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Non-resonant global mode in LHD partial collapse with net toroidal current

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Abstract

- A transition from an interchange mode to a non-resonant mode is found in the nonlinear MHD simulation for an LHD plasma with net toroidal current.
- This transition can occur when the magnetic shear is weak and the rotational transform is close to unity in the core region.
- In this transition, the mode number of the dominant Fourier component is reduced.
- In the case where the difference in the kinetic energy between the largest two components is small, the (m,n)=(1,1) component can be dominant, which qualitatively agrees with the LHD experiment.

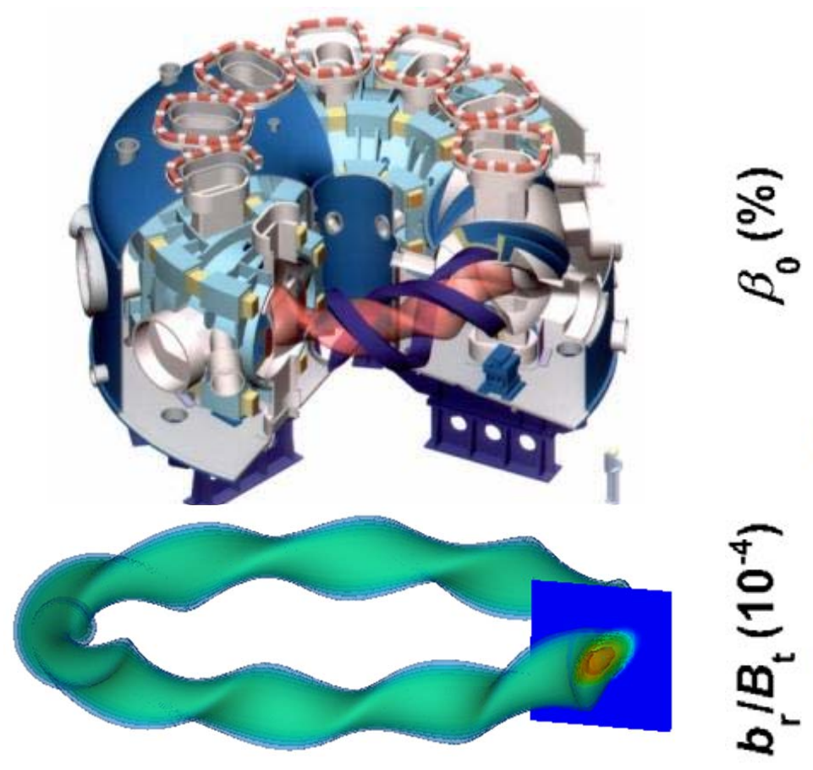
Background

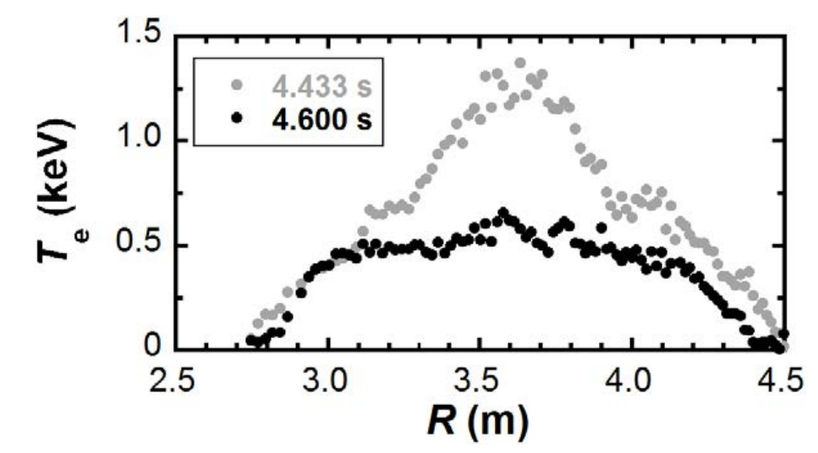
● Observation of partial collapse in LHD experiments

- The net toroidal current is increased and reaches a certain value, a partial collapse is observed.
- The partial collapses are ALWAYS caused by (m,n))=(1,1) mode.

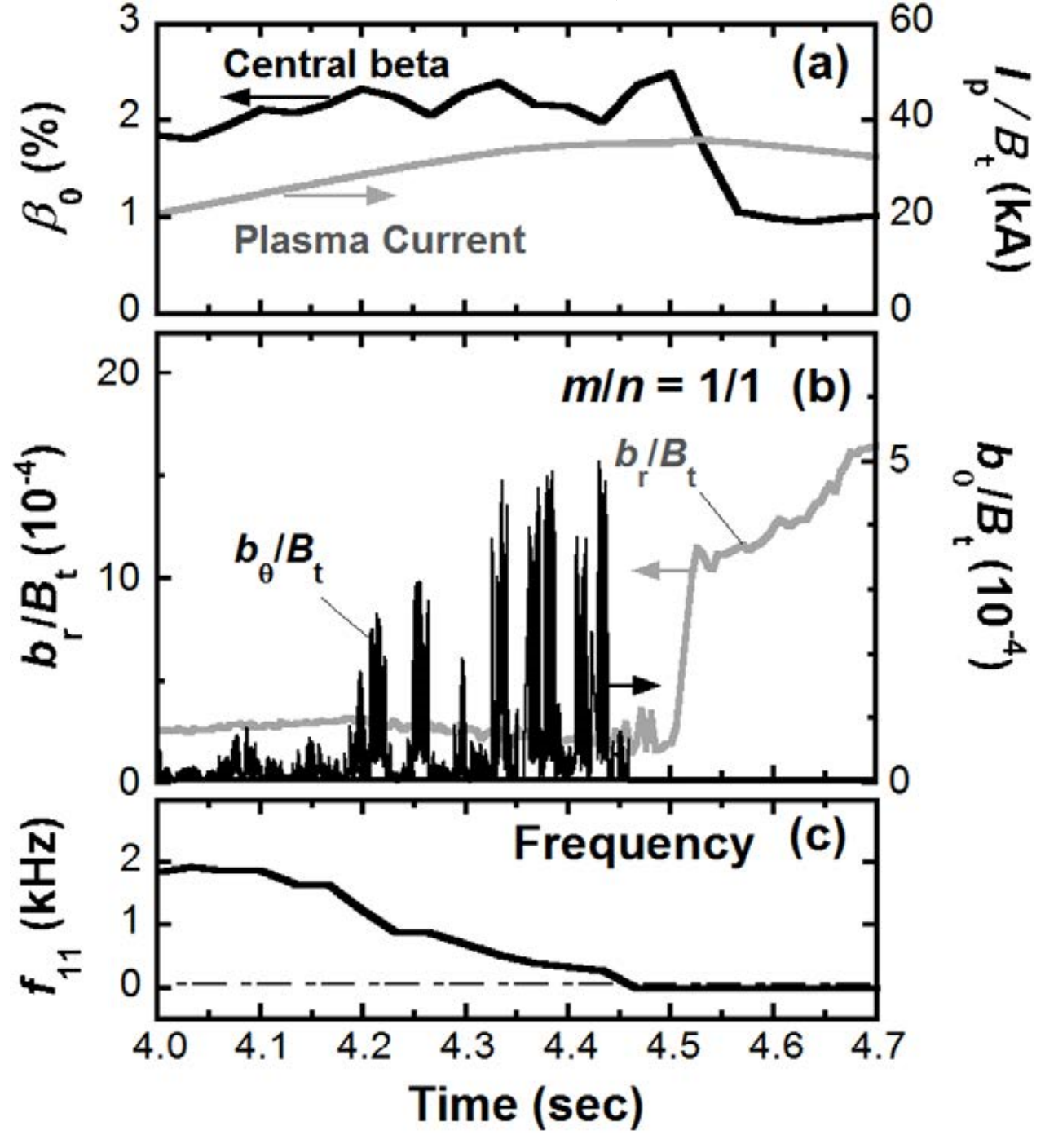
⇕ MYSTERY

- Theory for pressure driven modes: The linear growth rate is larger for higher mode numbers for pressure driven modes.





Sakakibara et al.,NF 2015



Numerical Method

● 3D equilibrium calculation : HINT code

- The HINT code (Y. Suzuki et al., NF (2006) calculates 3D equilibria without any assumption of the existence of nested flux surfaces by iterating 2 steps.

1st step : $\boldsymbol{B}\cdot\nabla P = 0$

2nd step:

$$\left\{\begin{aligned}\frac{\partial \boldsymbol{v}}{\partial t} &= -\nabla P + \boldsymbol{J}\times\boldsymbol{B} + \nu\nabla^2\boldsymbol{v}\\ \frac{\partial \boldsymbol{B}}{\partial t} &= \nabla\times(\boldsymbol{v}\times\boldsymbol{B} - \eta\boldsymbol{J})\end{aligned}\right.$$

● 3D stability analysis : MIPS code

- The MIPS code (Todo et al., PFR2010) solves the full MHD equations. The 4th order finite difference and 4th order Runge-Kutta method are employed.

$$\frac{\partial \rho}{\partial t} = -\nabla\cdot(\rho\boldsymbol{v})$$

$$\rho\frac{\partial \boldsymbol{v}}{\partial t} = -\rho\boldsymbol{w}\times\boldsymbol{v} - \rho\nabla\frac{v^2}{2} - \nabla P + \boldsymbol{J}\times\boldsymbol{B} + \frac{4}{3}\nabla[\nu\rho\nabla\cdot\boldsymbol{v}] - \nabla\times(\nu\rho\boldsymbol{w})$$

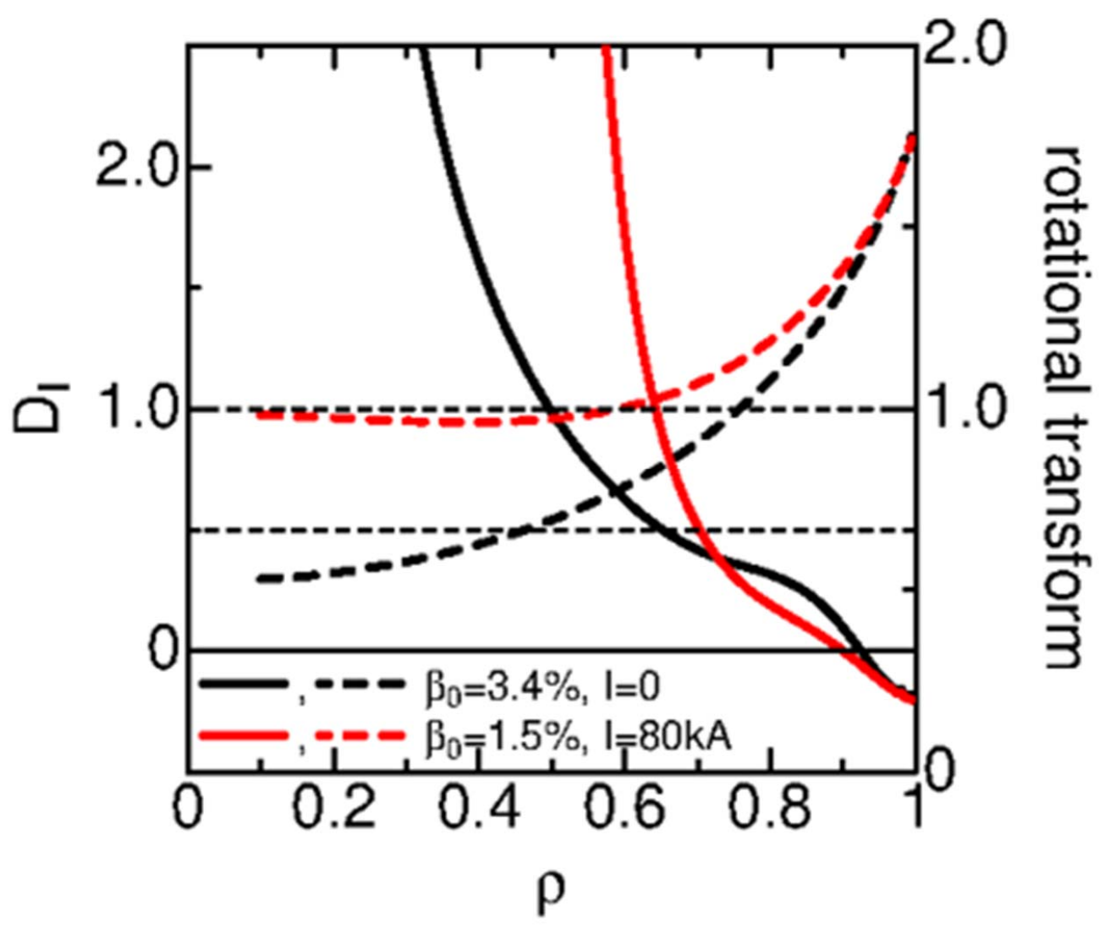
$$\frac{\partial P}{\partial t} = -\nabla\cdot(P\boldsymbol{v}) - (\Gamma-1)P\nabla\cdot\boldsymbol{v} + \chi_\perp\nabla_\perp^2 P + \chi_\parallel\nabla_\parallel^2 P$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times\boldsymbol{E}$$

$$\boldsymbol{J} = \frac{1}{\mu_0}\nabla\times\boldsymbol{B}, \quad \boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta(\boldsymbol{J}-\boldsymbol{J}_{eq}), \quad \boldsymbol{w} = \nabla\times\boldsymbol{v}$$

● Simulation conditions

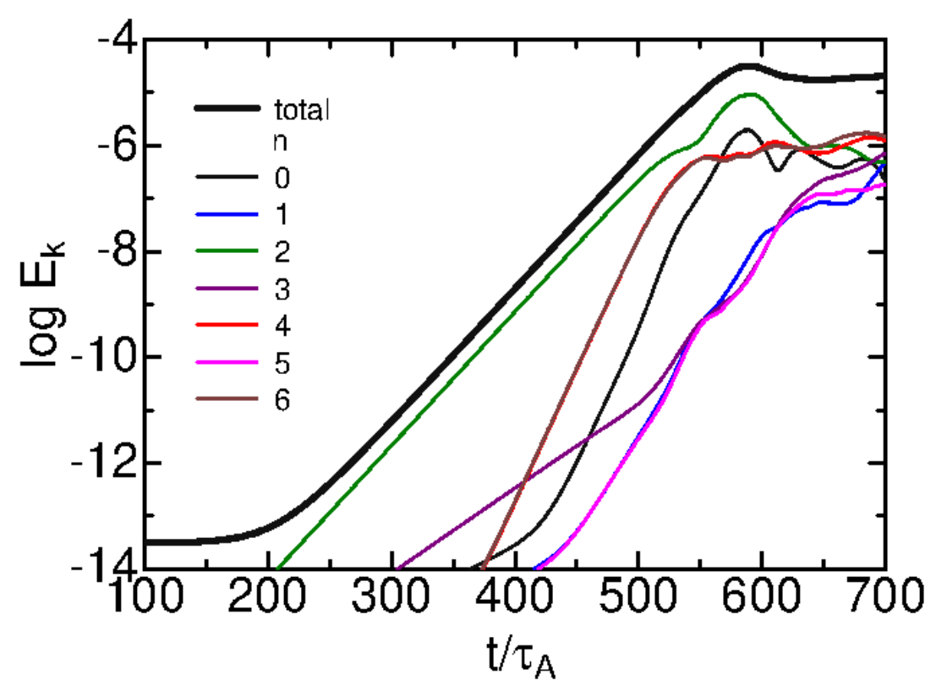
- Magnetic configuration : LHD, $\gamma_c = 1.1739,\ R_{ax} = 3.6\mathrm{m}$ (same as the above experiment)
- Equilibrium pressure profile : $P_{eq} = P_0(1-0.68\rho^2-0.32\rho^4)$
- Dissipation parameters : $S = 5.6\times10^6,\ \ \nu = \chi_\perp = 2.5\mathrm{m}^2/\mathrm{sec},\ \ \chi_\parallel = 10^3\chi_\perp$
- Equilibria with 2 kinds of net current
  Without net toroidal current case (reference) :
  $I = 0,\ \beta_0 = 3.4\%$ (higher than experiment)
  => high shear
  With net toroidal current case
  $I = 80\mathrm{kA}$ for $B_0 = 3\mathrm{T},\ \beta_0 = 1.5\%$ $\quad J_{eq} = J_0(1-\rho^2)^4$
  => weak shear

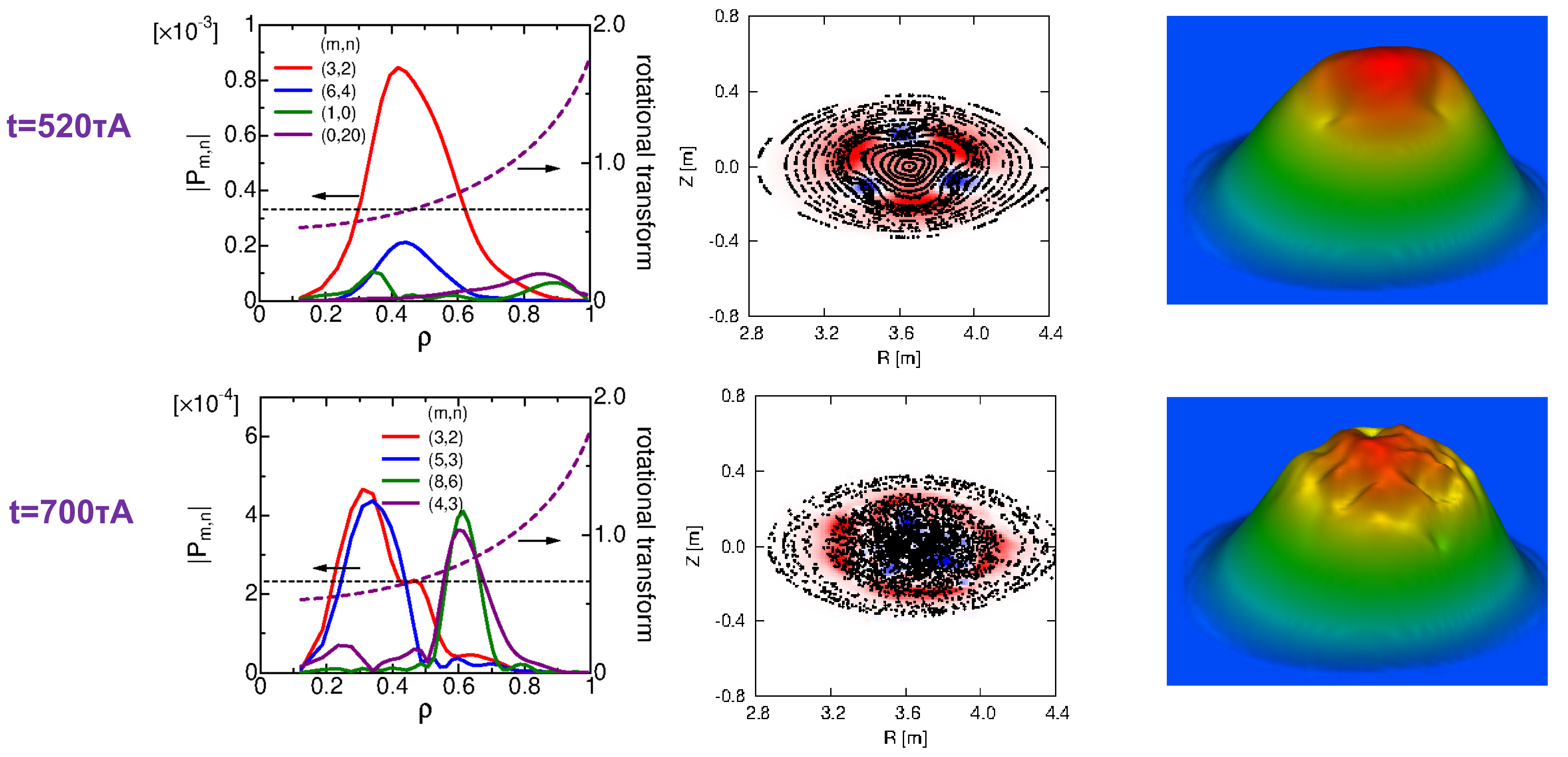


Dynamics of LHD plasma without net toroidal current

● Monotonic rotational transform with high shear

- At t=520τA (early nonlinear phase) :
  (3,2) component is localized at the resonant surface.
  Typical interchange mode.
- At t=700τA (further nonlinear phase) :
  Many side bands appear and make the pressure structure complicated.
  Not the case of the experiment.


Time evolution of kinetic energy


Fourier components of pressure perturbation

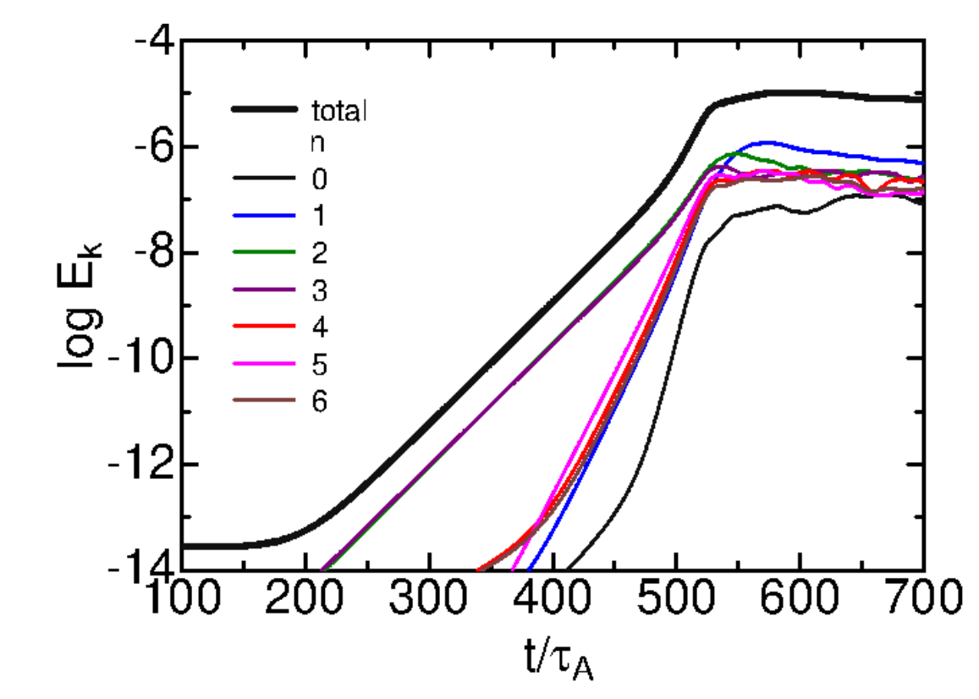
Puncture plots & pressure perturbation

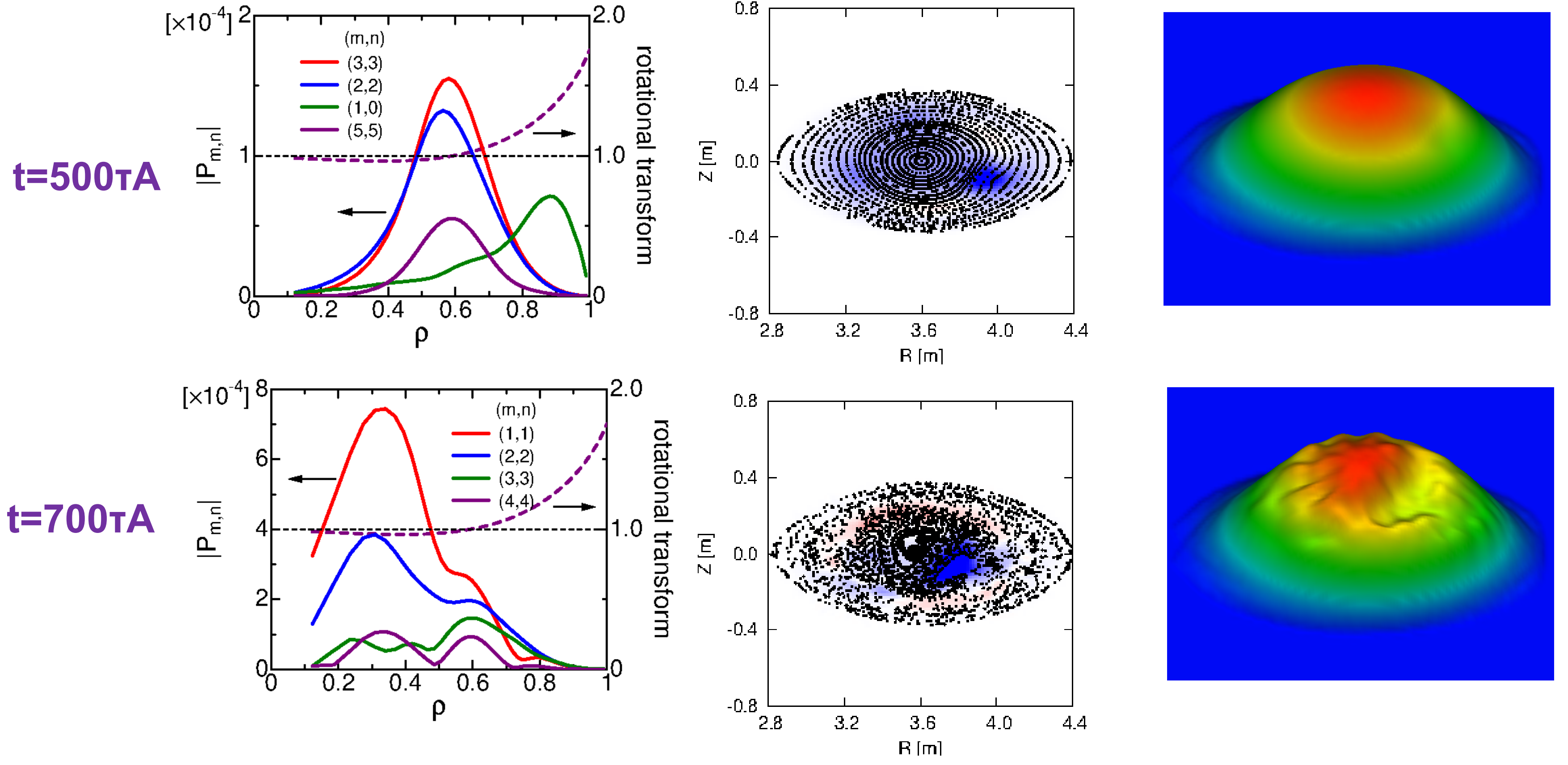
Total pressure

Dynamics of LHD plasma with net toroidal current

● Close dominant components case (1st choice of initial random numbers) : a transition to (1,1) mode

- At t=450τA (linear phase) :
  The n=2 and n=3 components have the largest Ek.
  Ek(n=2) / Ek(n=3) = 1.12 (very close)
- At t=500τA (early nonlinear phase) :
  The (3,3) and (2,2) are localized at the resonant surface.
  typical interchange mode
- At t=700τA (further nonlinear phase) :
  The non-resonant (1,1) becomes dominant at low shear region through the nonlinear coupling.
  The m=1 structure is kept for long duration after the transition.


Time evolution of kinetic energy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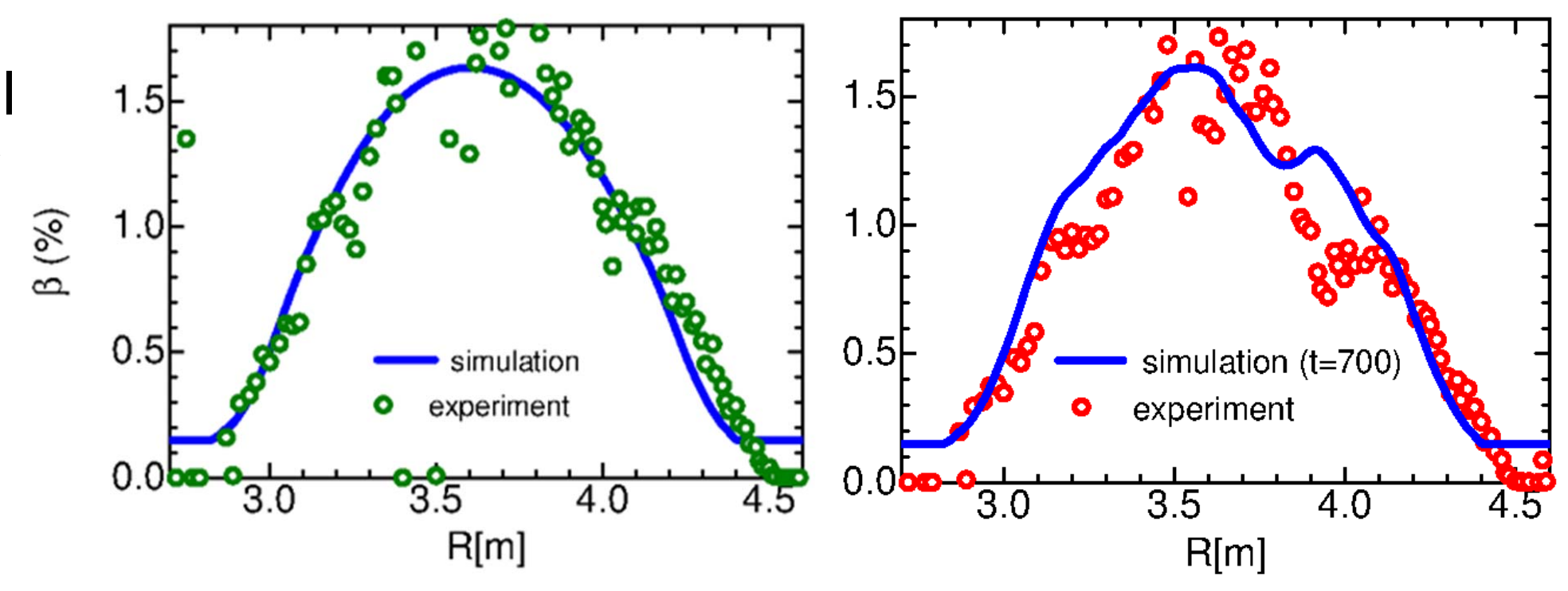
- Comparison of pressure with experimental data

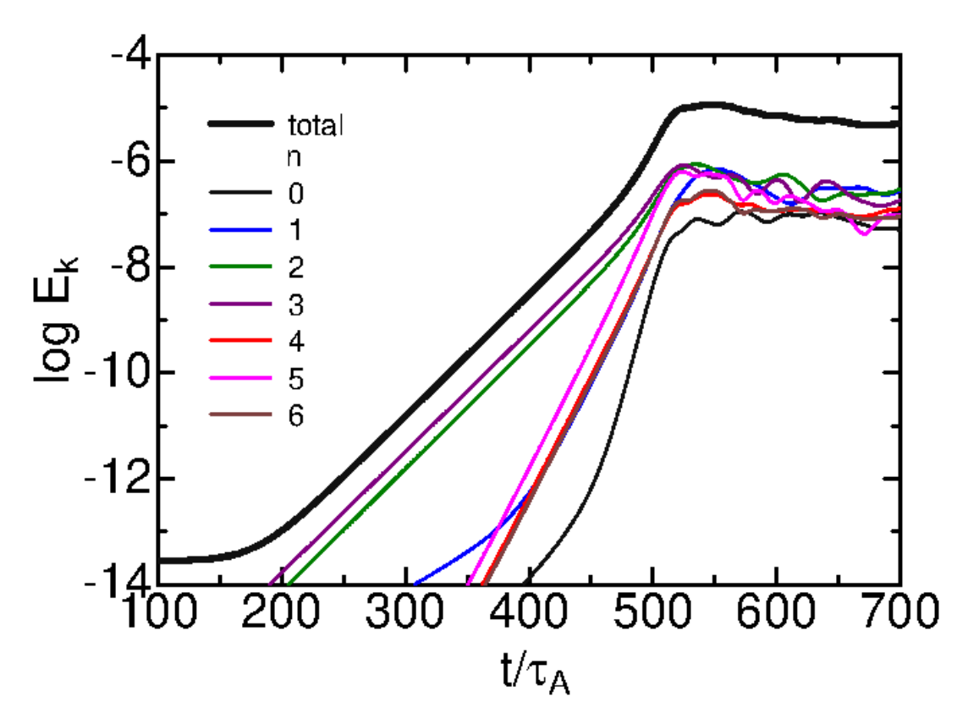
[left]
➢ The equilibrium pressure approximates well the experimental data in the almost steady beta region.

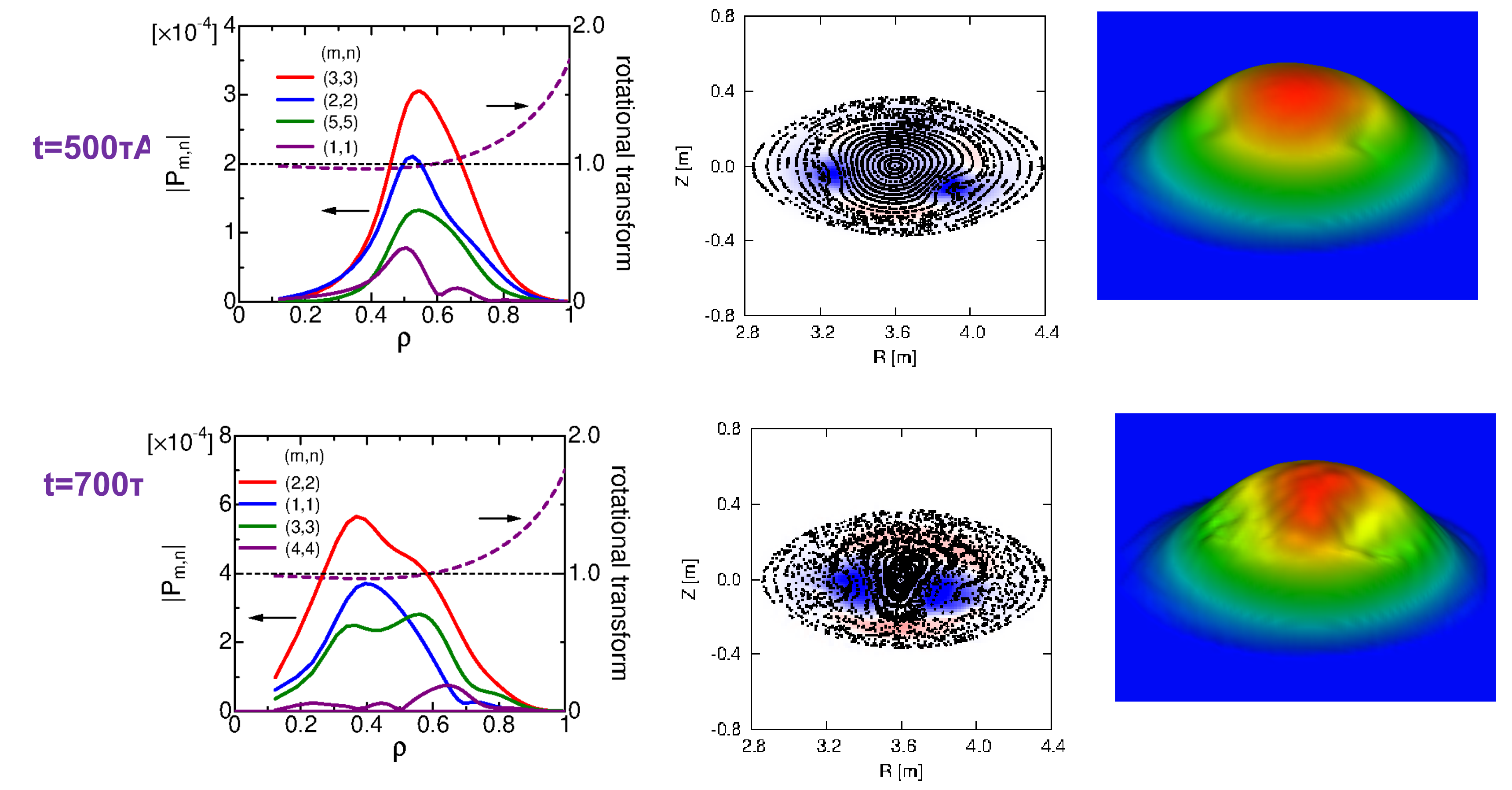
[right]
➢ Qualitative agreement is obtained with the profile just before the collapse in the experiment. (collapse form one direction)



● Spaced dominant components case (2nd choice of initial random numbers) : a transition to (2,2) mode

- At t=450τA (linear phase) :
  The n=3 component is clearly dominant. in Ek.
  Ek(n=3)/Ek(n=2) = 1.82 (spaced)
- At t=500τA (early nonlinear phase) :
  The (3,3) is localized at the resonant surface.
  typical interchange mode
- At t=700τA (further nonlinear phase) :
  The non-resonant (2,2) becomes dominant at low shear region.


Time evolution of kinetic energy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Total pressure

Concluding Remarks

- A transition from the interchange mode resonant the ι/2π=1 surface to a non-resonant mode in the nonlinear phase is obtained.
- This transition occurs in the equilibrium where the shear is weak and the rotational transform is close to unity.
- The mode number of the dominant component after the transition depends on the relation of the two dominant components in the linear phase.
- In the close dominant components case, the (1,1) component becomes dominant, which is considered one of the candidates of the (1,1) collapse observed in the experiments.
- In the spaced dominant components case, the (2,2) component becomes dominant.
- It is necessary to introduce additional physics such as background global flow and kinetic ion effects for the investigation of the mechanism for the robust (1,1) component observation in the LHD experiments.