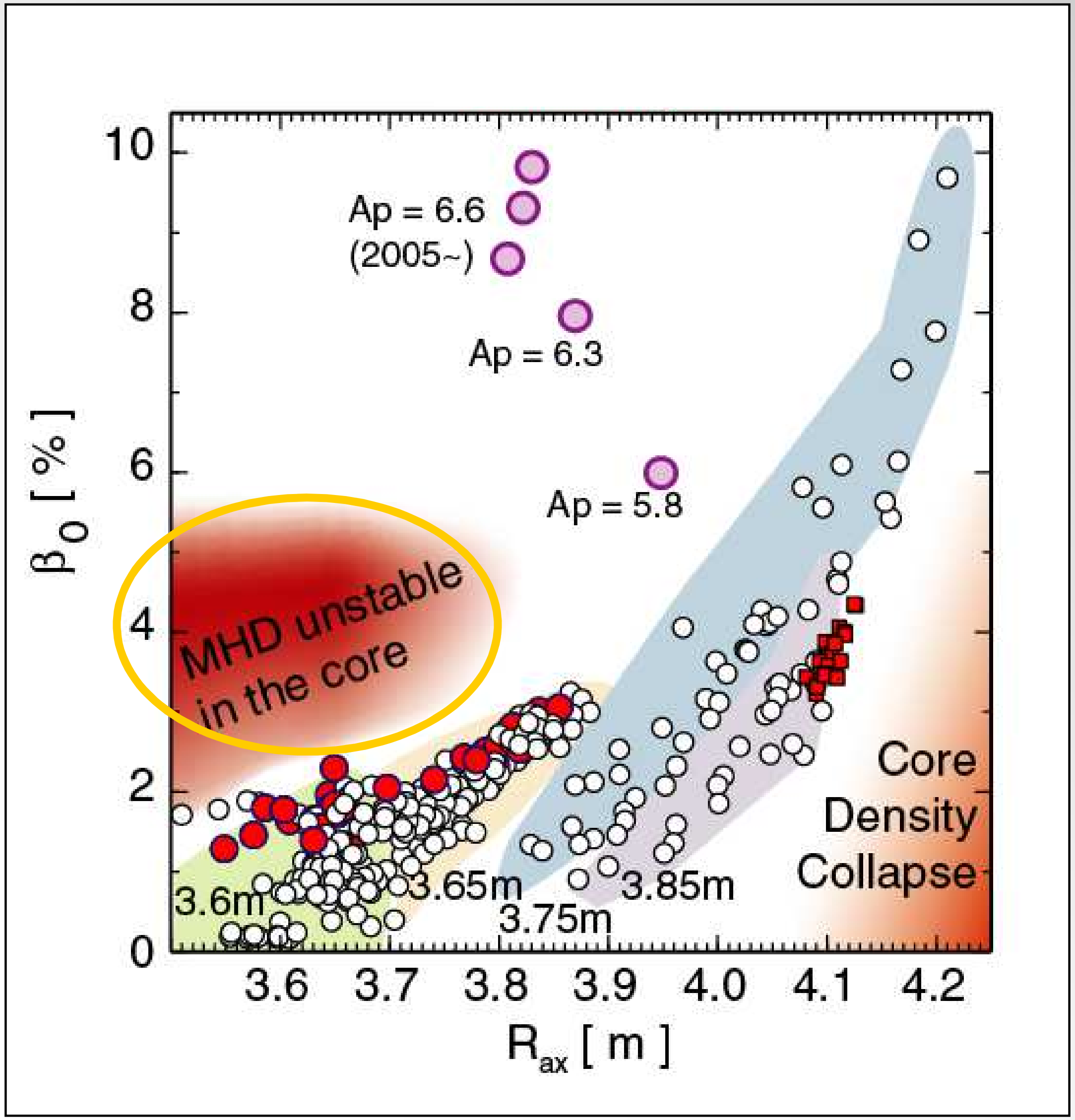
Sawtooth-like activity

Internal disruption

- **Sudden drop of system confinement efficiency.**
- **Large reduction of the central pressure.**
- **Unstable interchange modes 1/2.**
- **Magnetic island overlapping and strong magnetic reconnection in the inner plasma region.**

Internal disruption in Stellarator

An internal disruption can be driven in LHD ?



Theoretical results predicts an operation regime with unstable interchange modes in the inner plasma region.

Experimental evidence of LHD operation in this regimen without strong MHD activity. Internal disruptions are not driven.

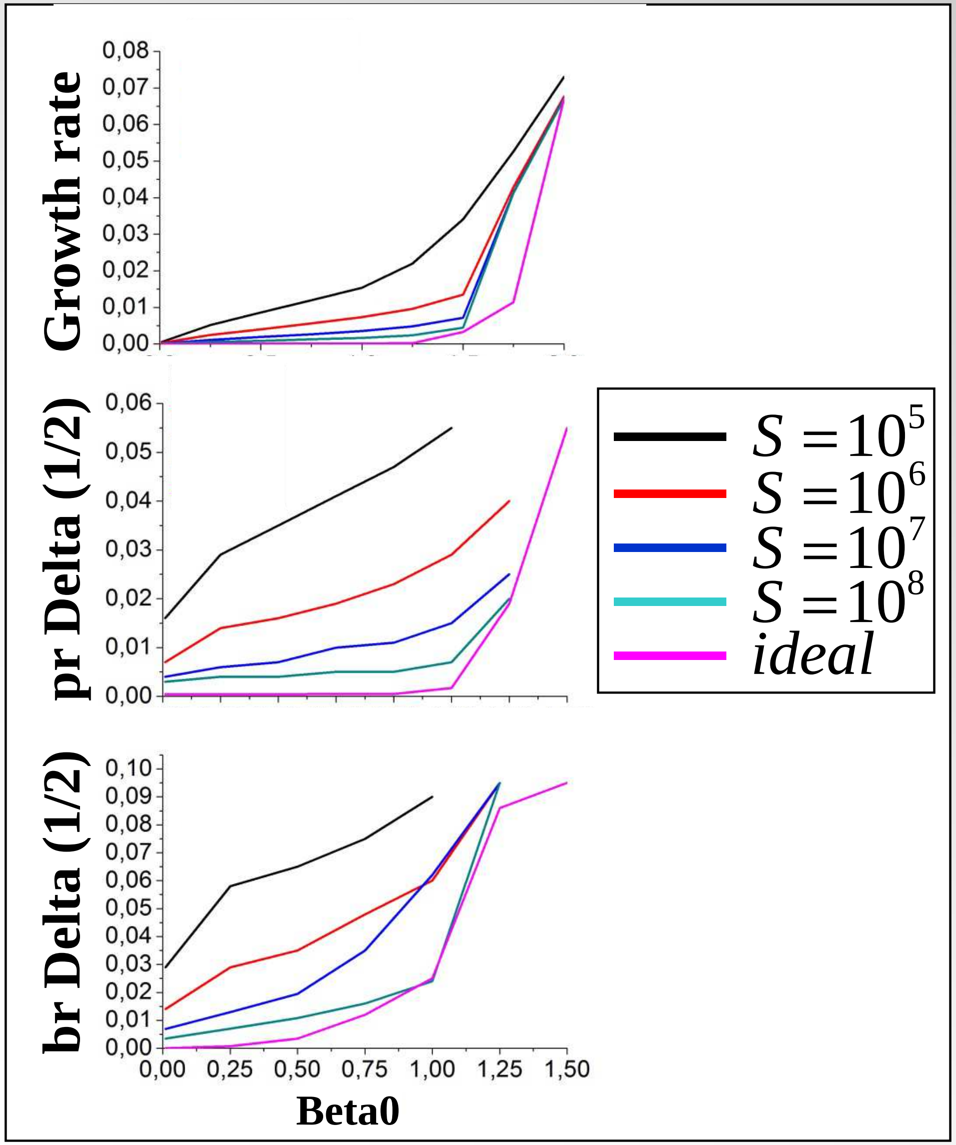
Why the internal disruptions are not driven in LHD ?

Lundquist number S

Higher density and B field in LHD than in Heliotron E

Reconnection regime

Internal disruption in LHD



A plasma with high S values behaves like an ideal plasma.

➔ **Plasma resistivity decreases.**

The linear growth rate of the n = 1/2 mode decreases with S.

➔ **MHD instability is weaker.**

Pr and Br function width for the mode 1/2 decrease with S.

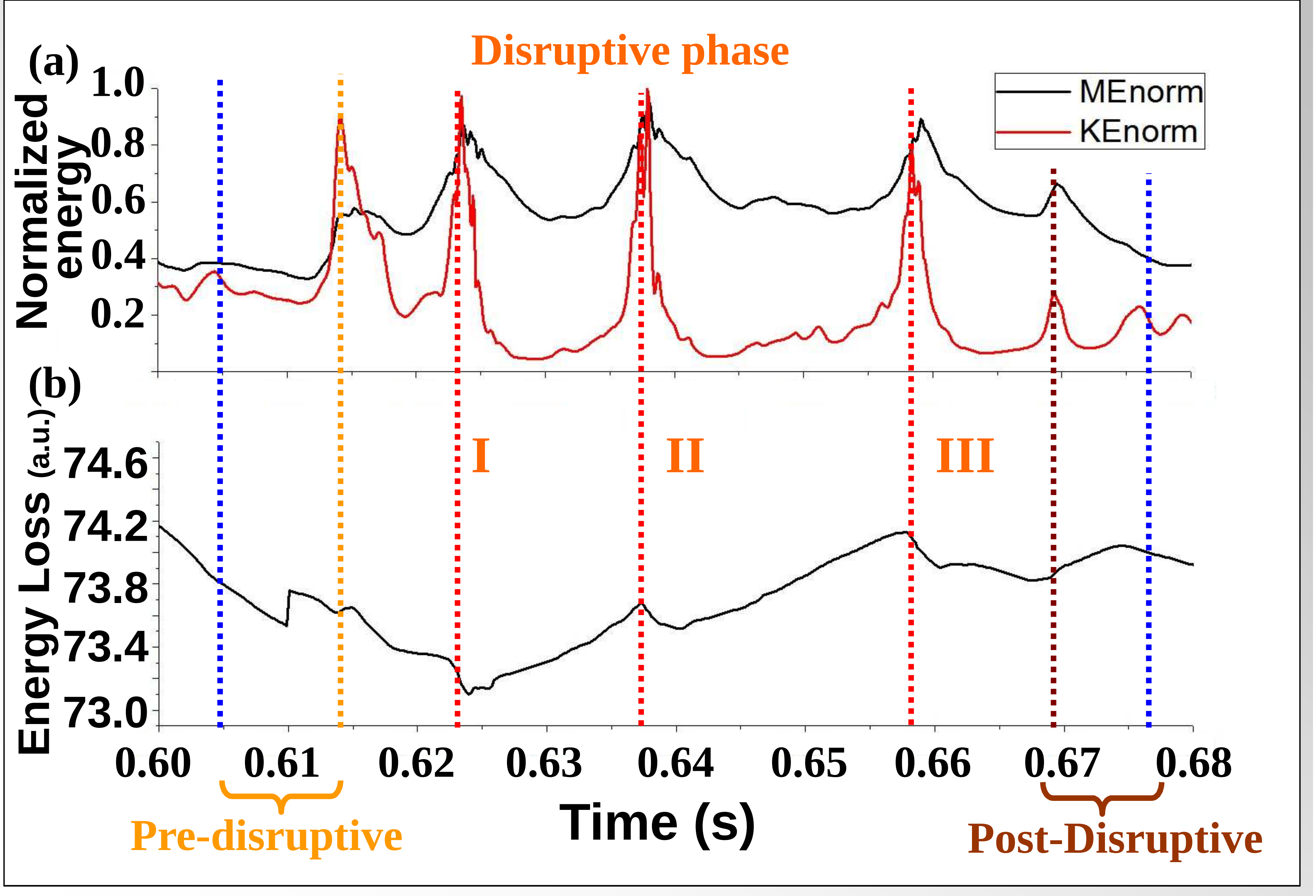
➔ **The magnetic islands size is smaller in high S plasmas.**

➔ **Magnetic islands overlapping is smaller in high S plasmas.**

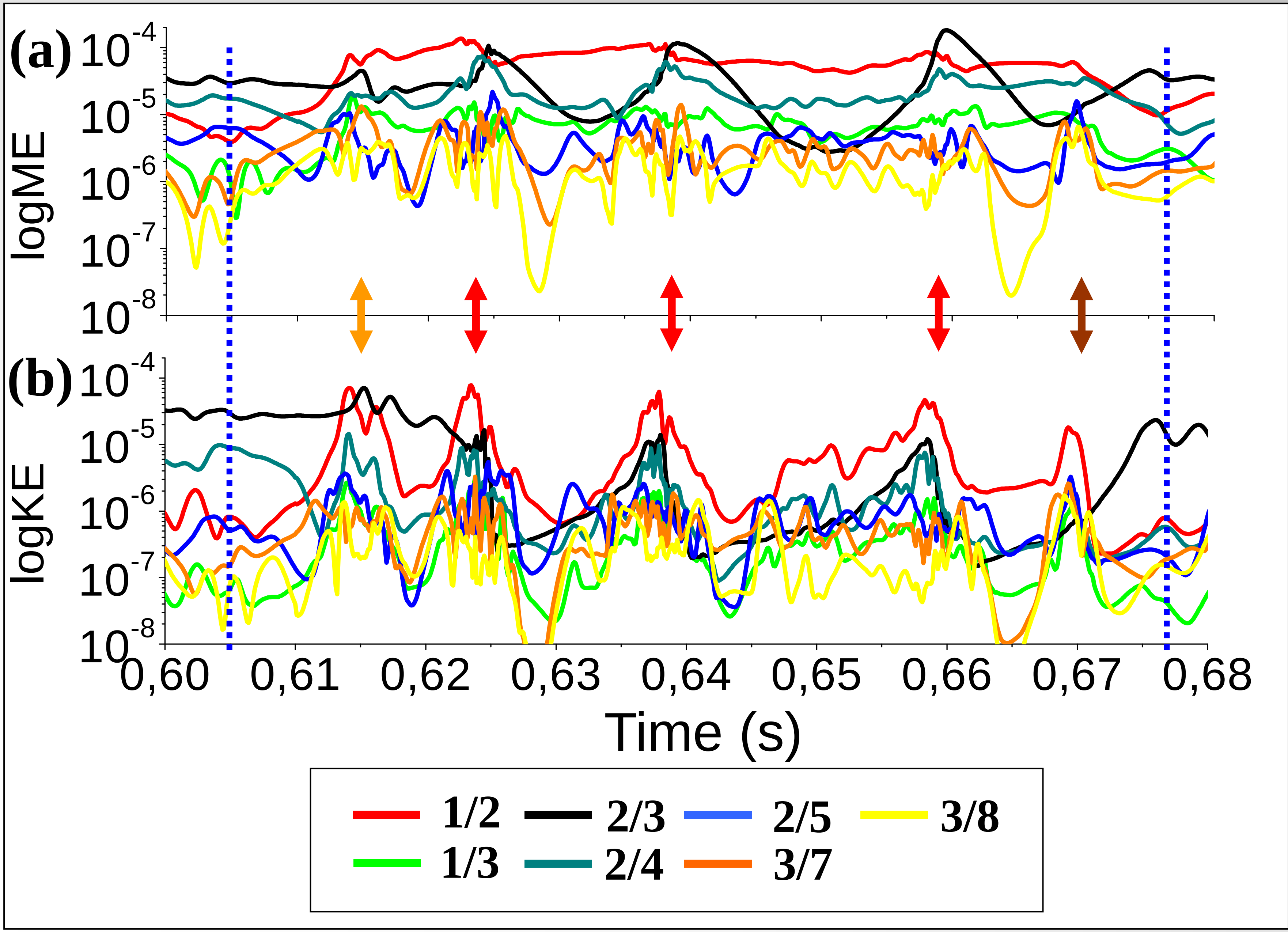
An internal disruption in LHD can be driven in low S operations ?

➔ **Simulation with** $S = 10^5$

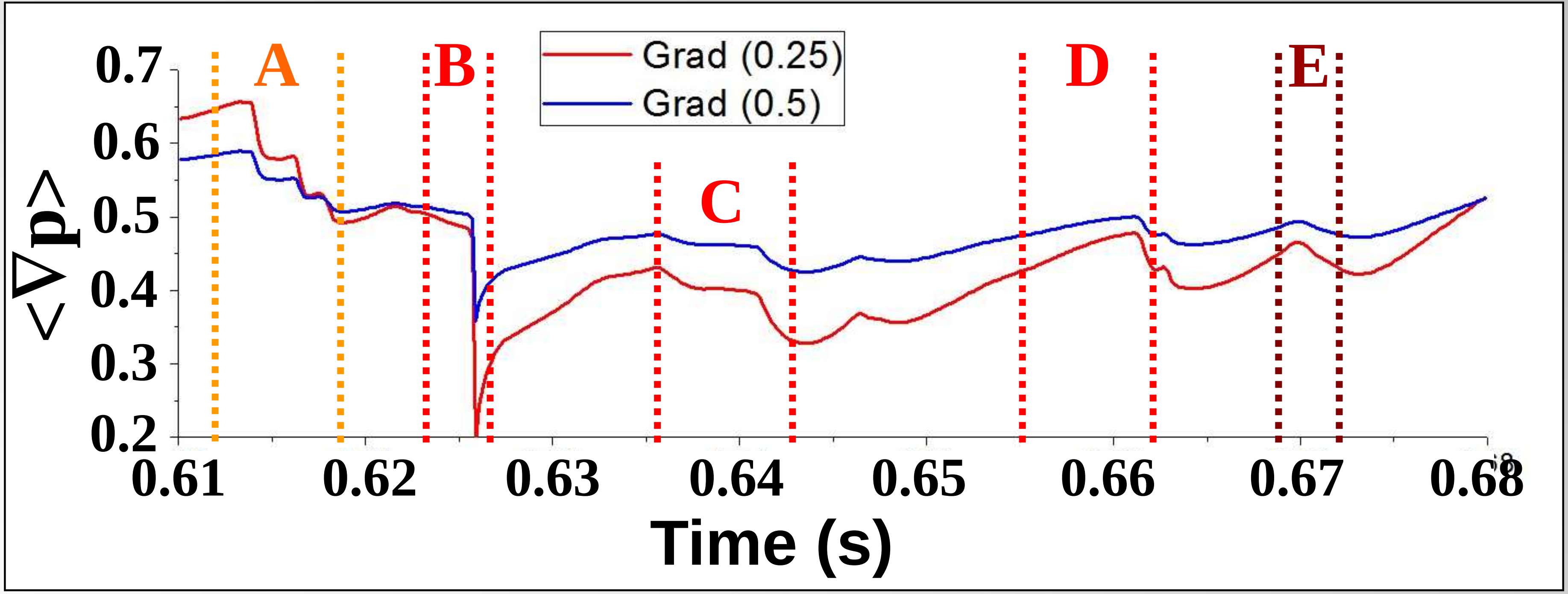
Internal disruption in LHD



Internal disruption



Internal disruption

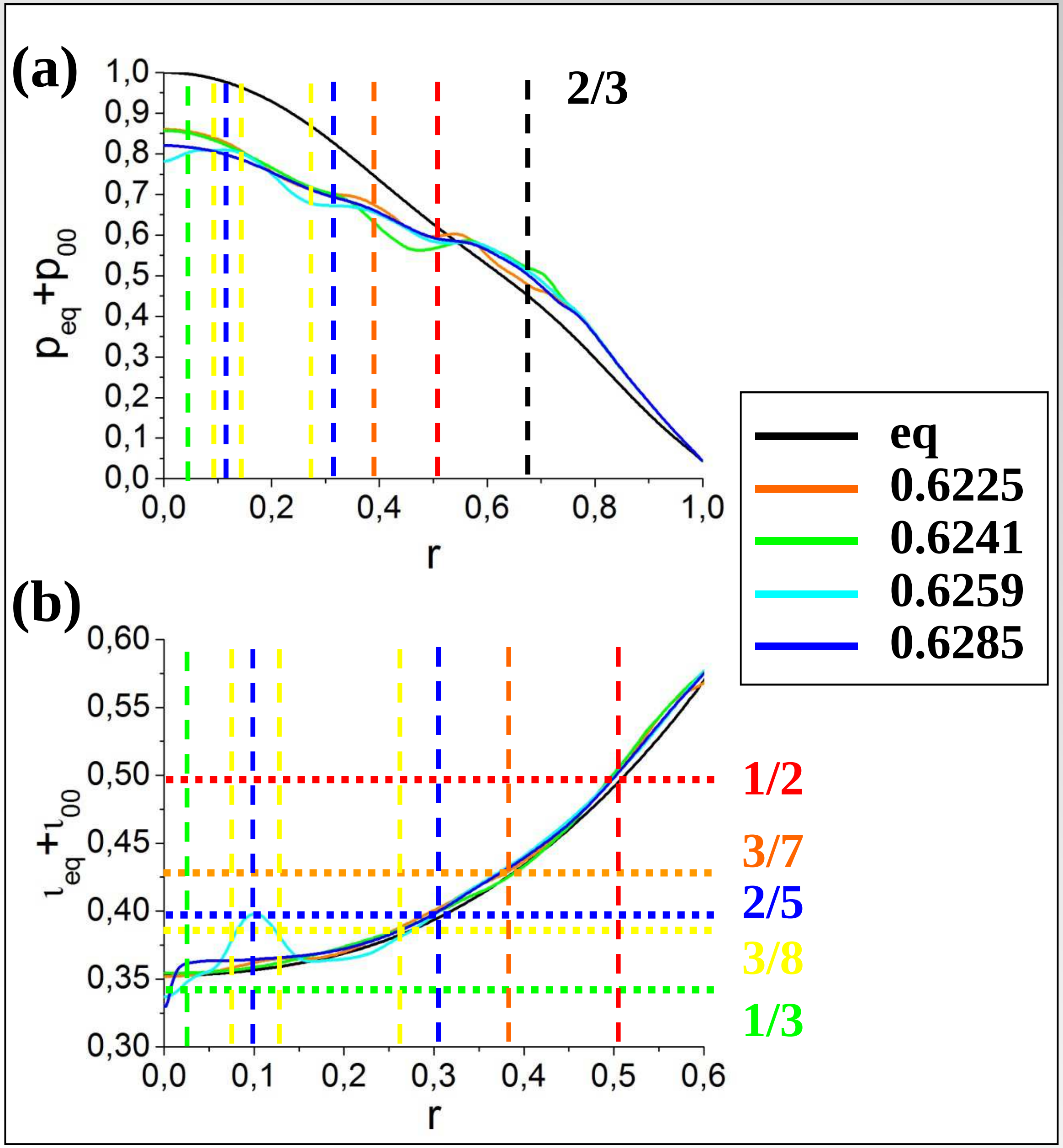


The pressure gradient reaches a critical value during the pre-disruptive phase (A) and a hard MHD instability is driven.

There is an inversion of the pressure gradient between the plasma core and the middle plasma during the disruptive phase (B – D).

After each internal disruption the pressure gradient drops. The pressure gradient inversion ends during the post-disruptive phase, and the soft MHD limit is recovered.

Internal disruption



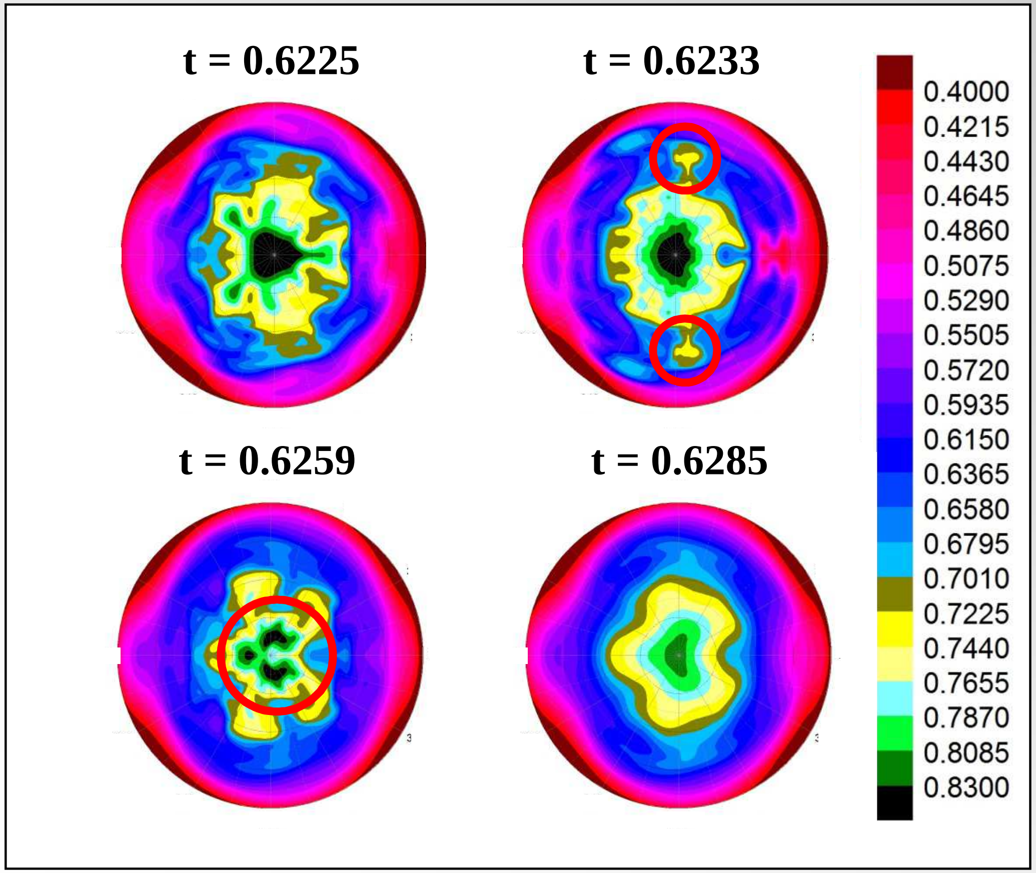
Strong deformation of the pressure profile in the middle plasma region driven by the mode 1/2, with a profile inversion, t = 0.6241 s.

New profile flattening appears in the inner plasmas around the rational surfaces 2/5, 3/7 and 3/8 , t = 0.6259 s.

The iota profile is deformed in the plasma core and it falls below ι = 1/3, t = 0.6259 s.

Pressure profile inversion near the magnetic axis driven by the mode 1/3.

Internal disruption

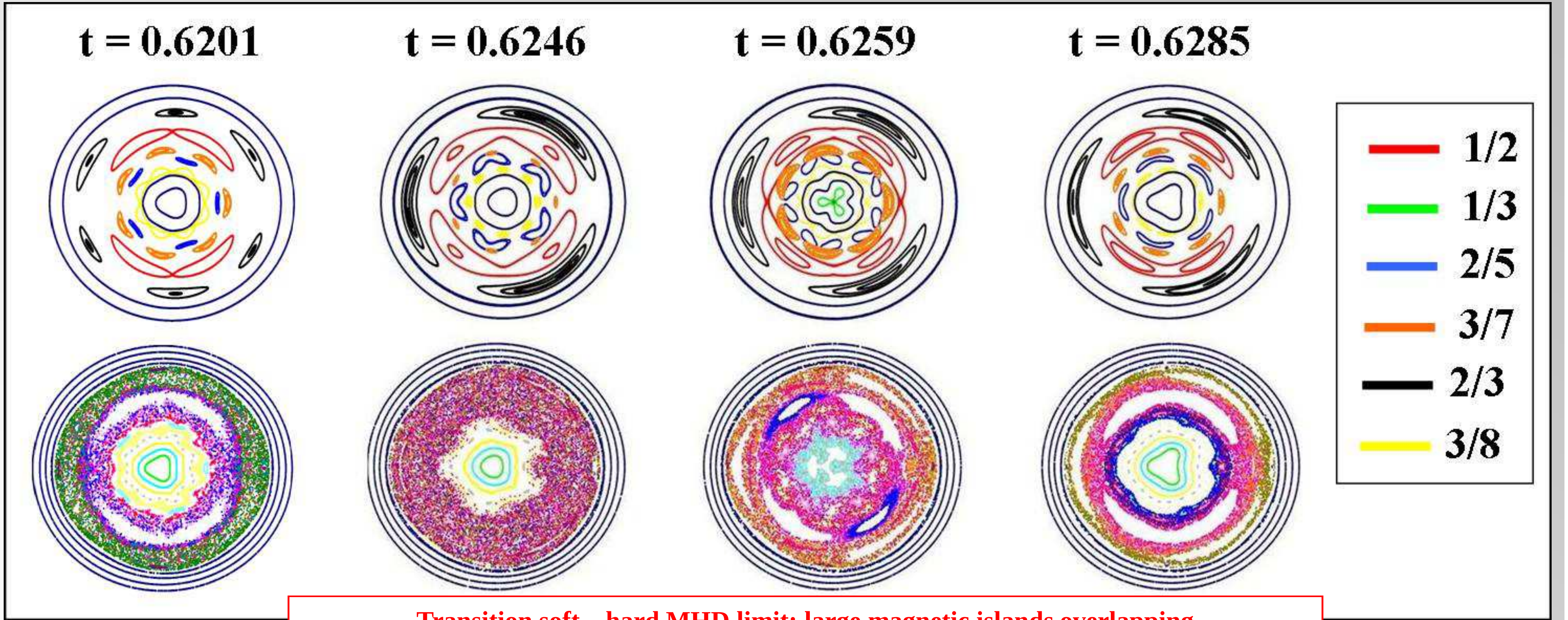


The flux surfaces in the middle plasma are perturbed by the destabilizing effect of the 1/2 mode, t = 0.6225 s.

The instability is strong enough to tear the flux surfaces (red circles). The plasma is expelled to the periphery, t = 0.6233 s.

The instability reaches the inner plasma and the flux surfaces are strongly deformed. The flux surfaces break down in the plasma core and three islands appear near the magnetic axis.

Internal disruption



Transition soft – hard MHD limit: large magnetic islands overlapping

Before the onset of the internal disruptions, t = 0.6201 s, the magnetic islands overlapping is weak.

The internal disruptions are driven when the magnetic islands overlap, t = 0.6246 s, and a large stochastic region appears between the middle plasma and the periphery.

The instability reaches the plasma core and the 1/3 islands appear near the magnetic axis, t = 0.6259 s.

J. Varela et al, Phys. Plasmas 19, 082512 2012

Summary and conclusions

- **Outward configurations:**
  - The helicoidal ballooning modes are driven.
  - Unfavorable magnetic field line curvature.
  - Hard MHD limit: Core Density Collapse.
- **Inward configurations:**
  - Interchange (toroidal ballooning modes) are unstable.
  - Soft MHD limit: non resonant 1/3 and ½ sawtooth-like events.
  - Hard MHD limit:
    - Large deformation of the iota profile in the inner plasma: 1/3 resonant sawtooth like events.
    - Mode 1/2 drives a large pressure profile deformation in the middle plasma and the S value is lower than $5*10^5$: internal disruption.

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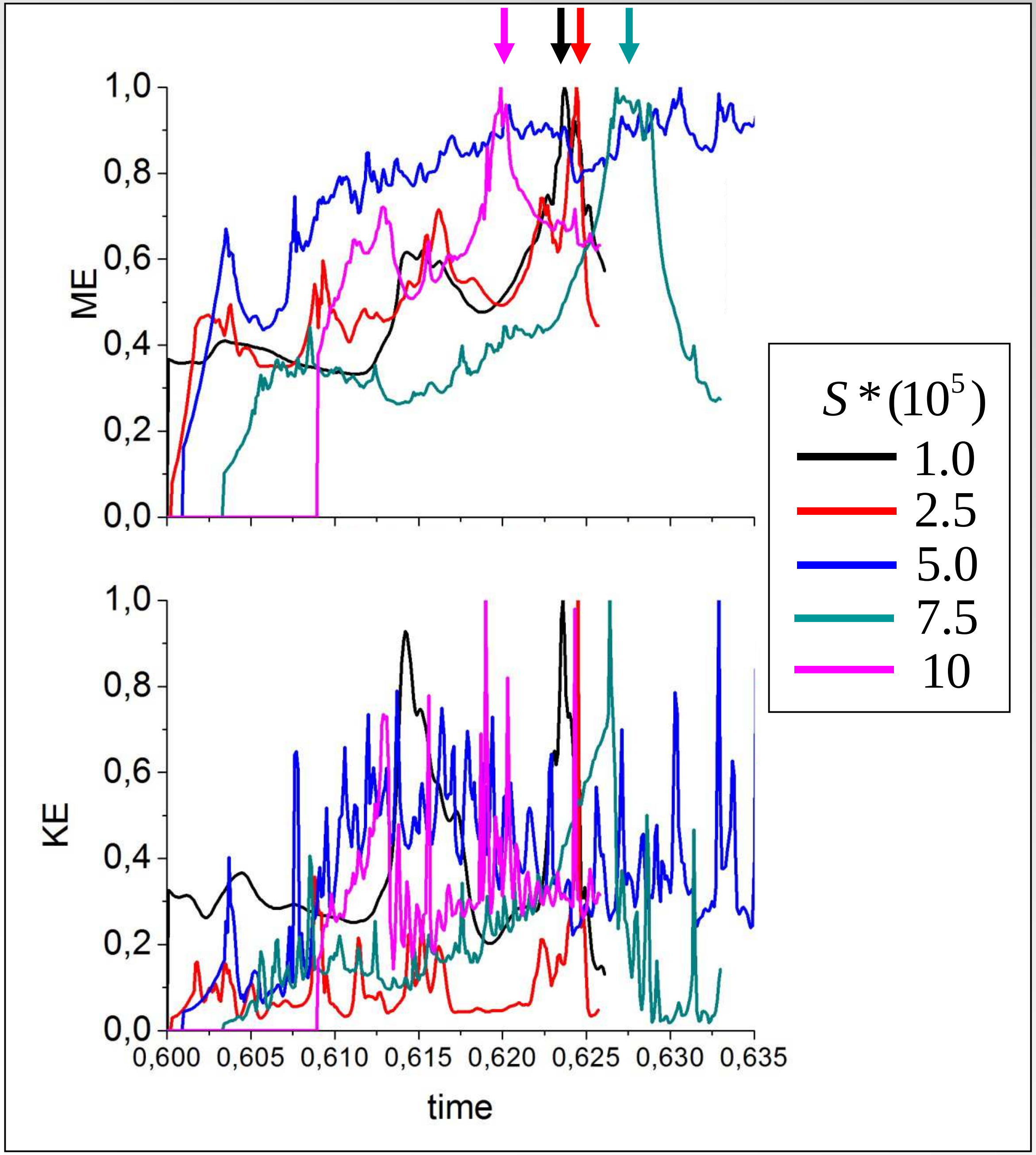
Internal disruptions and the magnetic turbulence



Study an internal disruption increasing the S value.

The magnetic energy peaks show the main events.

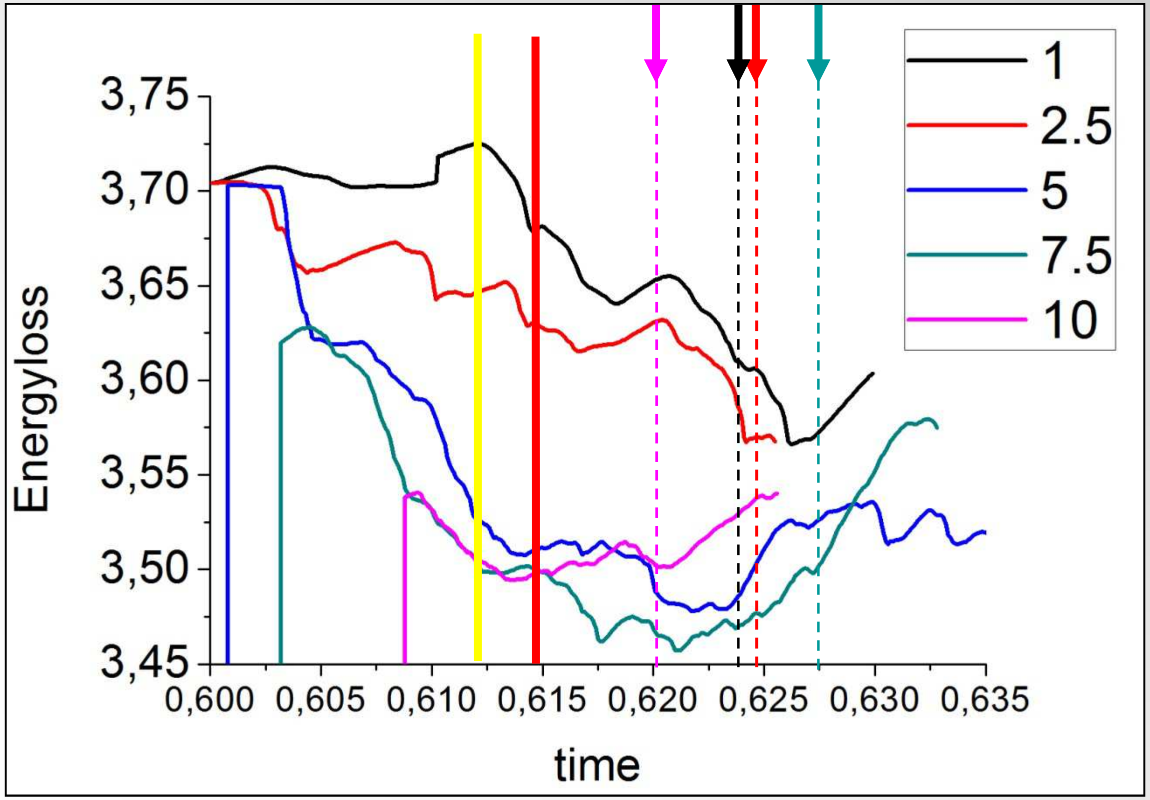
Similar ME evolution for the S = 1.0 and 2.5 cases.

No large ME peak for S = 5.0, MHD limit transition.

ME peak for the S = 7.5 and 10 out-phase with the low S cases.

KE oscillation frequency for the high S cases is higher than in low S cases. In high S cases there are more system relaxation but less energetic.

Internal disruptions and the magnetic turbulence



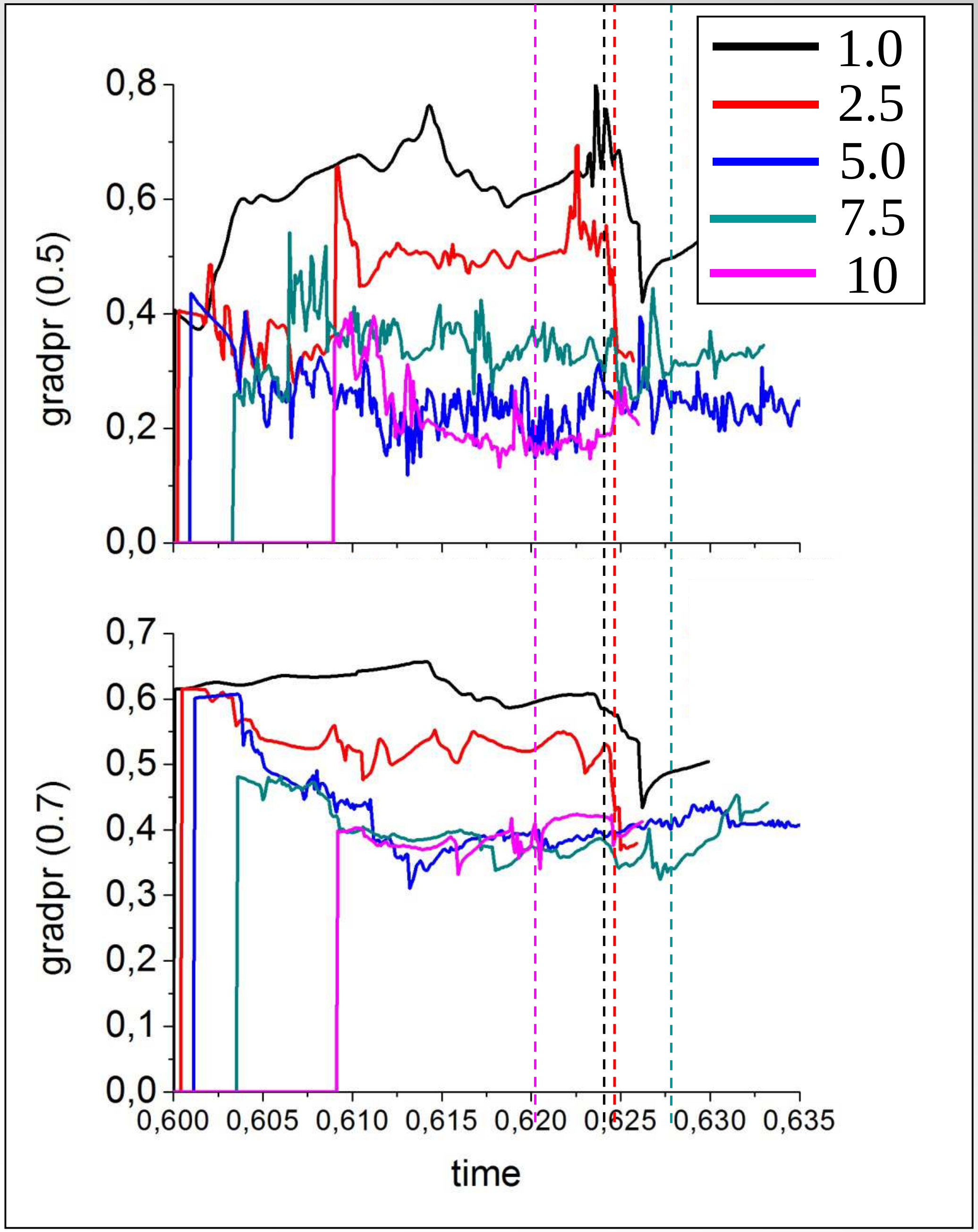
Large energy drops after the run up of the S value. Large overshot. Data analysis from the yellow line. Red lines shows the pre-disruptive phase main event.

Low S cases, large energy drops after the main events.

In the S = 5.0 case the larger energy drops are not correlated with energy peaks in the ME.

In the high S cases there are not energy drops. After the main events the energy profile slope is positive.

Internal disruptions and the magnetic turbulence



Low S cases, peaks of the pressure gradients in the inner plasma region.

High S cases, no large oscillations of the pressure gradient in the inner plasma.

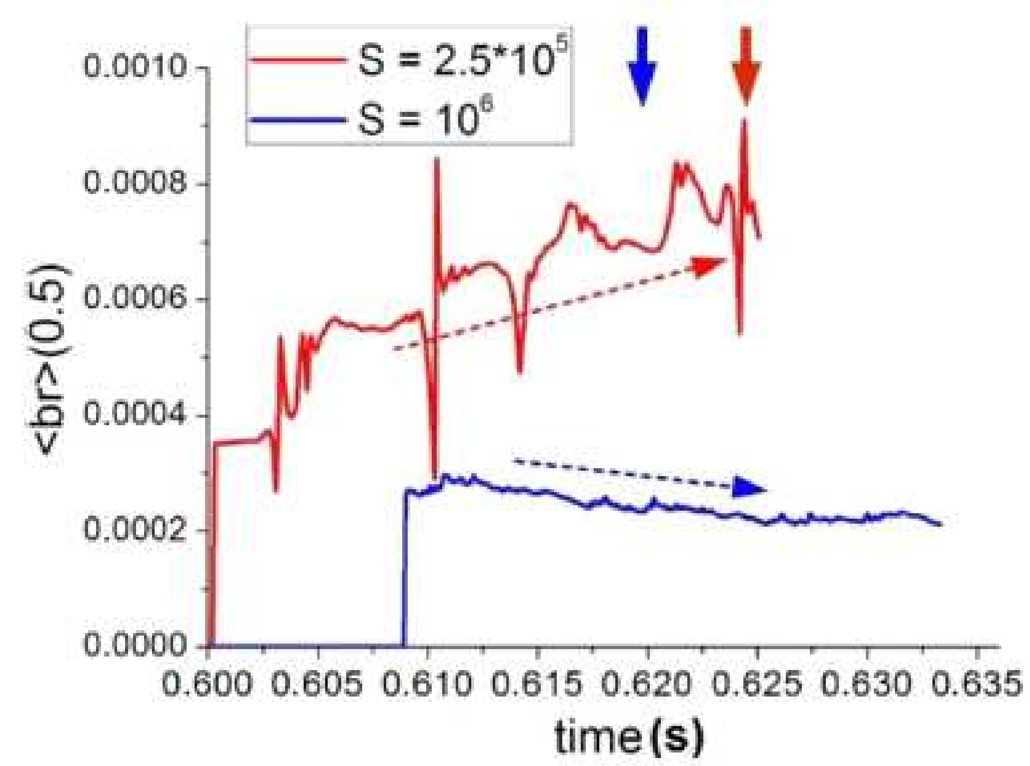
Low S cases, large pressure gradient drops in the middle and outer plasma.

High S cases, pressure gradient oscillations less stronger than in the low S case.

➔ Low S case; instability reaches the inner and outer plasma region

➔ High S case; instability is located between the middle and outer plasma region.

Internal disruptions and the magnetic turbulence



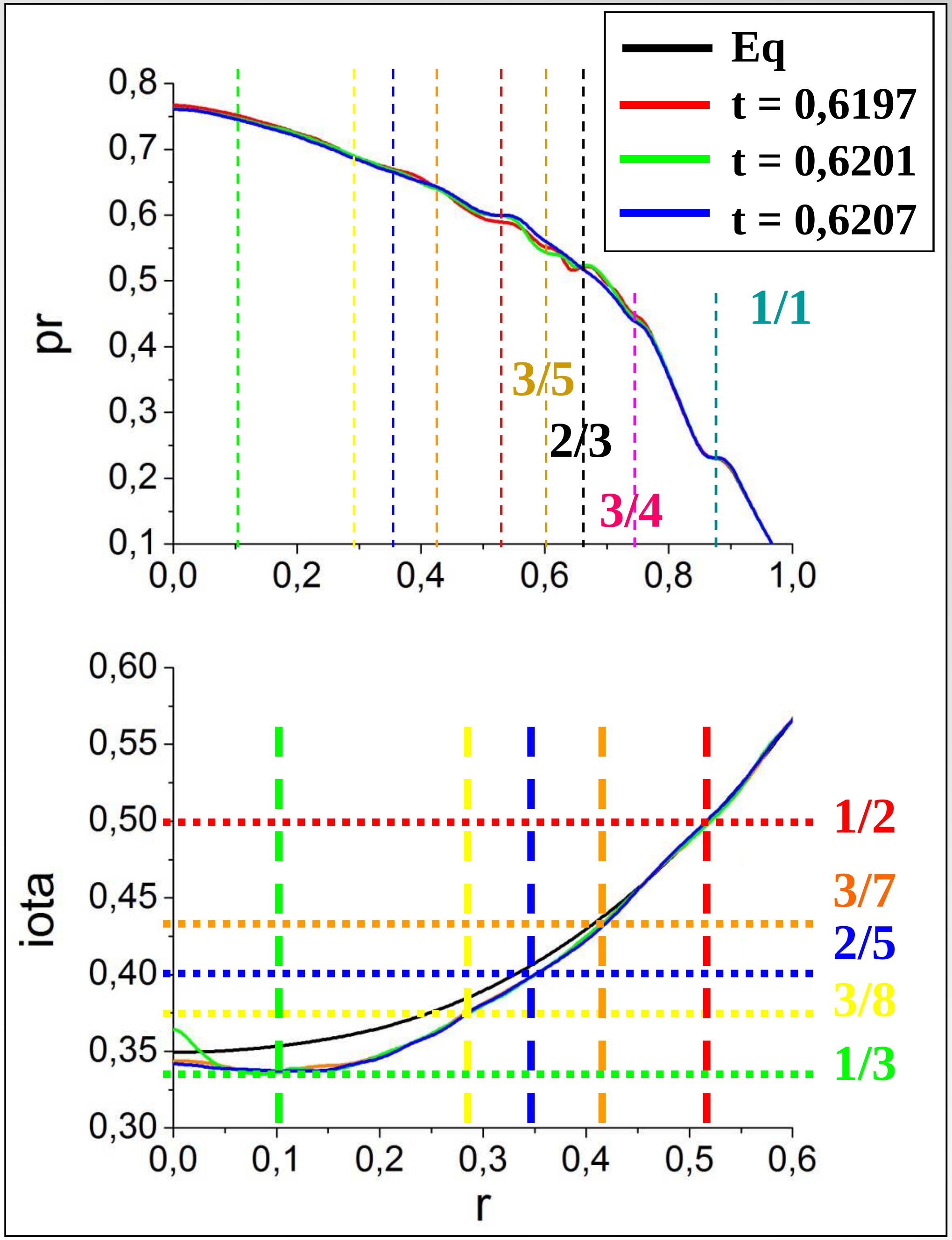
The magnetic turbulence increase along the low S simulation but decreases in the high S simulation.

The magnetic turbulence perturbs the flux and magnetic surfaces enhancing the pressure gradients.

Magnetic island size increase leading to a flux rearrangement that reinforce the turbulence and pressure gradient in a feedback.

The extreme case takes place if there is a large overlapping between magnetic island. The system enters in the hard MHD regime.

Internal disruptions and the magnetic turbulence



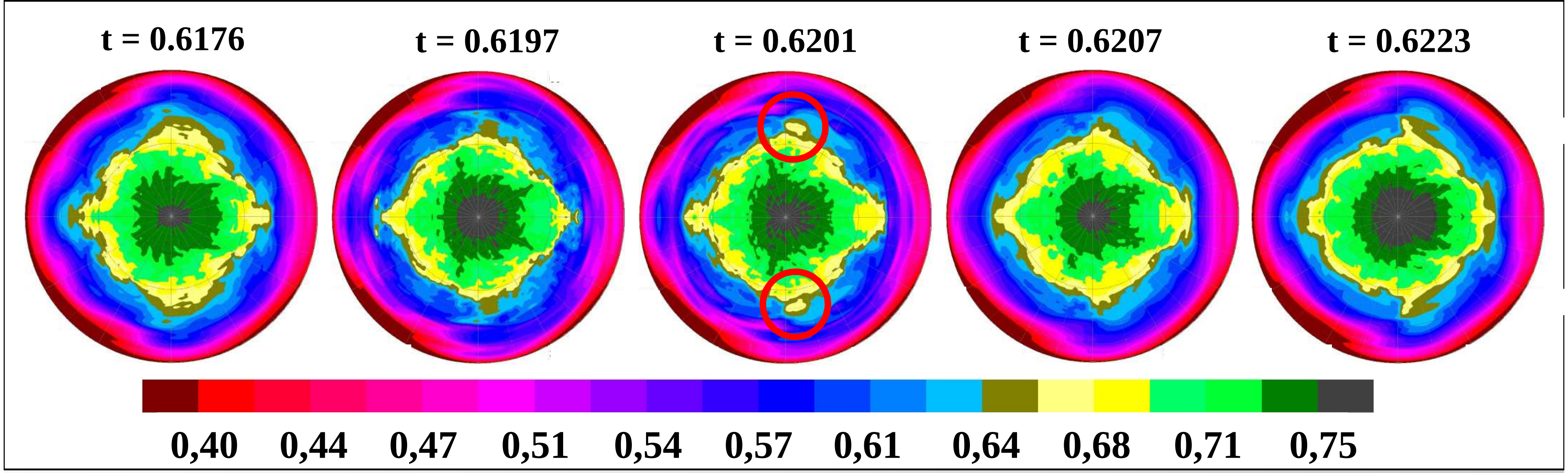
Analysis of the main event in the simulation with S = 10^6.

Mode 1/2 doesn't drive large pressure profile flattening in the middle plasma. No profile inversion.

Several profile flattening driven in the outer plasma region, modes 1/1, 2/3, 3/5 and 3/4.

Iota profile is deformed in the inner plasma, but the mode 1/3 effect is weak near the magnetic axis.

Internal disruptions and the magnetic turbulence



No large flux surface deformation between the middle and inner plasma.

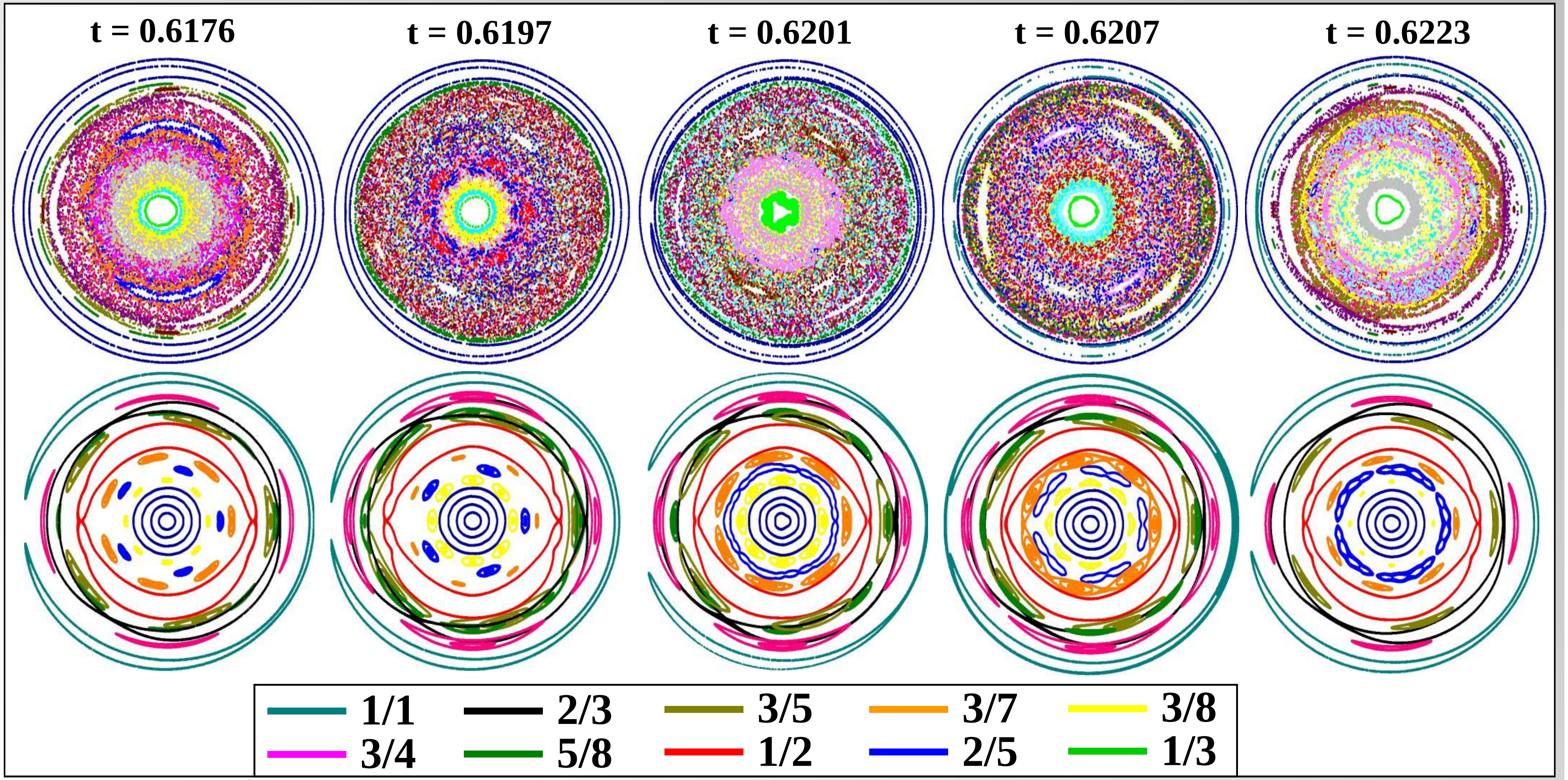
During the main event, t = 0.6197 – 0.6207 s, the flux surface between the middle and outer plasma are deformed.

The flux surfaces are torn between the middle and outer plasma at t = 0.6201 s.

No large flux surface deformation close to the magnetic axis by the mode 1/3 .

J. Varela et al, Phys. Plasmas 21, 092505, 2014

Internal disruptions and the magnetic turbulence



Why the internal disruptions are not driven in LHD device?. Feedback effect between the magnetic turbulence and the pressure gradients