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# 負磁気シアトカマクプラズマにおける抵抗性壁モードの回転による不安定化

## Destabilization of resistive wall mode by rotation in negative shear tokamak plasmas

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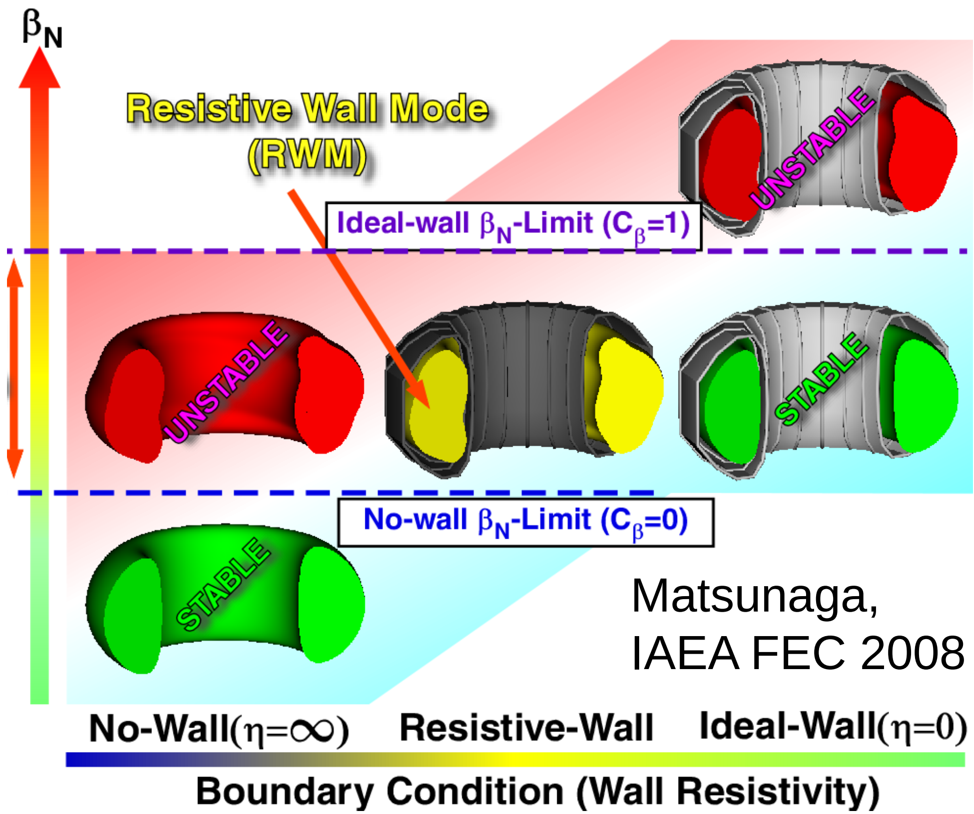
# MHD modes in high-$\beta$ tokamaks

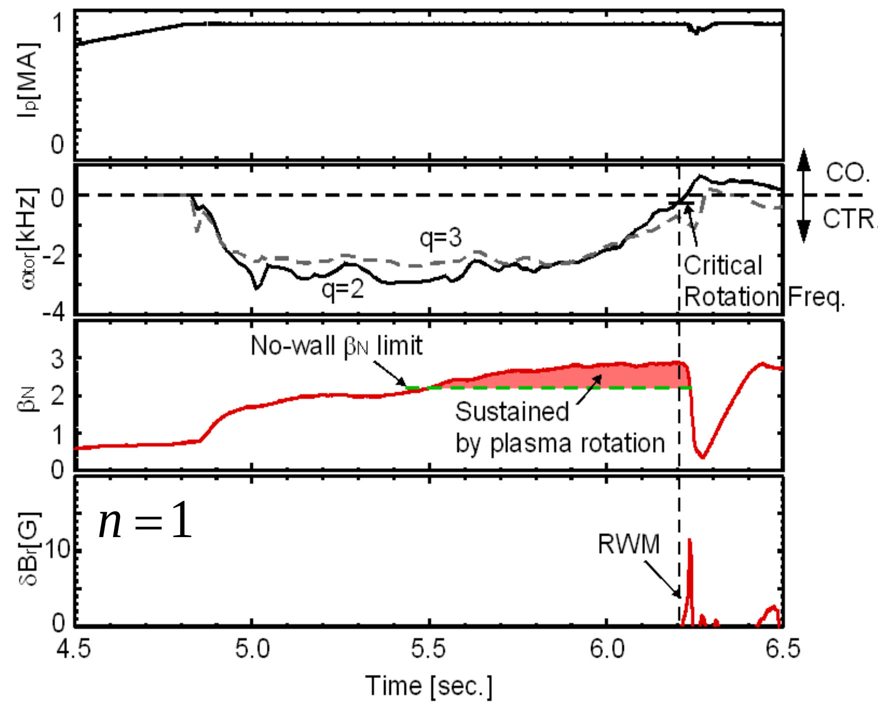
- For realizing economical fusion reactor, it is important to develop a MHD equilibrium with high-$\beta$; $\beta$ is the ratio between plasma pressure and magnetic pressure.
  In such a high-$\beta$ equilibrium, MHD modes sometimes become unstable, and a long wavelength mode induces "disruption".
- Such a MHD mode is usually stabilized by surrounding the plasma with conducting wall.
- However, if the conducting wall has resistivity, so-called resistive wall mode (RWM) becomes unstable.
  => disruption



# Rotation is responsible for RWM stability

- About 20 years ago, theoretical papers identified that RWM can be stabilized by plasma toroidal rotation [Bondeson, PoP. 1994 etc.].
- However, prediction of threshold rotation frequency for stabilizing RWM is still under discussion.
- Recent hot topic is the importance of non-ideal MHD effects on RWM.
- Question :
  Even with ideal MHD model, does plasma rotation always stabilize RWM?

➡ The answer is NO!




RWM experimental results in JT-60U

# Basic equations solved numerically

The ideal MHD stability code, MINERVA[Aiba, CPC 2009] solves the Frieman-Rotenberg equation [Frieman, RMP 1960].

$$\rho \frac{\partial^2 \xi}{\partial t^2} + 2\rho(\mathbf{u}\cdot\nabla)\frac{\partial \xi}{\partial t} = \mathbf{F}(\xi),$$

$$\mathbf{F}(\xi) = \mathbf{F}_s(\xi) + \nabla\otimes[\rho\xi\otimes(\mathbf{u}\cdot\nabla)\mathbf{u} - \rho\mathbf{u}\otimes(\mathbf{u}\cdot\nabla)\xi] = \mathbf{F}_s(\xi) + \mathbf{F}_d(\xi),$$

$\mathbf{F}_s$ : Force operator (same vector form as that in static equilibrium case)

$\mathbf{u}$ : Equilibrium rotation velocity

To identify RWM stability in tokamak plasmas, RWMaC [Shiraishi, IAEA FEC 2012] is implemented to MINERVA.
Quadratic form for identifying RWM stability with rotation

$$\underbrace{\left\langle \xi \middle| \rho \frac{\partial^2 \xi}{\partial t^2} \right\rangle + 2\langle \xi | \rho(\boldsymbol{u}\cdot\nabla)\frac{\partial \xi}{\partial t} - \langle \xi | \boldsymbol{F}(\xi)\rangle}_{\text{MINERVA}} + \underbrace{\delta W_V - \frac{\tau_{A0}}{\tau_w}\frac{\partial D_w}{\partial t}}_{\text{RWMaC}} = 0$$

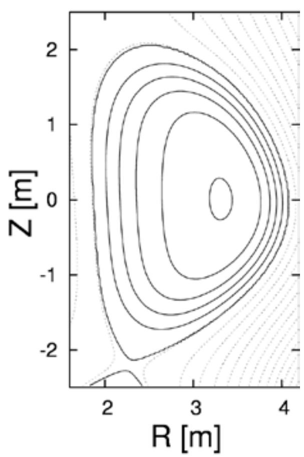
$\delta W_V$: vacuum energy

$D_w$ : energy dissipated in the resistive wall

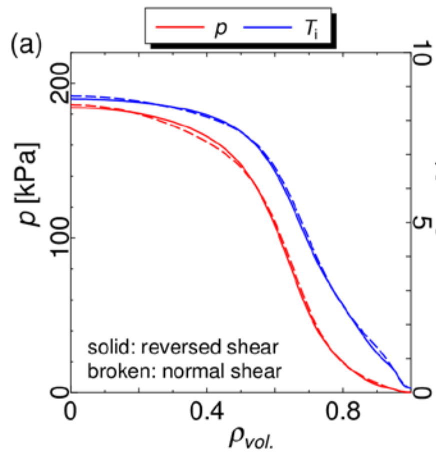
# RWM destabilization by rotation

With MINERVA/RWMaC, we analyze impacts of toroidal rotation on RWM stability in the equilibrium shown below.

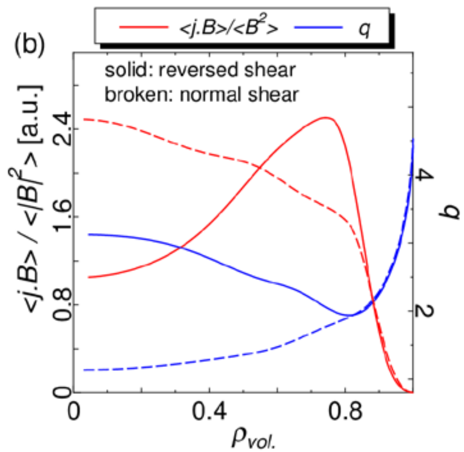
Contours of $\psi$



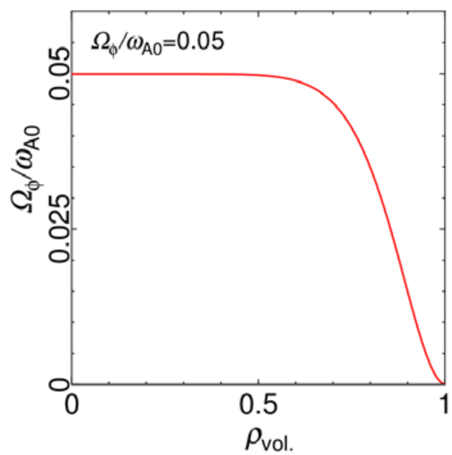

Profiles of $p$ and $Ti$




Profiles of $j_{\|}$ and $q$




$\beta_N = 5.0, I_\mathrm{p} = 2.9[\mathrm{MA}]$
$q_0 = 3.1, q_\mathrm{a} = 4.6$
$(q_{min} = 2.03)$




Ideal wall position required for marginal stability is the same in both normal shear and reversed shear plasmas ($d/a|_{ideal} = 1.43$).

Rotation profile is given artificially as

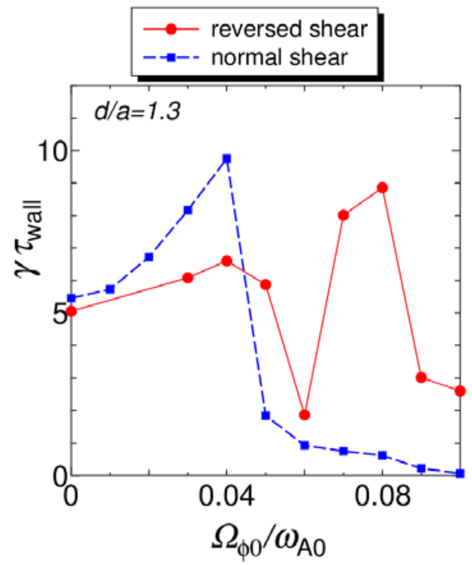
$$\Omega_\phi = \Omega_{\phi 0}(1-\psi^5)^2\omega_{A0}.$$

$\Omega_{\phi 0}$: rotation freq. on axis

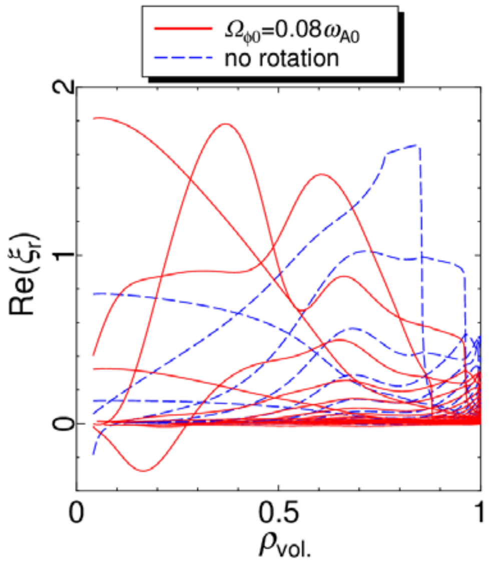
$\omega_{A0}$: Shear Alfven freq. on axis

# Rotation can destabilize MHD mode in reversed shear plasma

Dependence of $\gamma$ on $\Omega_{\phi0}$




Radial mode structure (w/o rotation and with $\Omega_{\phi0} = 0.08\omega_{A0}$)

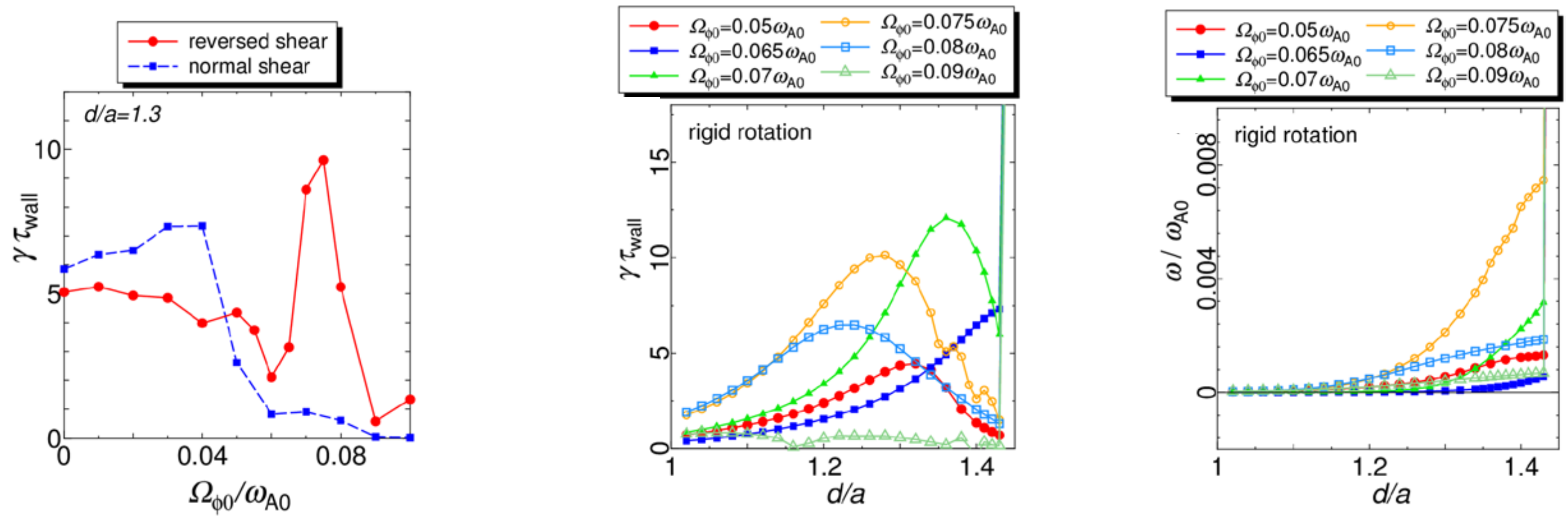



- RWM in the normal shear plasma is stabilized smoothly when $\bar{\Omega}_{\phi0} > 0.04$. ($\bar{\Omega}_{\phi0} = \Omega_{\phi0}/\omega_{A0}$)
- On the other hand, RWM in the reversed shear plasma is once stabilized by rotation, but a MHD mode becomes unstable again near $\bar{\Omega}_{\phi0} \simeq 0.07$.
- Mode structure of this re-destabilized mode has large amplitude in high-$\beta_N$ region ($\rho_{vol.} \leq 0.6$).

→ Why does an unstable mode appear again?

# Rigid rotation also destabilize this mode

To simplify the problem, we replace rotation profile with rigid rotation and neglect centrifugal force (C.F.) on equilibrium and Eq. of motion.




- Since rigid rotation can recreate qualitatively this re-destabilized mode, rotation shear and centrifugal force have only side-effects.
- Re-destabilized mode start to be unstable when $\bar{\Omega}_{\phi 0} \simeq 0.065$.
- This mode appears from $d/a$ near $d/a|_{ideal}$(=1.43).
- The peak of $\gamma$ moves to smaller $d/a$ as $\Omega_{\phi 0}$ increases.
- Frequency of this mode is basically about 0, but increases as $\bar{\Omega}_{\phi 0}$ becomes larger from $0.065$ to $0.075$.

# Theoretical works predicted rotation can destabilize RWM

- In a cylindrical plasma, several theoretical works identified that RWM can be destabilized due to

a. coupling between RWM and stable MHD discrete mode. [Finn, PoP1996, Lashmore-Davies PoP2001 and JPP2005]

b. wall resistivity destabilizing negative energy modes. [Lashmore-Davies, JPP2005, Hirota, PST2009]

c. resonance between stable MHD discrete mode and continuum when their energies have opposite signs. [Betti, PRL1995, Zheng, PRL2005, Hirota, PST2009]

Which is the strongest candidate as the origin of the re-destabilized RWM in the present numerical result?

# Mode coupling is a strong candidate as the destabilizing mechanism

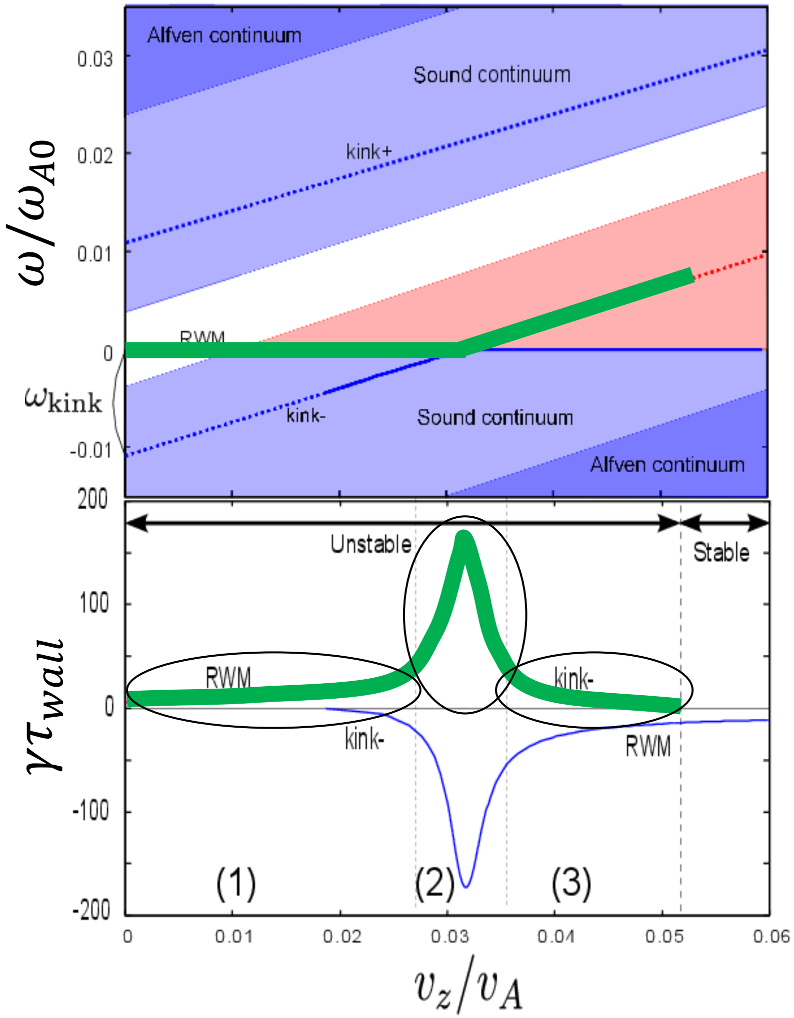
- In the schematic view, the unstable mode in each region is

(1) Original RWM.

(2) Destabilized RWM/kink mode due to mode coupling a).

(3) “Negative energy” kink mode destabilized by wall resistivity b).

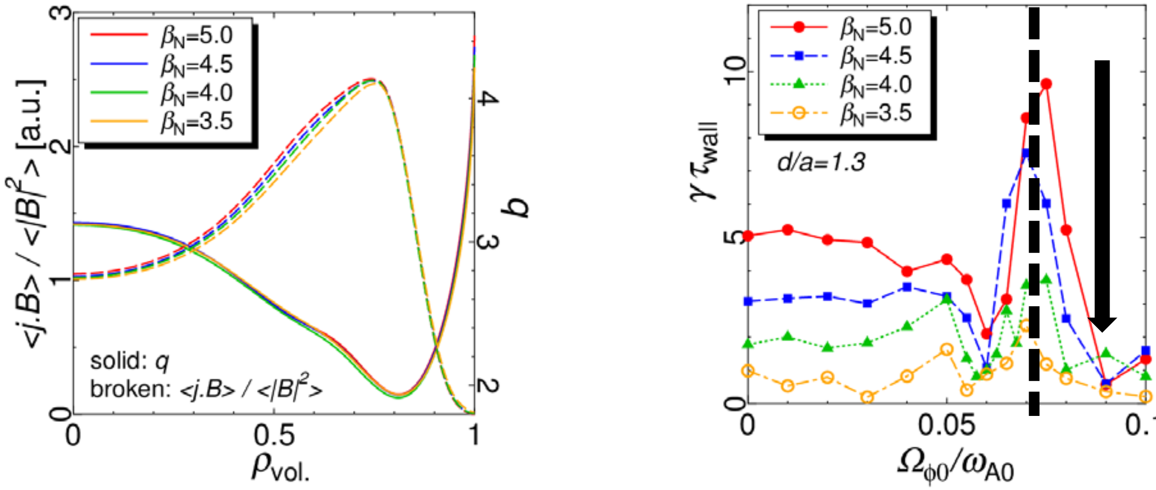
The dependences of both $\gamma$ and $\omega$ on $v_z$ imply that the mode coupling between RWM and discrete MHD mode would play an important role for destabilizing RWM again.




What mode is responsible for this mode coupling destabilization?

# Only $\gamma$ of Re-destabilized RWM has $\beta_N$ dependence

A $\beta_N$ scan is performed with (almost) fixed $q$ profile.




$\gamma$ decreases as $\beta_N$ becomes smaller.

- The growth rate of re-destabilized RWM decreases as $\beta_N$ becomes smaller.
  => Internal energy is important for destabilizing RWM again.
- The rotation frequency destabilizing this mode is almost unchanged as $\overline{\Omega}_{\phi 0}\sim 0.07$.

Stable Internal kink-ballooning like mode is one of the candidates of re-destabilized RWM, but unclear physics remains.

# Summary

- RWM in reversed shear plasma can become unstable again by toroidal rotation even when this mode is once stabilized.
- This re-destabilization is thought to be related to the coupling mechanism between RWM and stable MHD mode.
- This stable MHD mode is still unclear, but  several numerical results imply this has internal kink-ballooning like feature, though the frequency doesn't depend on plasma beta.