"Mode locking" in LHD
~Dynamics of static island~

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on behalf of collaborators in NIFS, CIEMAT and UW-Madison

Outline

Introduction
   -The Large Helical Device (LHD)

Back ground
   -Typical island behavior in LHD
                (steady (saturated) state)

Transition of magnetic island
   -RMP dependence (mode penetration)
   -Beta dependence

Discussion & Summary

LHD : Large Helical device (Heliotron)

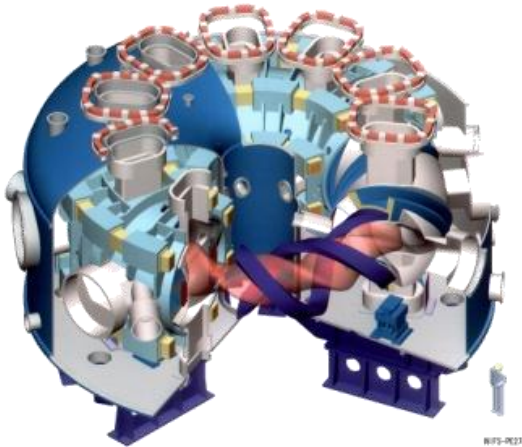**Major radius** $R_0 = 3.5\text{~}4.1\,[\text{m}]$
Minor radius $a \sim 0.6\,[\text{m}]$
Magnetic field $B_t \leq 3\,[\text{T}]$
Heating
   NBI, ECH, ICRF
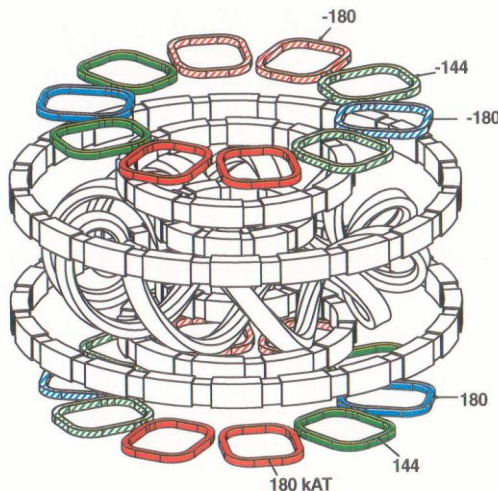**Super conducting coils**
   A pair of helical coils $L/M = 2/10$
   3 pairs of poloidal coils
Rotational transform (1/q)
   $\iota_{(0)}/2\pi \sim 0.4$
   $\iota_{(a)}/2\pi \sim 1.6$

Correction coil system
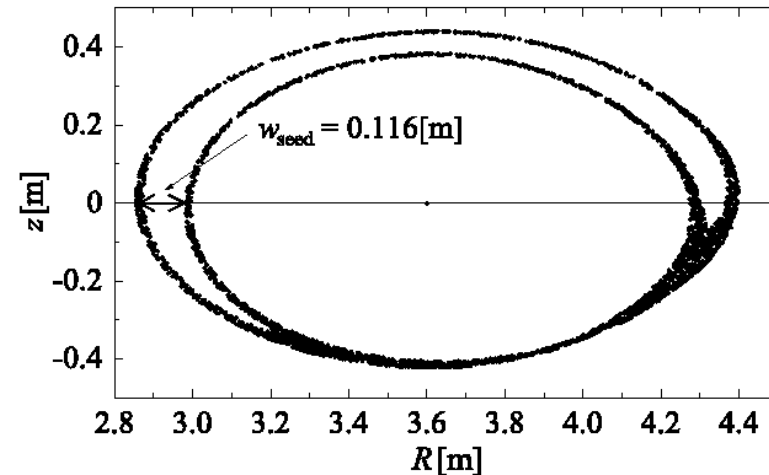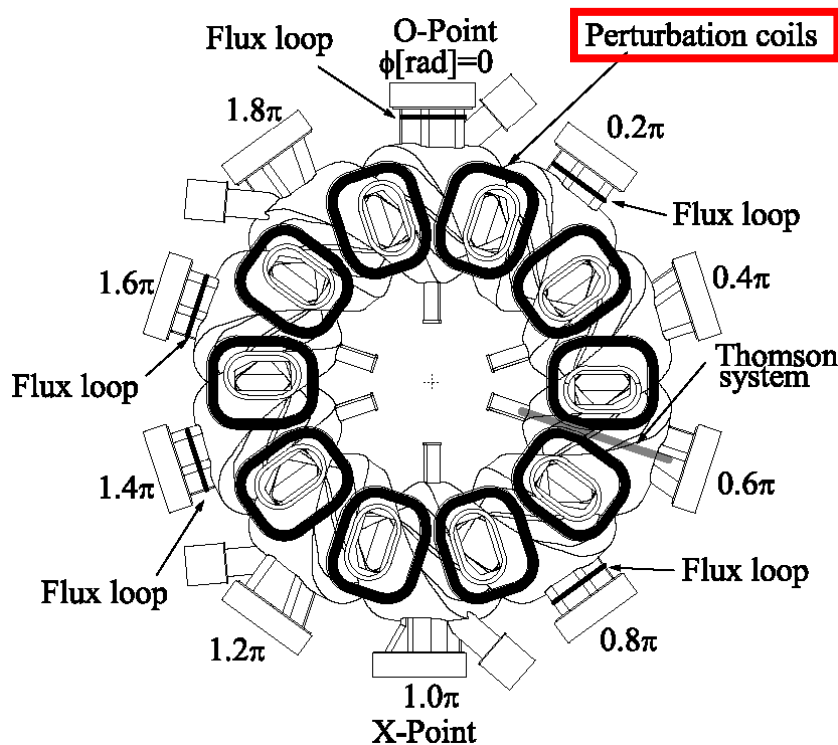**-To compensate natural error field**
-Perturbation coil for RMP
   Normal conductor coils
   $m/n = 1/1$ **and/or** $2/1$
   3 power supplies

How to make vacuum island in LHD

Perturbation coil system
makes STATIC magnetic island

☞ **Vacuum island**
☞ $m/n = 1/1$

Islands in LHD are non-rotating

Tokamak
Rotating magnetic island
☞ Locking magnetic islands bring instabilities
☞ Mode locking has to be avoided

LHD
Non-rotating magnetic island
☞ Growth of island has been observed
☞ No disruption even though beta decreases

**Terminology of "MODE locking" is not familiar.
(Magnetic island does not rotate.)**

Locking ➔ **Growth**
Unlocking ➔ **Healing**

Next "Back ground"
🏝 ☞ Typical behavior of island

Typical island behavior in LHD

Vacuum island

[Y. NARUSHIMA, *et al* NF 48 (2008) 075010]

$w_{seed} = 0.116$ [m]

Vacuum

Growth   **Healing**

Thomson

T_e[keV]   #43619 t=2.13[s]

T_e[keV]   #67923 t=2.4[s]
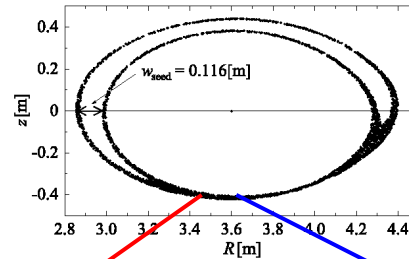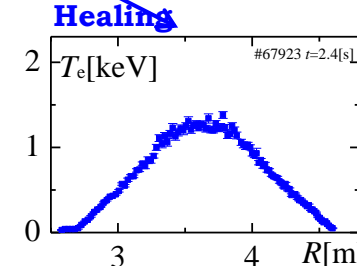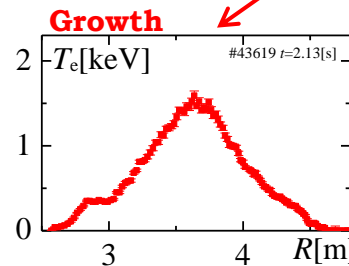
Plasma

Plasma response field

$\delta b_1^{n=1}/B_t$ [10^{-5}]

$\delta b_1^{n=1}/B_t$ [10^{-5}]

ϕ[πrad] ϕ[πrad]
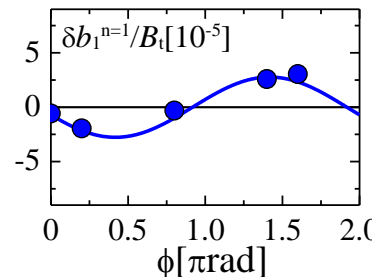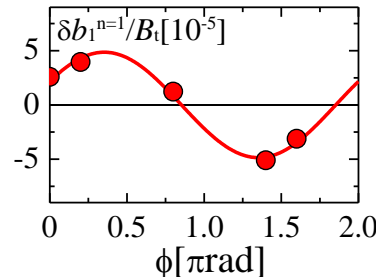
☞T_e **profile**
   Local flattening for growth
   No flattening for healing
☞**Plasma response**
   Finite plasma response field is detected in both cases

Typical island behavior in LHD

Magnetic island in quasi-steady state

[Y. NARUSHIMA, *et al* NF 48 (2008) 075010]

Region of growth/healing

Lower β
Higher ν
Growth

Higher β
Lower ν
Healing
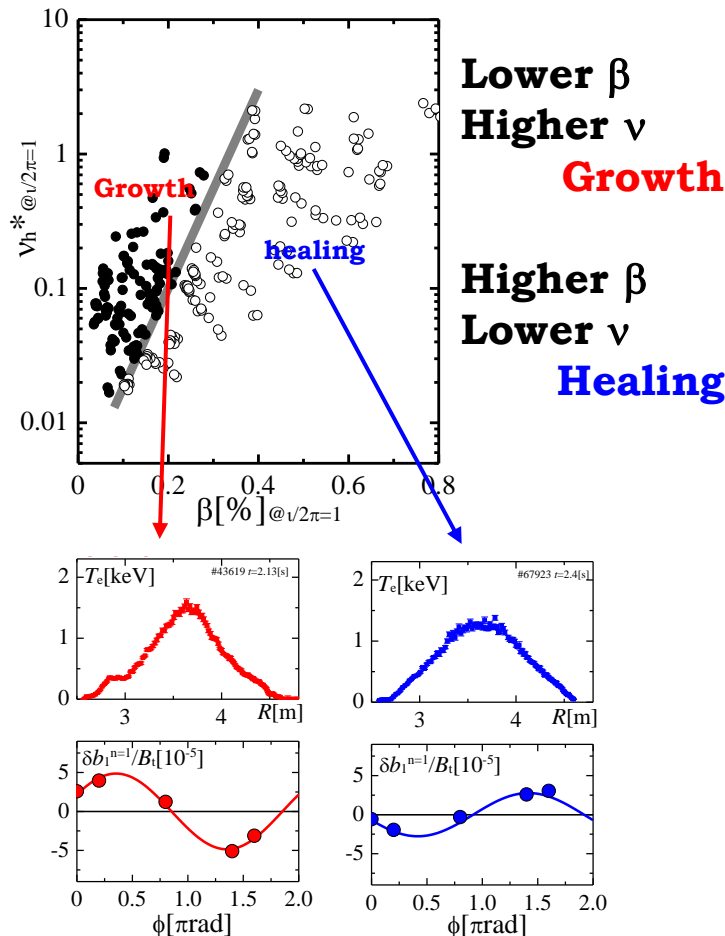
Structure of plasma response field
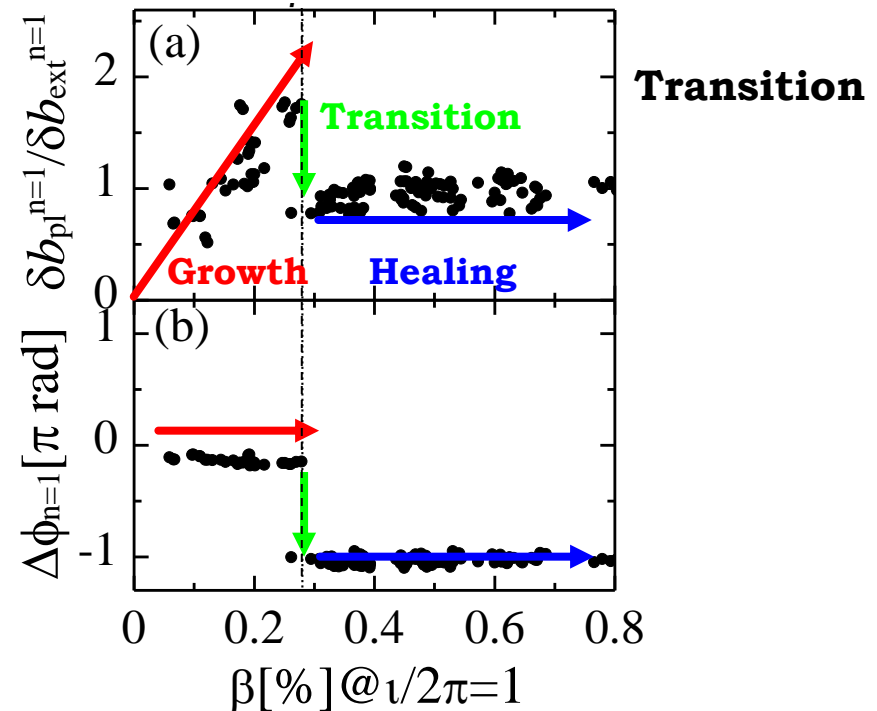
Transition

☞ **LHD observations are reminiscent of mode locking/unlocking physics in Tokamaks**

Transition of magnetic island

To clarify the mechanism of island behavior

Steady state

Transient dynamics should be investigated

Behavior of island to changing RMP and β
-RMP dependence (mode penetration)
-Beta dependence

🏝 Next "Transition of island"
☞ RMP dependence is presented

RMP dependence (mode penetration)

Experiment of error field penetration
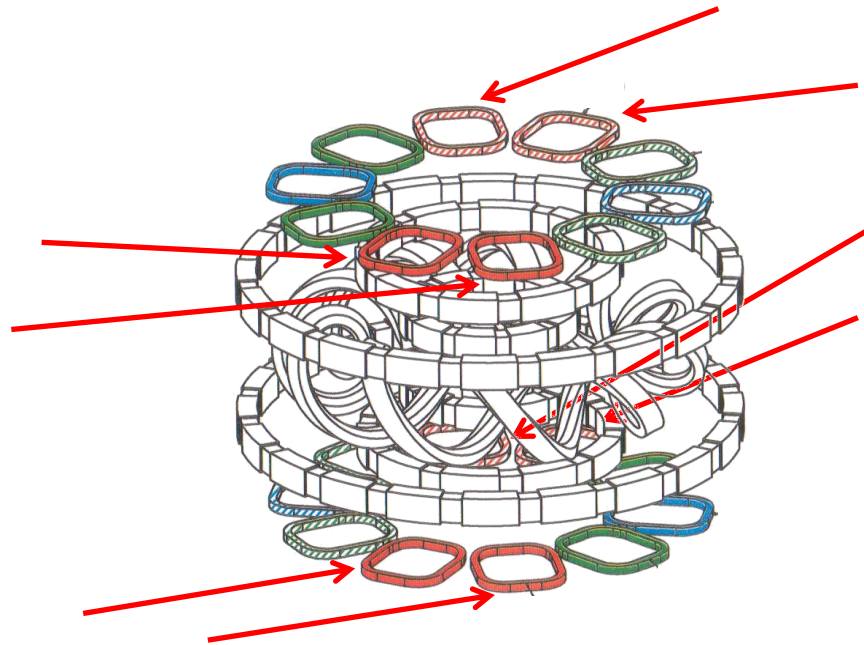
-Current in perturbation coils is swept
-m/n = 1/1

Error field penetration (RMP sweep)

RMP ramp up
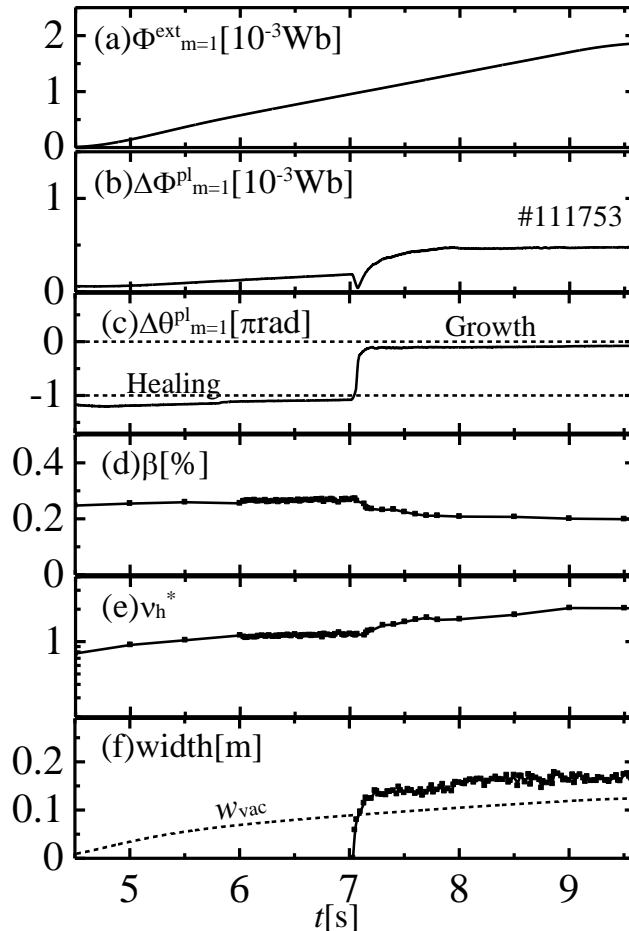
RMP ramp down

☝ **Island suddenly appears**
☝ **Its width exceeds vacuum island width**
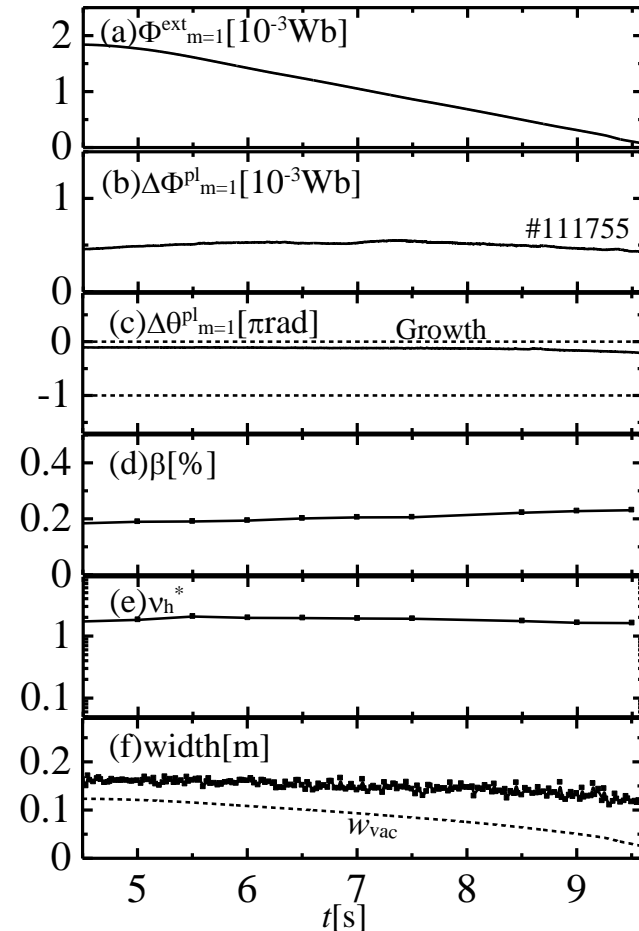
☝ **Island width maintains $w > w_{vac}$**
☝ **w gradually decreases but does not disappear**

Hysteresis can be seen in RMP sweep
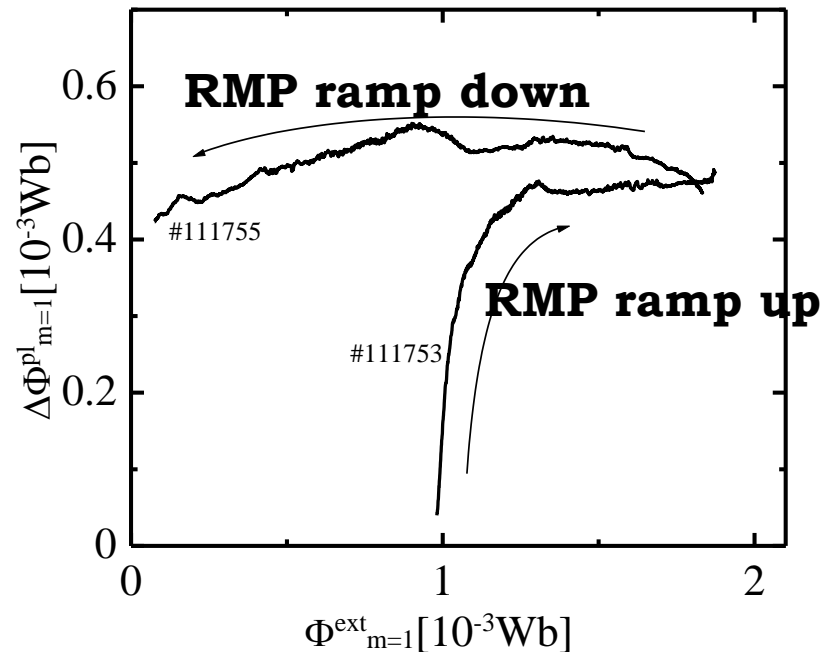
- ☞ **Threshold of RMP for island growth can be seen**
- ☞ **Island does not disappear even if RMP is close to zero** ☞ **Threshold for healing?**
- ☞ **Relationship between RMP and plasma response field shows hysteresis**

🏝 **Next "Beta dependence experiment"**

Beta dependence experiment

Control of NB power to change beta during discharge with static RMP

Transition of magnetic island
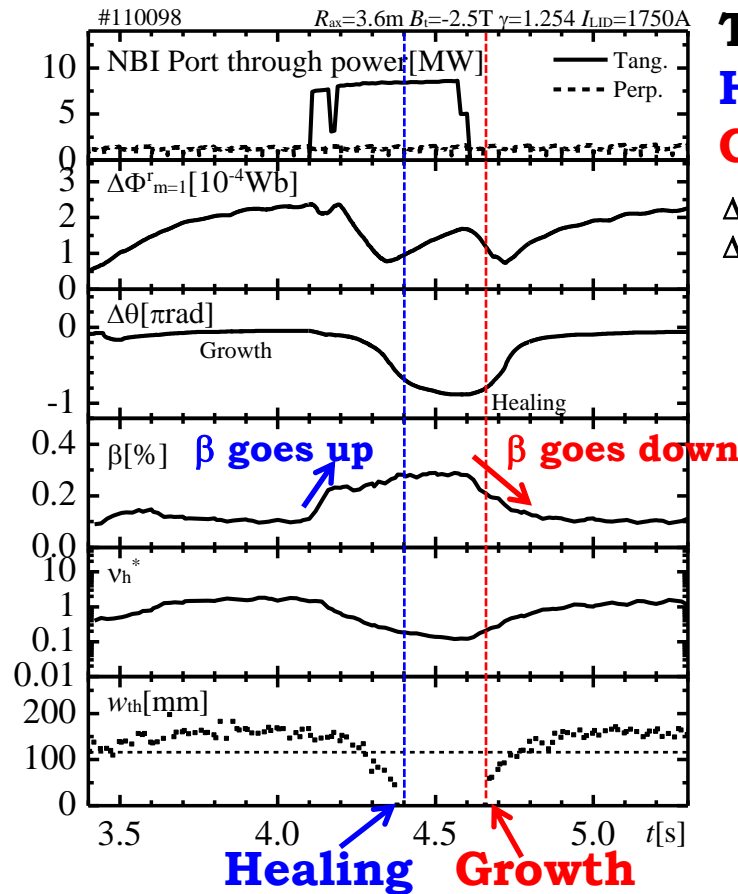
Two times transitions
Healing : after beta increases
Growth : when beta decreases

$\Delta\Phi^r_{m=1}$: Plasma response amplitude
$\Delta\theta$: Phase shift from vacuum island
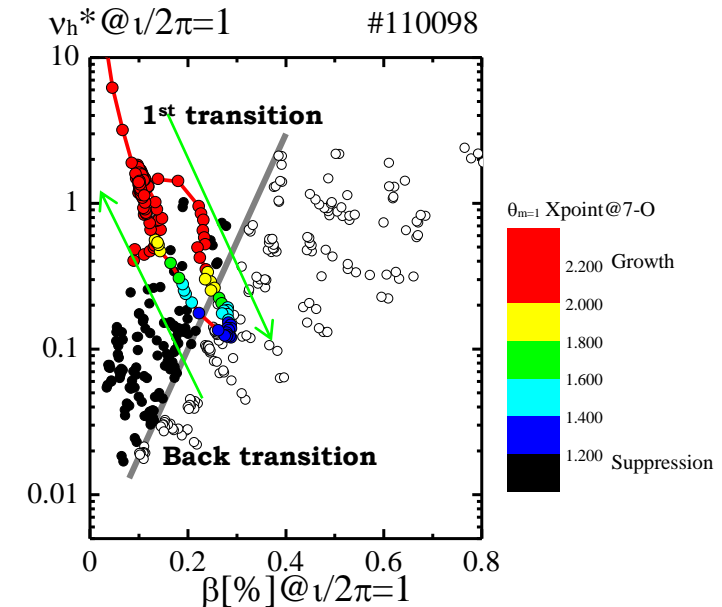
Similar round trip trajectories

🖎 **Thresholds of beta are different**
($\beta_{healing} > \beta_{growth}$) ☞ **Hysteresis**

Thresholds of beta are different

$\beta_{healing} > \beta_{growth}$ ☞ **Hysteresis**

Relationship between phase difference and beta shows hysteresis in island transition

☞ **What acts on island?**

β **itself does not affect island directly**

☞ **Plasma flow**

🏝 **Next "Poloidal flow dependence"** ➡

Poloidal flow and island (1)
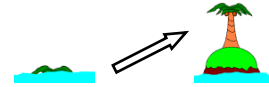
Mode locking in LHD

Introduction

Back ground

Transition of island

**RMP dependence
Beta dependence
Poloidal flow dependence**

Discussion & Summary

Healing to growth

- **Plasma crosses boundary from** healing **to** growth **region**

#104712
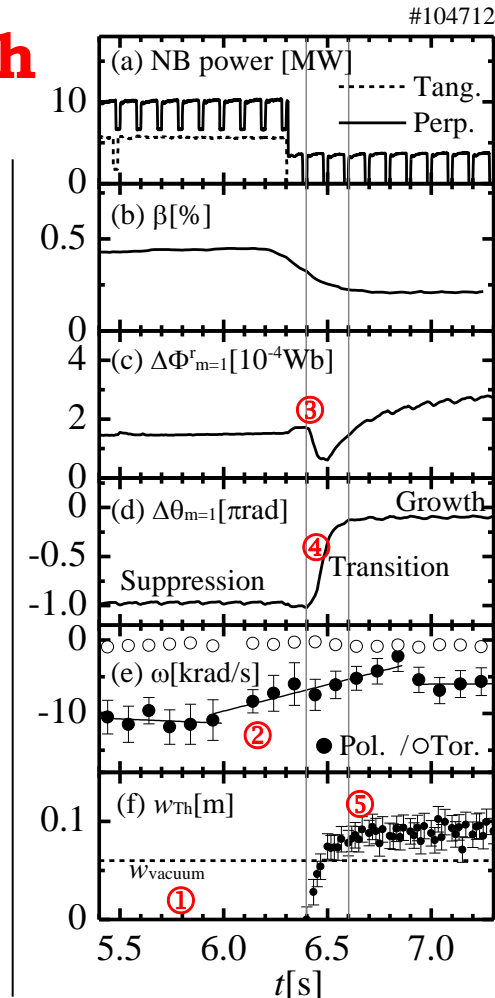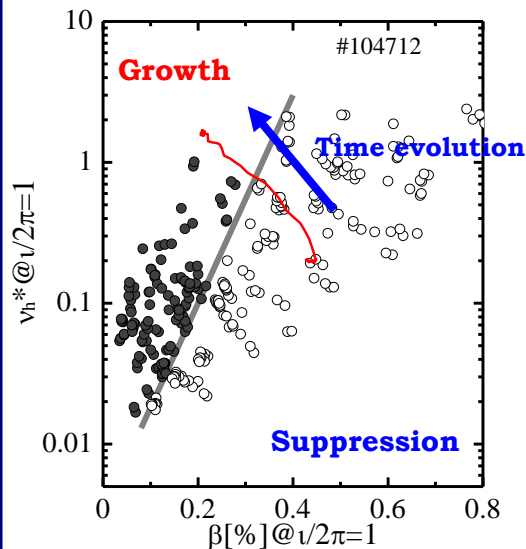
① **Healing**

② $|\omega_{pol}|$ **decreases** **(e-dia. direction)**

③ $\Delta\Phi^r_{m=1}$ **starts decreasing**

④ $\Delta\theta_{m=1}$ **starts shifting** **(i-dia. direction)**

⑤ **Growth**

ω_{pol} : poloidal rotation outside $\iota/2\pi=1$
ω_{tor} : toroidal rotation at $\iota/2\pi=1$

(a) NB power [MW] — Tang. / Perp.
(b) β[%]
(c) $\Delta\Phi^r_{m=1}$[10^{-4}Wb] ③
(d) $\Delta\theta_{m=1}$[πrad] — Growth / Suppression / Transition ④
(e) ω[krad/s] ② Pol. /○Tor.
(f) w_{Th}[m] ⑤ w_{vacuum} ①

t[s]

#104712
Growth
Time evolution
Suppression
ν_h*@$\iota/2\pi=1$
β[%]@$\iota/2\pi=1$

☞ $\omega_{tor} \ll \omega_{pol}$
☞ ω_{pol} (**e-dia. direction**) **decreases prior to island growth**
☞ **Phase shift ($\Delta\theta_{m=1}$) travels to i-dia. direction**

Poloidal flow and island (2) 🏝️ ➡️ 🏝️

Growth to healing

- **Plasma crosses boundary from growth to healing region**

#92210

(a) NB power [MW] Tang Perp.

(b) β[%]

(c) $\Delta\Phi^r_{m=1}/B_t [10^{-4} Wb/T]$ ③

(d) $\Delta\theta_{m=1}[\pi rad]$ Growth Transition ⑤ Suppression

(e) $\omega_{pol}[krad/s]$ ② ④

(f) $w_{Th}[m]$ ① Vacuum width ⑥
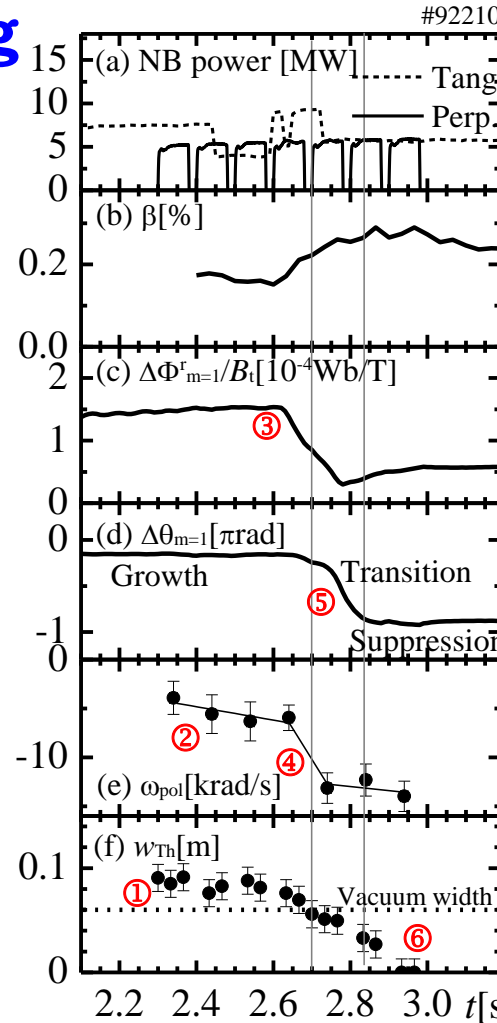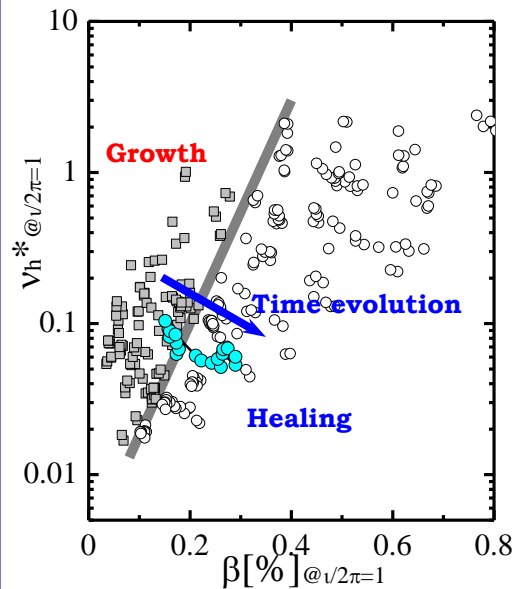
① **Growth**

② **$|\omega_{pol}|$ increases**
(e-dia. direction)

③ **$\Delta\Phi^r_{m=1}$ starts decreasing**
(Island width decreases)

④ **$|\omega_{pol}|$ further increases**

⑤ **$\Delta\theta_{m=1}$ starts shifting**
(e-dia. direction)

⑥ **Healing**

☞ **ω_{pol} (e-dia. direction) increases prior to island healing**
☞ **Phase shift ($\Delta\theta_{m=1}$) travels to e-dia. direction**

17/22

Thresholds of ω_{pol} are different

Relationship between $\Delta\theta_{m=1}$ and ω_{pol}

(a) $\omega_{pol}^{healing}$ = -9.0krad/s

Growth

Suppression

(b) ω_{pol}^{growth} = -6.6krad/s

Growth

Suppression

$\Delta\theta_{m=1}[\pi rad]$

$-\omega_{pol}[krad/s]$
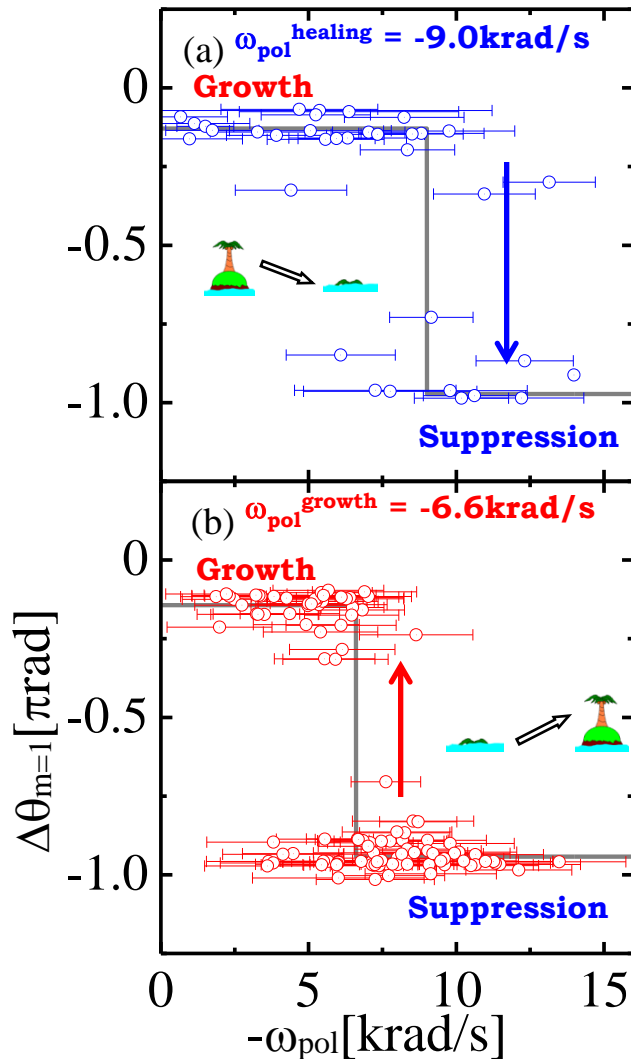
$$\omega_{pol}^{healing} > \omega_{pol}^{growth}$$

☞ **Different thresholds (ω_{pol})**

$\omega_{pol}^{healing} > \omega_{pol}^{growth}$
☞ **Hysteresis**

Transition of magnetic island

☞ **Thresholds of ω_{pol}^{th} and β are different**

☞ **Hysteresis**

☞ **Magnetic island can be healed not by toroidal rotation but by poloidal rotation**

☞ **Once magnetic island is healed , it lasts until poloidal rotation becomes small enough ($\omega_{pol}^{healing} > \omega_{pol}^{growth}$)**

🏝 **Next "Discussion"**

Discussion

Attempts have been made to explain experimental facts by theory

☞ **Thresholds of poloidal rotation are different**
$$(|\omega_{\text{suppression}}| > |\omega_{\text{growth}}|)$$

☞ **Thresholds of beta are different**
$$(\beta_{\text{suppression}} > \beta_{\text{growth}})$$

☞ **Thresholds of RMPs are different**
$$(\text{RMP}_{\text{growth}} > \text{RMP}_{\text{suppression}})$$

Theory based on torque balance

Mode locking in LHD

Introduction

Back ground

Transition of island

RMP dependence
Beta dependence
Poloidal flow dependence

Discussion & Summary

Balance of electromagnetic and viscous torques

[C. C. Hegna, Nucl. Fusion 51 (2011) 113017]

Electromagnetic torque

$T_{EM0} \propto j_{pl}^{m/n=1/1} \times B_{ext}^{m/n=1/1}$

Viscous torque

$T_{V0} \propto d\omega_{pol}/dr$
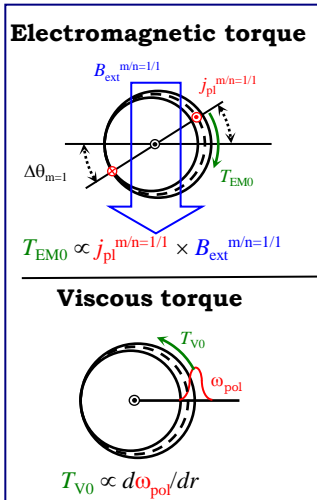
Torques are different at each transition as initial condition
Growth to Suppression

Large island is locked → Poloidal flow appears / Viscous torque arises → Poloidal flow increases / Shielding effect makes island width decrease → T_{V0} overwhelms T_{EM0} / Phase difference occurs → Phase difference exceeds criterion / Island is suppressed

Suppression to Growth

Suppression / Plasma is rotating at rational surface / Localized eddy current prohibits reconnection → Flow decreases at ı/2π = 1 → Poloidal flow decreases / T_{EM0} counters T_{V0} / Phase difference attempt to return / Island width increases → Poloidal flow decreases / Phase difference becomes zero / Island width increases → Large island is locked
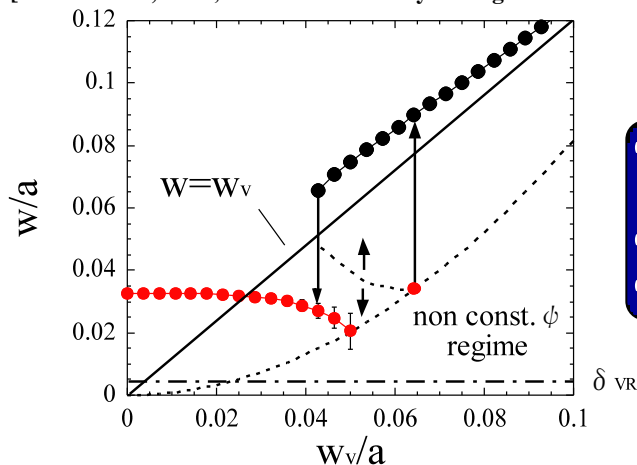
[S. Nishimura, *et al*., Plasma Fusion Res. 5 (2010) 040]
[S. Nishimura, *et al*., "Nonlinear stability of magnetic islands in a helical plasma" submitted to Plasma Fusion Res.]

☞ **Torque balance (T_{EM0} +T_{V0} = 0) at each transition causes hysteresis**
☞ ω_{pol} **(for growth) < ω_{pol} (for suppression)**
☞ **RMP(for growth) > RMP(for suppression)**

🏝️ **Next "Summary"** ⟹

Summary

Island dynamics in LHD
Mode penetration

☞ **Threshold of RMP for island growth**
☞ **Island does not disappear even if RMP is close to zero**
☞ **Relationship between RMP and plasma response field shows hysteresis**

Poloidal rotation

☞ **Thresholds of ω_{pol} and β are different   ☞ Hysteresis**
☞ **Magnetic island can be healed not by toroidal rotation but by poloidal rotation**

Theory

☞ **Based on a balance of electromagnetic and viscous torques at the rational surface**