Recent MHD topics in Large Helical Device

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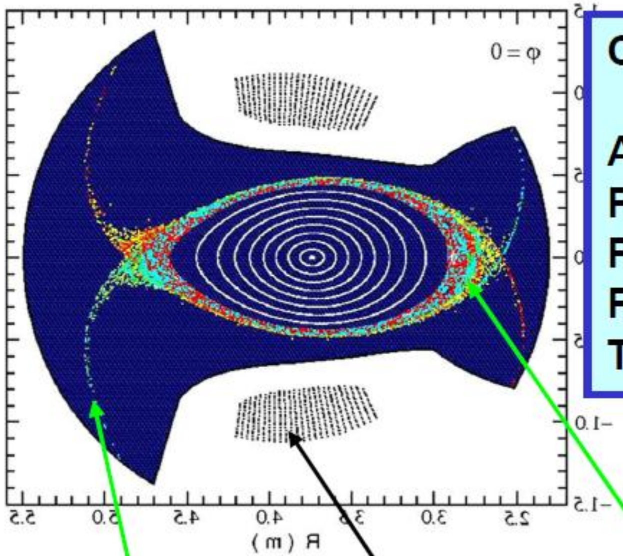
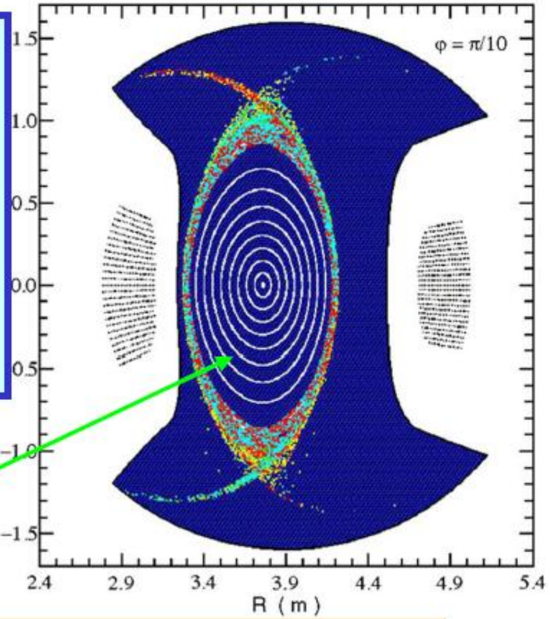
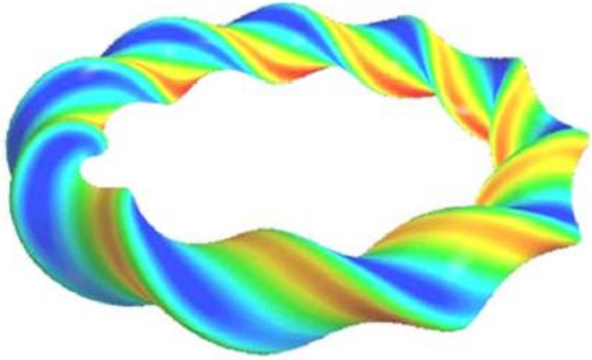
Structure and plasma achievement of LHD



Continuous helical coils of
l=2/m=10 field period
All superconducting coil system
Plasma major radius ~3.7 m
Plasma minor radius ~0.6 m
Plasma volume ~30 m^3
Toroidal field strength 3 T





High beta
$\langle\beta\rangle = 5.1$ % at B = 0.43 T
$\langle\beta\rangle = 4.1$ % at B = 1.0 T
High density
$n_e(0) = 1.2\times10^{21}m^{-3}$ at B = 2.5 T
High ion temperature
T_i = 10 keV at n_e =$1.6\times10^{19}m^{-3}$
High ion and electron temperature
T_i 8.7 keV / T_e 8.7 keV at $n_e = 1.6\times10^{19}m^{-3}$
Long pulse : 1.2MW for 48min.
Fusion product; $n\,\tau_E\,T = 5\times10^{19}\ m^{-3}$ s keV

Outline

This presentation highlights recent research outcomes on MHD phenomena in the LHD experiment, with the aim of fostering collaborative studies across the helical device community

- The final LHD experiment campaign will be held from mid-September to the end of December 2025.

We introduce four key topics that address challenges commonly shared among helical systems:

- **External RMP physics**
- **Magnetic Island Dynamics**
- **Frequency determination mechanisms of MHD activities**
- **AI-Assisted Prediction of Abrupt MHD Events**

External RMP physics

- RMP Stabilization of MHD Instabilities
- Modelling of RMP penetration thresholds

Topics of external RMP

- In tokamaks, external RMPs have been successfully applied to stabilize RWMs and ELMs [Evans et al., Nature Physics **2**, 419–423 (2006)]

- In helical plasmas, the stabilization of resistive interchange modes, which are pressure-driven instabilities, has also been experimentally demonstrated using external RMPs [Ito et al., PFR 18, 2402007 (2023)]

→ Understanding the scaling of stabilization conditions is essential for extrapolating to future fusion devices.

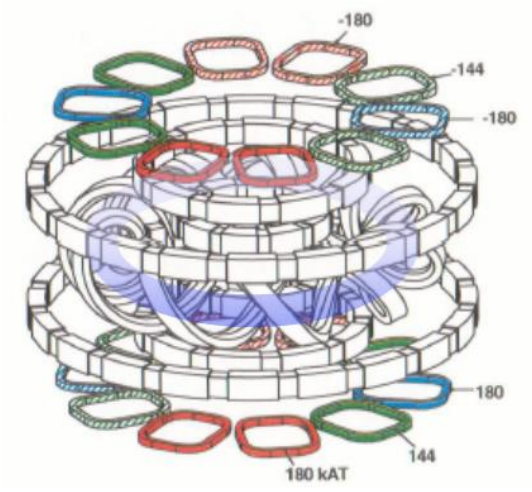
- However, when the applied RMP is too strong, it may penetrate into the plasma, leading to the formation of large magnetic islands and subsequent degradation of confinement.

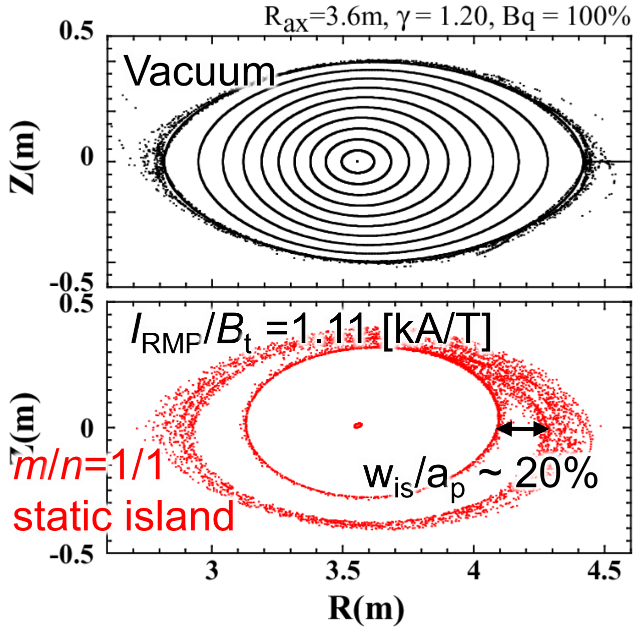
→ To prevent undesirable effects, it is essential to develop a predictive model that captures the physics of RMP penetration.

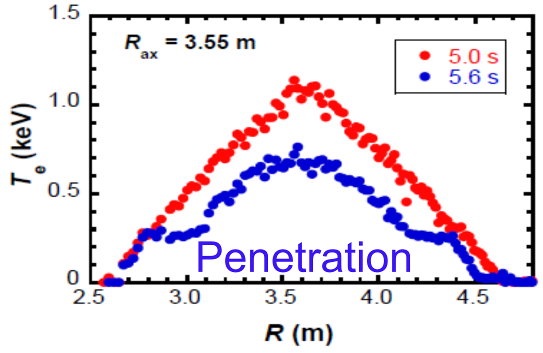
RMP coil system and example of RMP penetration

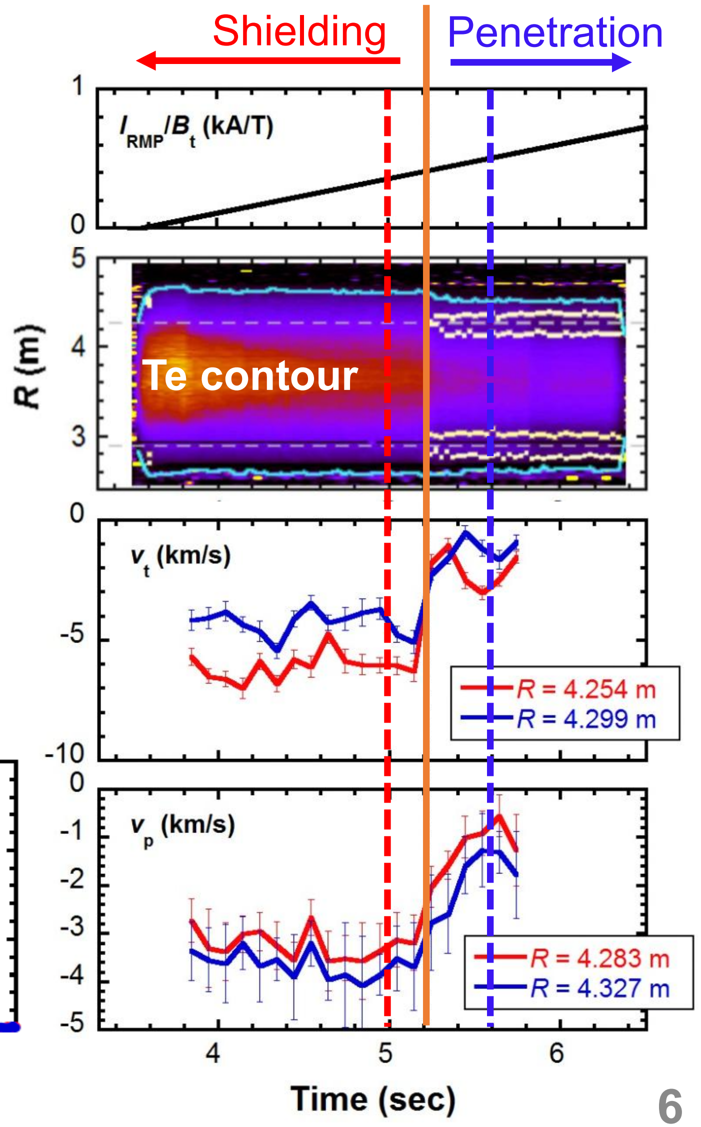
- RMP coil system can alters spatial structure (mainly m/n = 1/1, or 2/1), width and position of formed magnetic islands
- If external RMP penetrates to plasmas and forms magnetic islands, confinement property is significantly reduced

→ Important to control MHD instabilities keeping its shielding



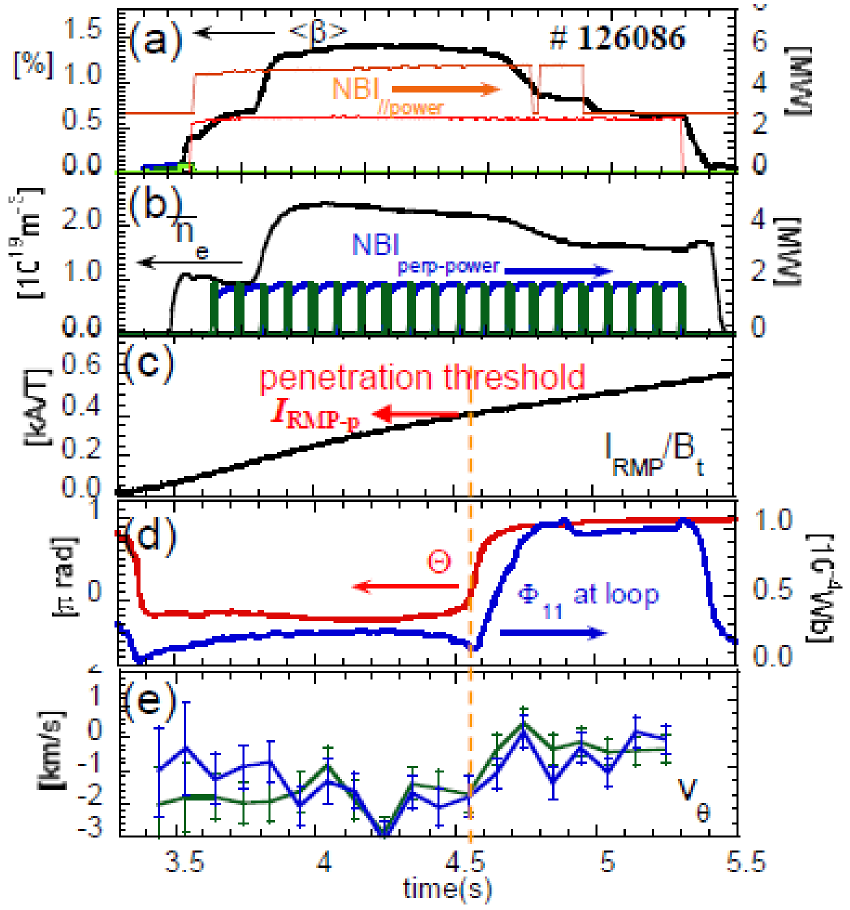






Dependence of RMP penetration threshold on plasma parameters in LHD

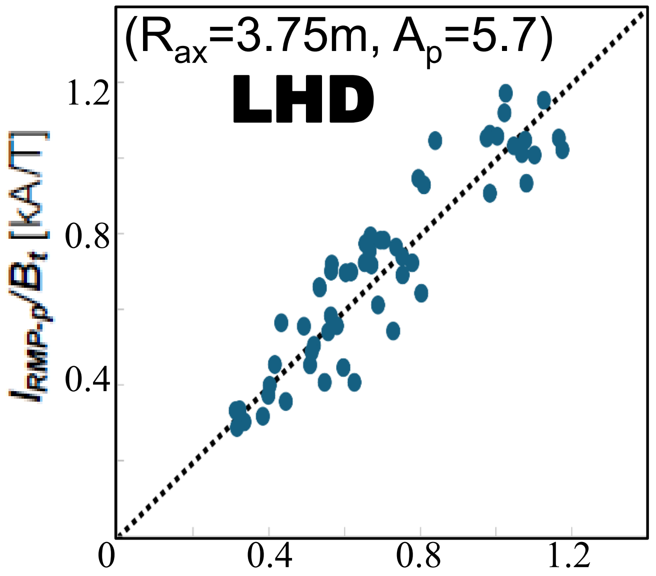
Rump-up RMP experiment



RMP penetration threshold scaling in Ohmic tokamak discharges

[Y. GIRBOV, in Meeting of ITPA MHD TG, Oct. 2017]

$$B_{pen}/B_t \propto n_e^{1.4\pm0.13} B_t^{-1.8\pm0.16} R^{0.81\pm0.24} \beta_N^{-0.86\pm0.14}$$



$$0.78 \cdot \beta^{1.2} \cdot \nu_{*b}^{-0.038} \cdot \rho_*^{-0.48} \propto n_e^{0.35} \cdot B_t^{-0.15} \cdot \beta^{0.88}$$

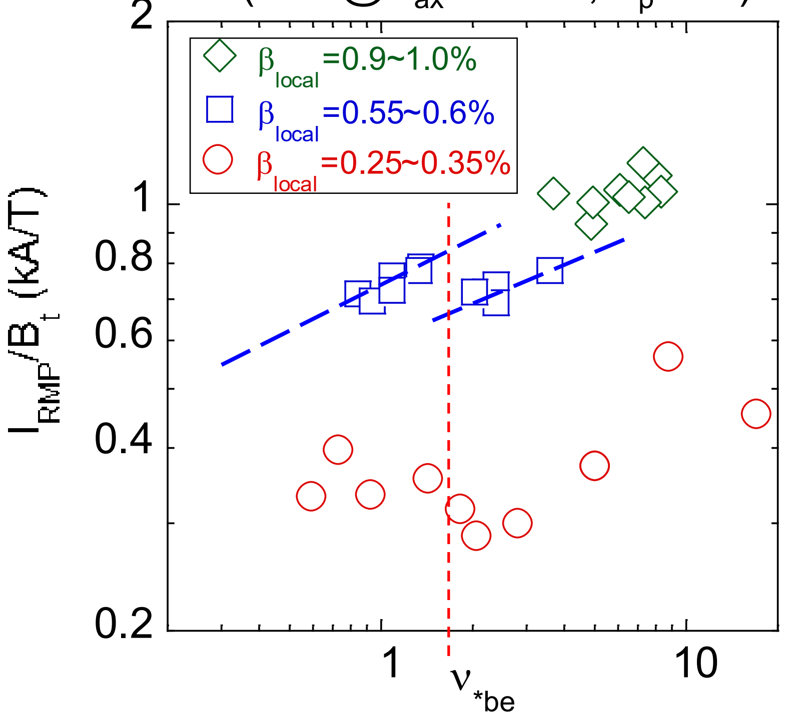
Threshold dependence on n_e and B_t is qualitative similar with that in Ohmic tokamak plasmas, and the dependence on β is opposite to the tokamaks.

- Shielding mechanism is different between helical and tokamak!!
- Why does this scattering occur?→ **How about the collisionality effect?**

Dependence of RMP penetration threshold on plasma parameters in LHD (II)

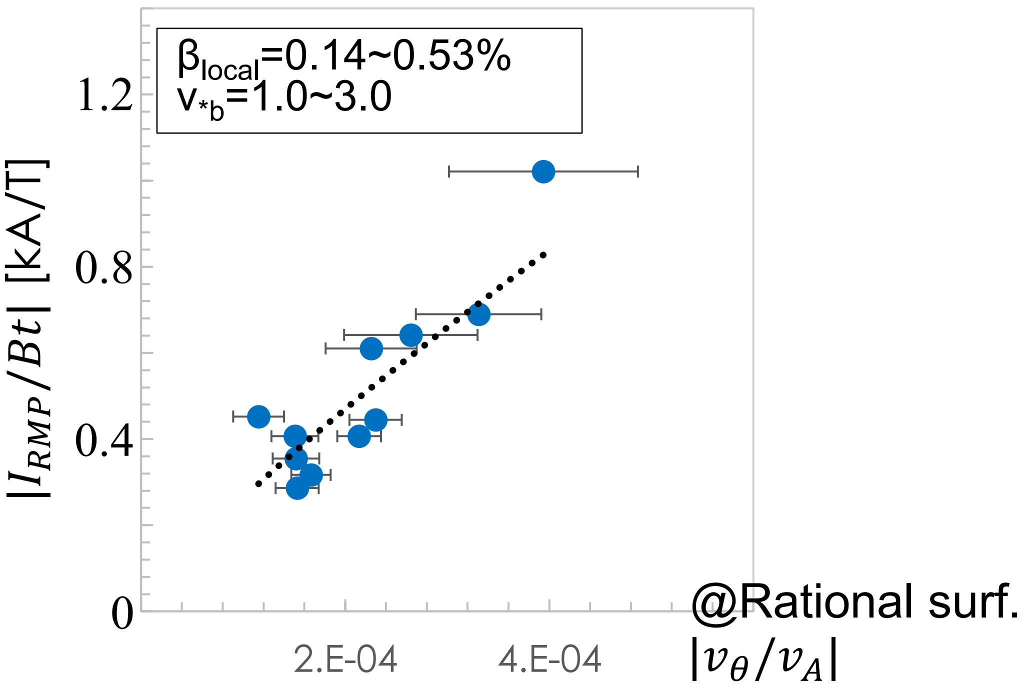
Dependence on collisionality

(LHD@R_{ax}=3.75m, A_p=5.7)



Dependence on poloidal velocity

(LHD@R_{ax}=3.75m, A_p=5.7)



Dependence seems to change depending on the collisionality regimes.

Pen. threshold is proportional to the normalized poloidal flow velocity with high correlation.

→ The determination mechanism is likely related to poloidal NC viscosity, which governs poloidal flow and varies with the collisionality regime in helical plasmas.

Dependence of RMP penetration threshold on plasma parameters in LHD (III)

Model Eqs.

[Nishimura PoP 2012]

Time evolution of island width (w)

$$\frac{dw}{dt} = -\frac{\eta_{\parallel}\Delta_0'}{I_1\mu_0}\left(\frac{aI_{RMP}/B}{w^2}\cos\Theta - 1\right)$$

Time evolution of island phase (Θ)

$$\frac{\partial\Theta}{\partial t} = -\frac{v_\theta}{r_s}$$

Mometum eq. of poloidal flow velocity (v_θ)

$$\frac{\partial v_\theta}{\partial t} = -C\,\Delta_0'\frac{I_{RMP}}{B}w\sin\Theta - \frac{e}{\varepsilon_\perp B}\left(\Gamma_i^{neo} - \Gamma_e^{neo}\right)$$

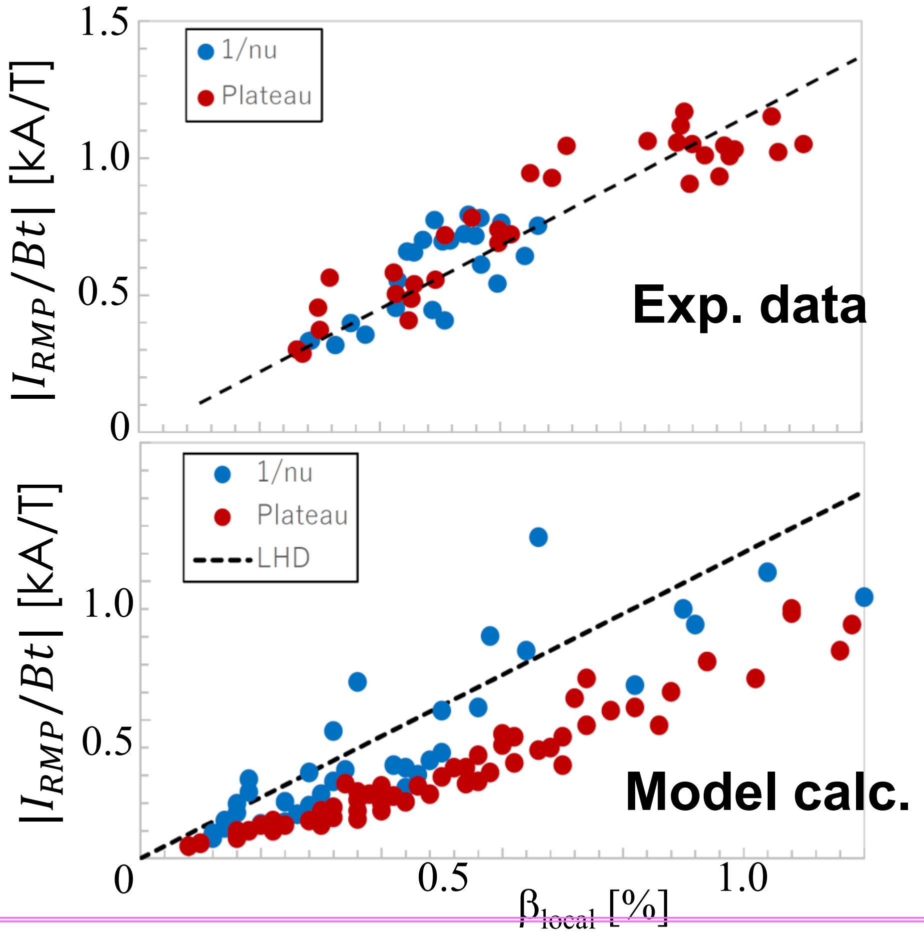
$$\Gamma_a^{neo}(NC\ radial\ particle\ \ flux) \propto \langle \boldsymbol{B}_\theta \cdot \boldsymbol{\nabla} \cdot \boldsymbol{\Pi}_a \rangle (pol.viscos)$$

1/ν-regime

$$-\frac{e}{\varepsilon_\perp B}\Gamma_i^{\frac{1}{\nu}} = \frac{\varepsilon_t^2\varepsilon_h^{1.5}v_A^2}{12r_s^2}\frac{1}{\nu_{tha}}\beta\left(\frac{T_i}{q_iB}\left(\frac{n_i'}{n_i} + \frac{T_i'}{T_i} - \frac{q_iB}{T_i}v_\theta\right)\right)$$

plateau regime

$$-\frac{e}{\varepsilon_\perp B}\Gamma_i^{pl} = \frac{5\sqrt{\pi}(1+5\varepsilon_t^2)\varepsilon_t\varepsilon_h^2v_A^2}{8r_s(T_i/m_i)^{0.5}}\beta\left(\frac{T_i}{q_iB}\left(\frac{n_i'}{n_i} + \frac{3T_i'}{2T_i} - \frac{q_iB}{T_i}v_\theta\right)\right)$$



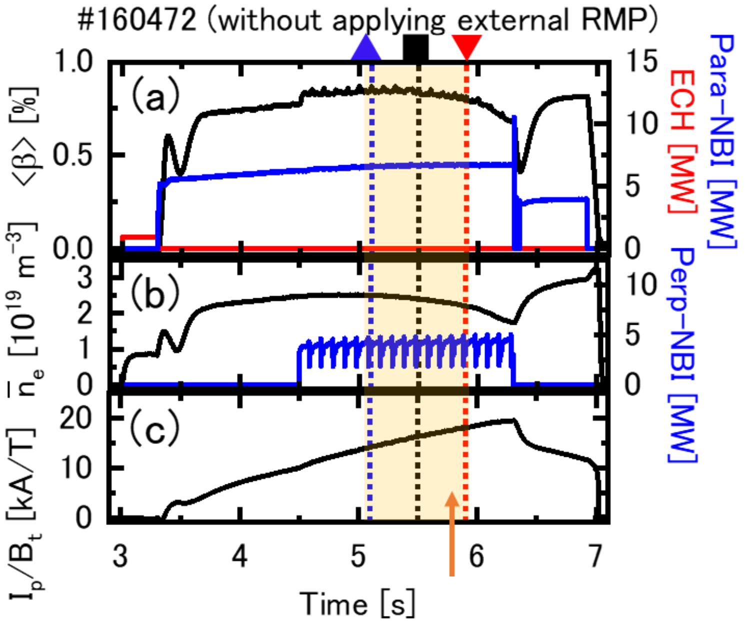
Pred. of Model qualitatively coincides Exp. data.

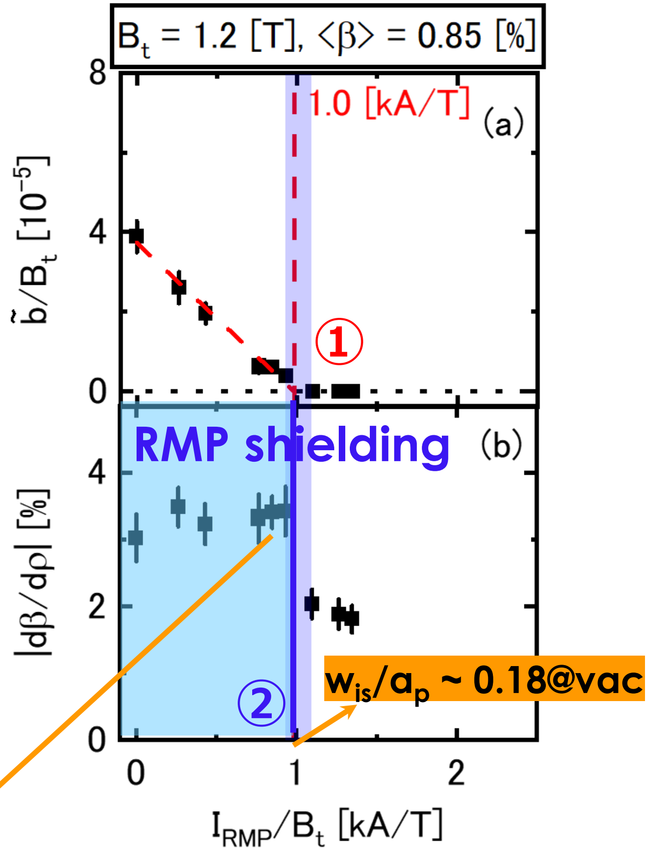
However, quantitatively does not coincide.

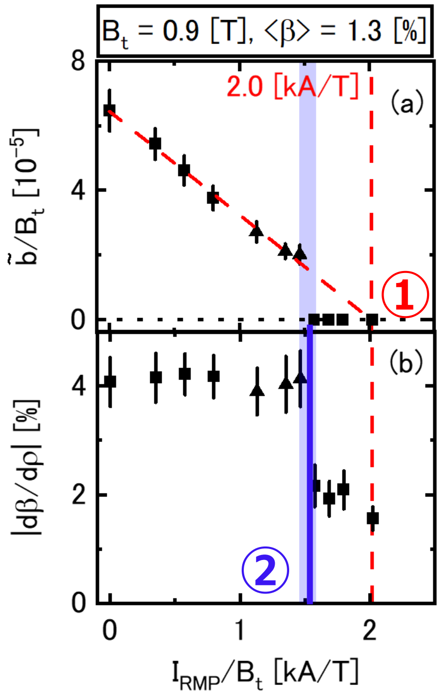
→ We should blush up the model of NCV, or apply the other model like viscosity driven by turbulence???

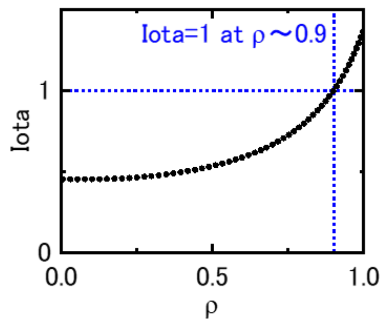
Mode stabilization by RMP

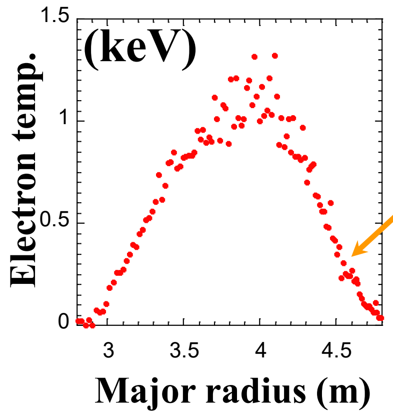
Res.-Interchange insta. (RIC) response to ext.-RMP











Amplitude of Ext.-RMP depend on exp. conditions

① Ext.-RMP to completely suppress Mag. fluc. (RIC-mode stabilize)

② Penetration threshold of ext.-RMP (Mag. island appears)

m/n=1/1 static external RMP suppresses m/n=1/1 interchange instability with the shielding of the Ext.-RMP (with no degradation of pressure gradient)

Config. with mag. axis torus location R_{ax}=3.75m

How do they depend??

Experiments to construct scaling laws

- In a same vacuum mag. configuration of the LHD, res. interchange insta. suppression experiments by ext.-RMP are done under the 20 series with various conditions of mag. field strength, electron density and heating power, which changes independently.

Operation regimes	
Mag. field strength@Mag. axis B_t[T]	**0.75~1.7**
Elec. density@res. surf. $n_e[10^{19}m^{-3}]$	**1.7~4.6**
Elec. temp.@res. surf. T_e[eV]	**160~400**

- Try to construct Scaling laws depending on 2 non-dimensional parameters for the following values with Multiple Regression Analysis

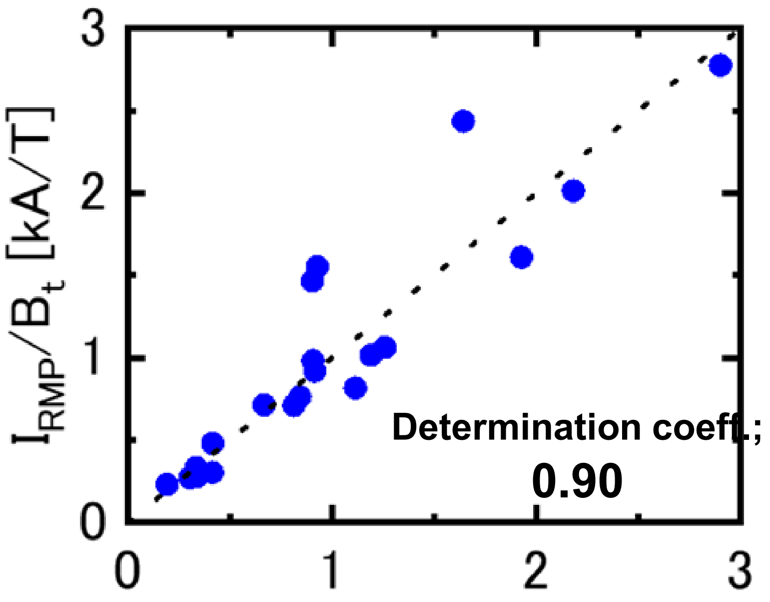
① **Amp. of ext.-RMP to completely suppress Mag. fluc.,**

② **Penetration threshold of ext.-RMP,**

As 3 independent non-dimensional parameters, we select the followings, which are commonly used for the confinement performance

Beta value; β , Normalized colisionality; ν* , Normalized ion gyro-radius; ρ*

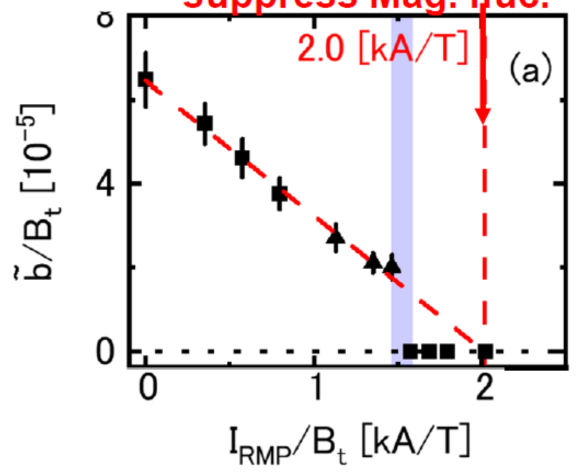
Scaling law for Ext.-RMP to completely suppress Mag. fluc.



$7.1 \times 10^2 \cdot \beta^{1.8} \cdot \nu *^{0.24} \cdot \rho *^{0.85}$

Operation regimes	
Beta value; β	0.20~0.59
Normalized colisionality; ν*	1.2~8.0
Normalized ion gyro-radius; ρ*	0.0018~0.0033

Correlation coeff.(Log)	
β <=> ν*	0.86
β <=> ρ*	0.47
ν* <=> ρ*	0.24

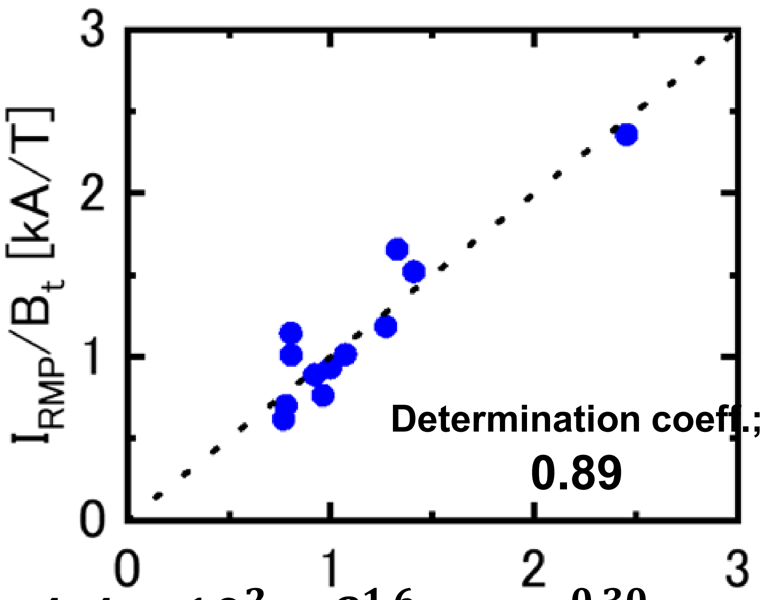


- **[Ext.-RMP amp. to completely suppress Mag. fluc.]**
  $= 7.1 \times 10^2 \cdot \beta^{1.8} \cdot \nu *^{0.24} \cdot \rho *^{0.85}$
  - **Note; Identification accuracy of the power of β and ν* is relatively poor because correlation coeff. between β and ν*.**

Scaling law for penetration threshold of ext.-RMP

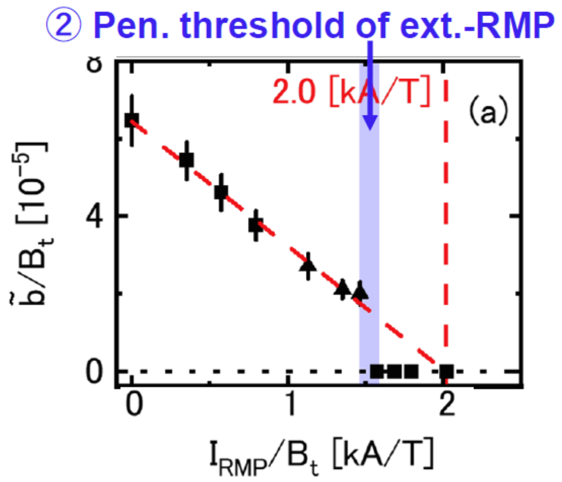
・Penetration of ext.-RMP is observed in 12 series among 20 experiment series

Operation regimes	
Beta value; β	0.37~0.59
Normalized colisionality; ν*	2.9~8.0
Normalized ion gyro-radius; ρ*	0.0019~0.0033



$$4.4 \times 10^2 \cdot \beta^{1.6} \cdot \nu*^{-0.30} \cdot \rho*^{0.68}$$

Correlation coeff.(Log)	
β <=> ν*	0.54
β <=> ρ*	0.60
ν* <=> ρ*	-0.06



・[Pen. threshold of Ext.-RMP]

$$= 4.4 \times 10^2 \cdot \beta^{1.6} \cdot \nu*^{-0.30} \cdot \rho*^{0.68}$$

Summary for the scaling law

- Empirical scaling laws of ① Ext.-RMP to completely suppress Mag. fluc. and ② Penetration threshold of ext.-RMP on 3 non-dimensional parameters (β, ν*, ρ*) are obtained by Multiple Regression Analysis

① **[Ext.-RMP to completely suppress Mag. fluc.]** $= 7.1 \times 10^2 \cdot \beta^{1.8} \cdot \nu *^{0.24} \cdot \rho *^{0.85}$

② **[Penetration threshold of ext.-RMP]** $= 4.4 \times 10^2 \cdot \beta^{1.6} \cdot \nu *^{-0.30} \cdot \rho *^{0.68}$

- β and $\rho *$ dependence of ① and ② are similar. However, **$\nu *$ dependence of ① and ② is quite different**, which leads to the following prediction;

- Operation regime to suppress instability without degradation due to ext.-RMP penetration is wider as the colisionality is lower under the same beta and normalized ion gyro-radius.

CAUTION!!;;

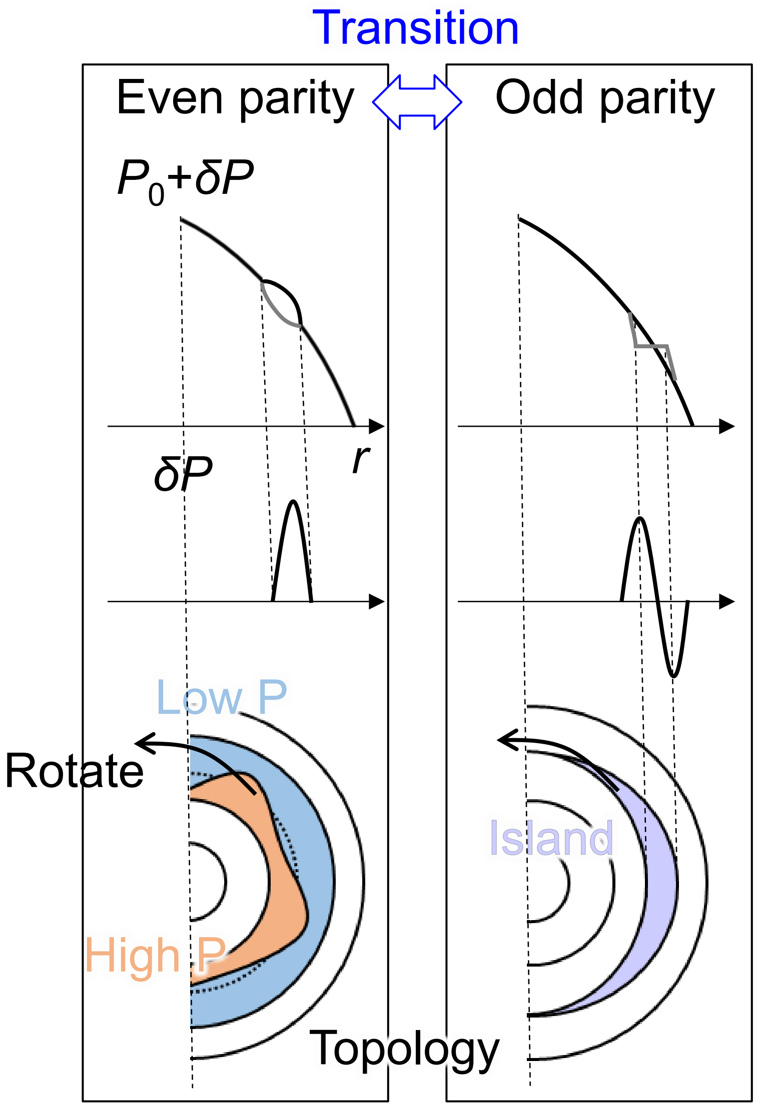
The situation would change because the pen. threshold dependence on collisionality changes depending on the mag. configuration. Ex. In R_{ax}=3.60m config. , pen. threshold is proportional to $\nu *^{+??}$

Magnetic Island Dynamics

What is parity transition?

- In magnetically confined fusion plasmas, parity of radial structure of MHD fluctuations is strongly related to topology of magnetic vessel
  - Odd parity shows existence of island structure that degrades plasma confinement property
- ‘Parity transition’ means rapid change in radial structure of dominant MHD fluctuation while its toroidal/poloidal mode number(m/n) and mode location are maintained
- Parity transition corresponds to change in magnetic topology
  - Even-to-Odd transition: island formation
  - Odd-to-Even transition: island disappearance

→Understanding physical mechanism of parity transition provides new insights into magnetic island physics



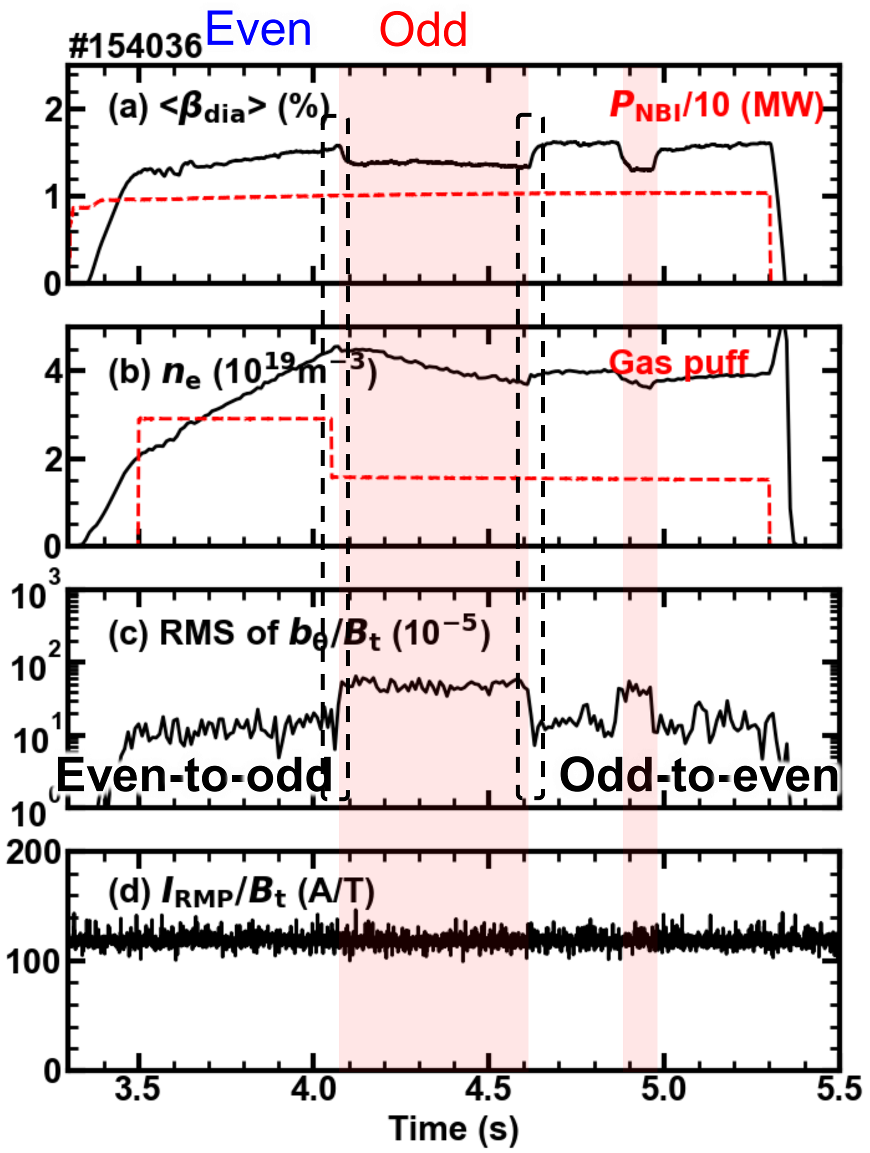
MHD Instabilities with Magnetic Islands in LHD and Island Formation/Disappearance

- The most expected MHD instability in LHD is the **resistive interchange mode**.
  - According to linear theory, RIC is **not accompanied by magnetic island formation**.
  - Indeed, observed MHD fluctuations have the local mode structure with no island [Watanabe et al., Phys. Plasmas, 2011].
- However, under specific experimental conditions, **an instability with an island has been observed** [Takemura et al., Phys. Plasmas, 2022].

In addition, **parity transitions** have been reported:

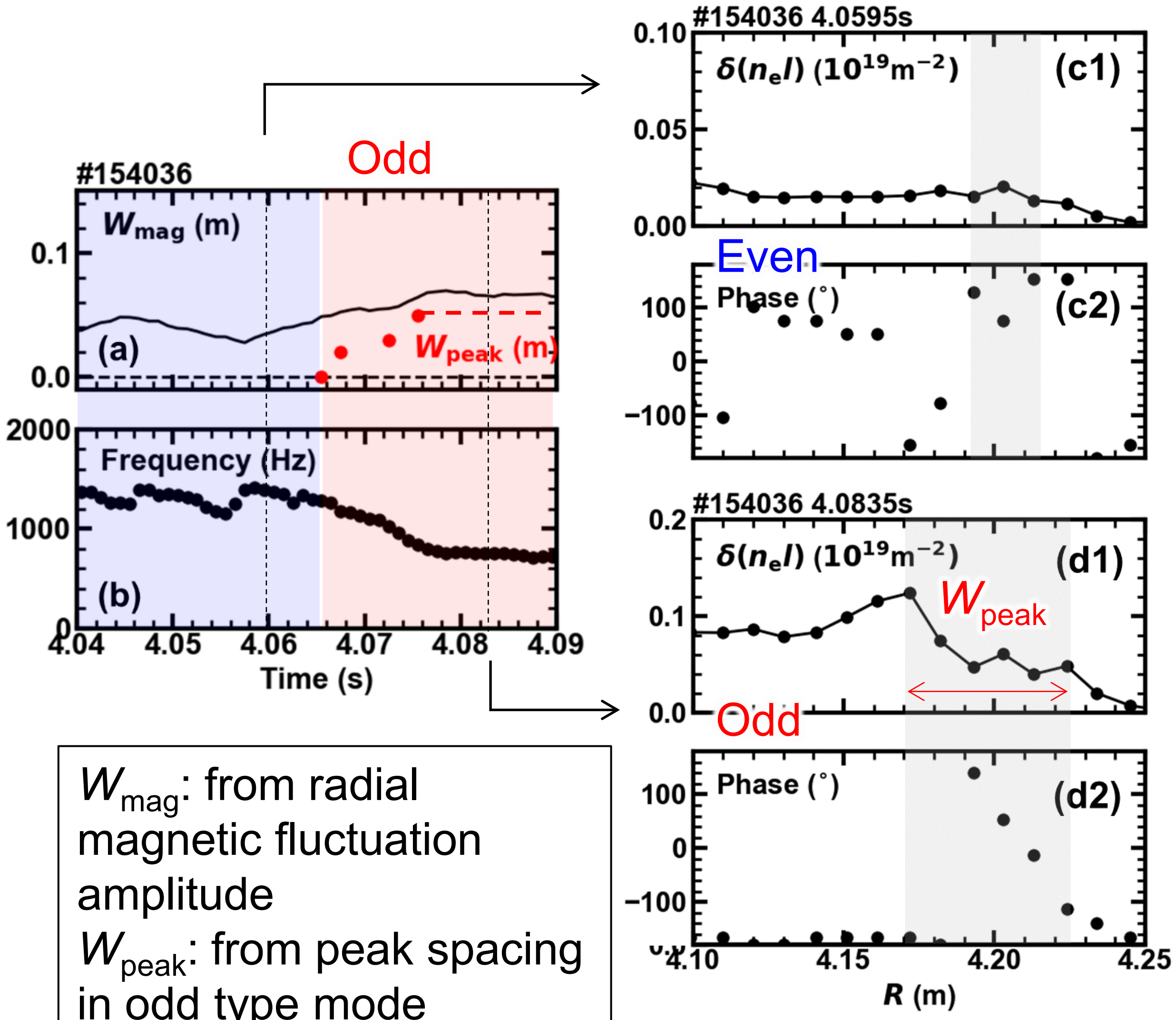
- From an even-parity mode to an odd-parity mode
- Or the reverse: from odd to even parity

→ The **first observation** reported in LHD
[Takemura et al., Scientific Reports, 2025]



Process of even-to-odd parity transition

- At t ~ 4.067 s, W_{peak} is finite
  →Island formation
- Around t ~ 4.06 s, the magnetic fluctuation amplitude rapidly grows, and after 5 to 6 cycles, W_{peak}, begins to expand
- W_{peak} saturates approximately 10 ms after the start of the expansion
  - W_{mag} and W_{peak} are in good agreement

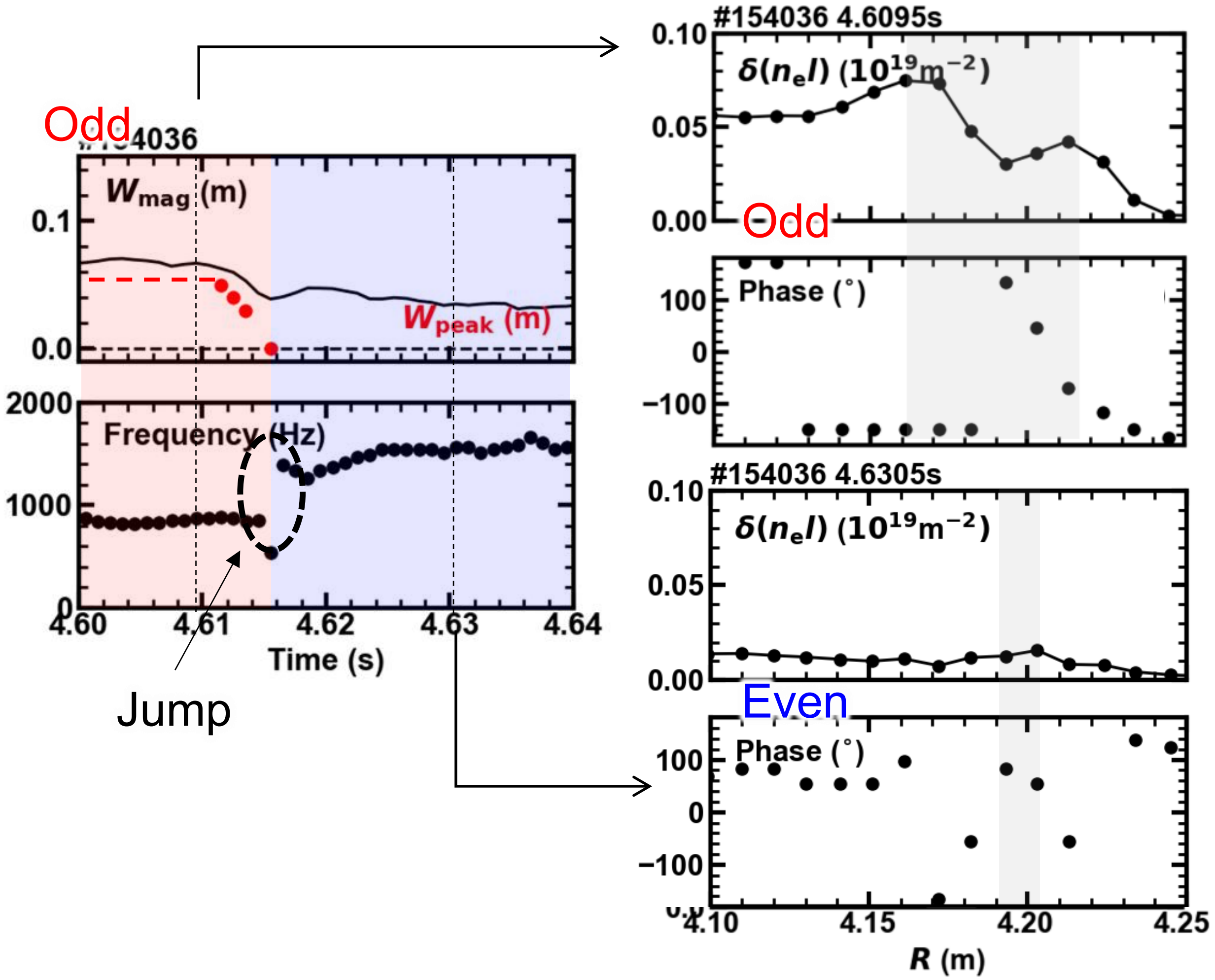


W_{mag}: from radial magnetic fluctuation amplitude
W_{peak}: from peak spacing in odd type mode structure

Process of odd-to-even parity transition

- The timescale for the magnetic island to disappear is approximately 4 ms
- W_{peak} begins to decrease together with the reduction in mode amplitude
- The mode frequency abruptly increases after island disappearance

→ The observed parity transition is thought to result from the competition between even- and odd-parity modes.



Frequency determination mechanisms of MHD activities

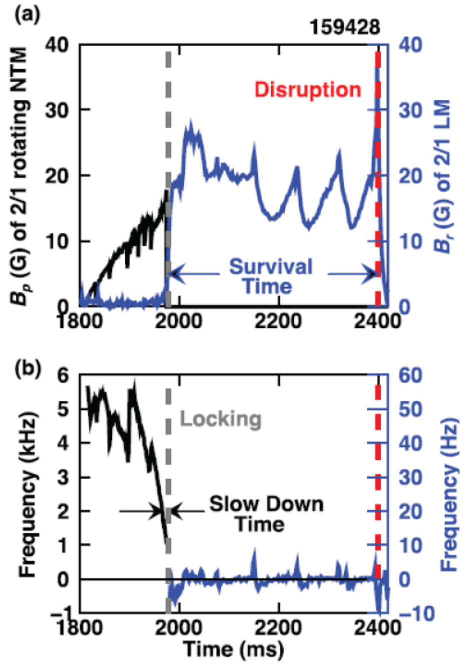
Importance of Studying Frequency Characteristics of MHD Instabilities

- Low-n MHD instabilities can lead to a rapid degradation of plasma confinement following a decrease in magnetic fluctuation frequency caused by the instability.
  - **Locked mode in tokamaks** (Sweeney et al., 2017)
  - **Locked-mode-like instability in LHD** (Sakakibara et al., 2015)

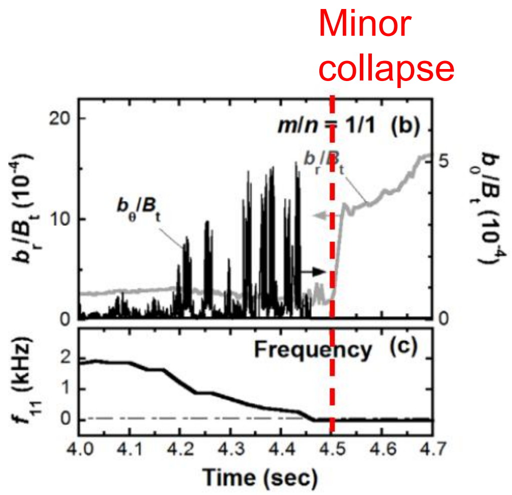
→ This study aims to clarify the physical mechanisms that determine the magnetic fluctuation frequency associated with MHD stability.

→ We investigate the frequency characteristics of MHD instabilities and compare them with existing torque balance models.

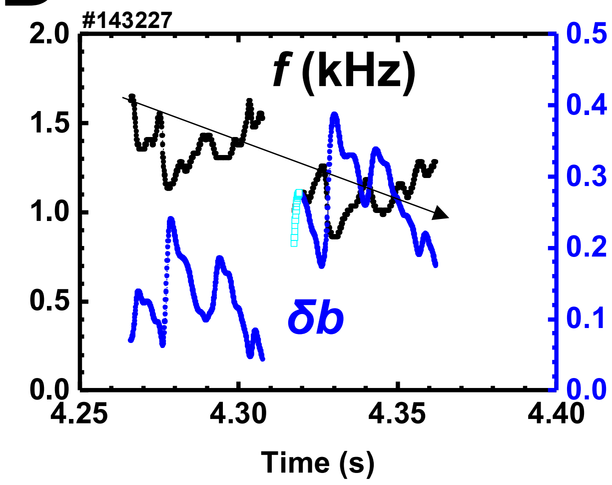
Locked mode (DIII-D) [Sweeney2017]



LM-like inst. (LHD) [Sakakibara2015]

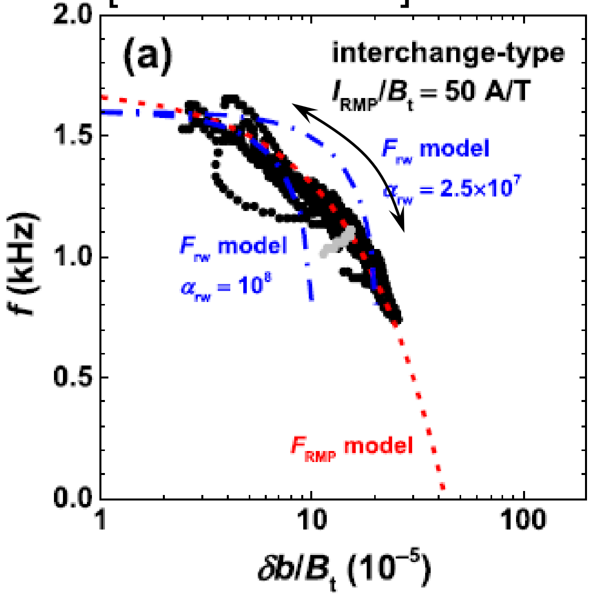


Comparison between Observed δb–f Trajectories and the Torque Balance Model in LHD



- In high-current LHD plasmas → **Locked-mode-like instability** (Takemura et al., 2019; 2021)
  - The instantaneous frequency exhibits transient increases and decreases.
  - Despite these variations, the δb–f trajectory follows the same path during both frequency rise and fall.
- This trajectory is consistent with the **torque balance model** proposed by Fitzpatrick (1993), which includes:
  - **Driving force from viscous torque**
  - **Braking force due to J × B interaction with external RMPs**

LM-like inst. (LHD) [Takemura2021]



Driving force NC viscosity $F_{\mathrm{VC}} \equiv \mu(\omega_0 - \omega)$

Braking force

$J \times B$ force between perturbed current due to instability and perturbed mag. field due to external RMP

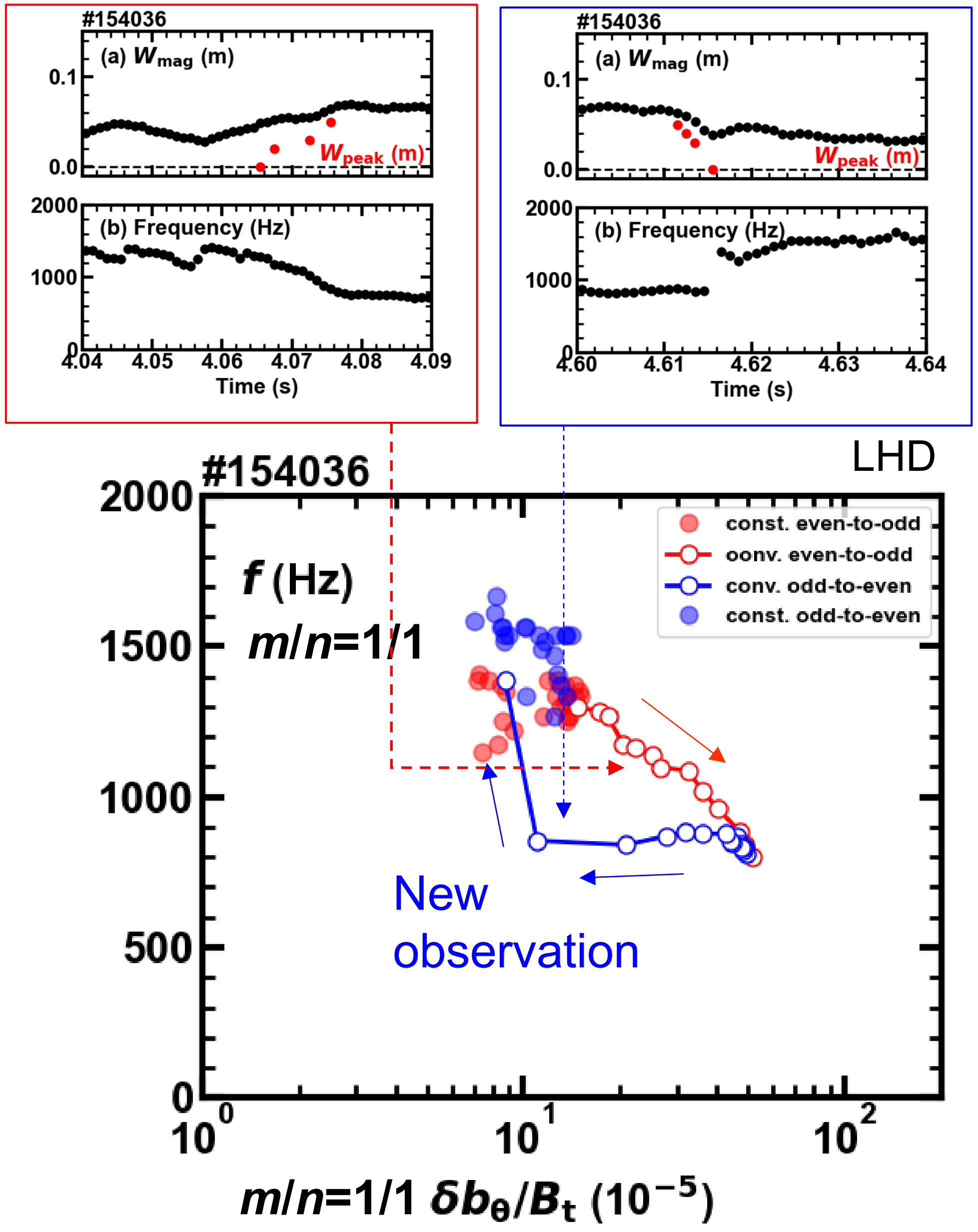
$$F_{\mathrm{RMP}} \equiv \delta b \delta b_{\mathrm{RMP}} \frac{\omega \tau_{\mathrm{v}}}{\sqrt{1 + \omega^2 \tau_{\mathrm{v}}^2}}$$

τ_{v}: wall constant time

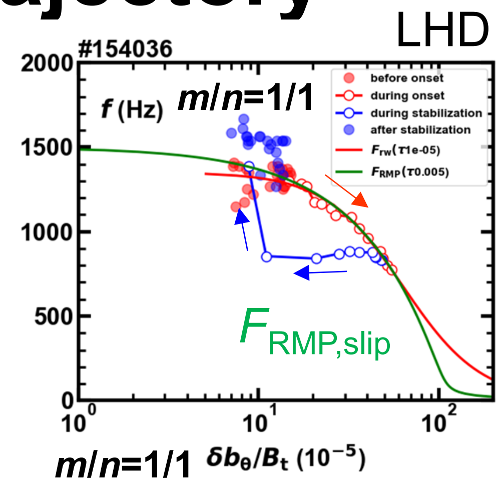
Observed Hysteresis in δb–f Trajectories

- In relatively high-density LHD plasmas, MHD instability with an island repeatedly grows and stabilizes (Takemura et al., 2021).
- A **hysteresis** is found in the δb–f trajectory
- **During the frequency-decreasing phase**:
  - The frequency gradually decreases in response to the increasing fluctuation amplitude.
- **During the frequency-increasing phase (a newly observed behavior)**:
  - The frequency remains nearly constant even as the amplitude decreases, followed by a **sudden jump in frequency**.

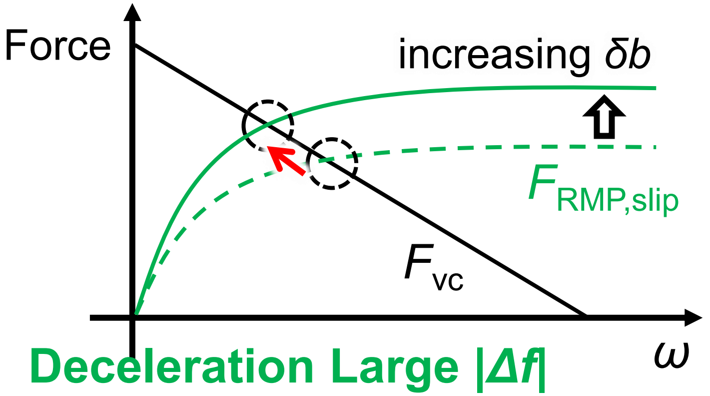
→ This behavior **cannot be explained by conventional torque balance models.**



Interpretation of Hysteresis in the δb–f Trajectory



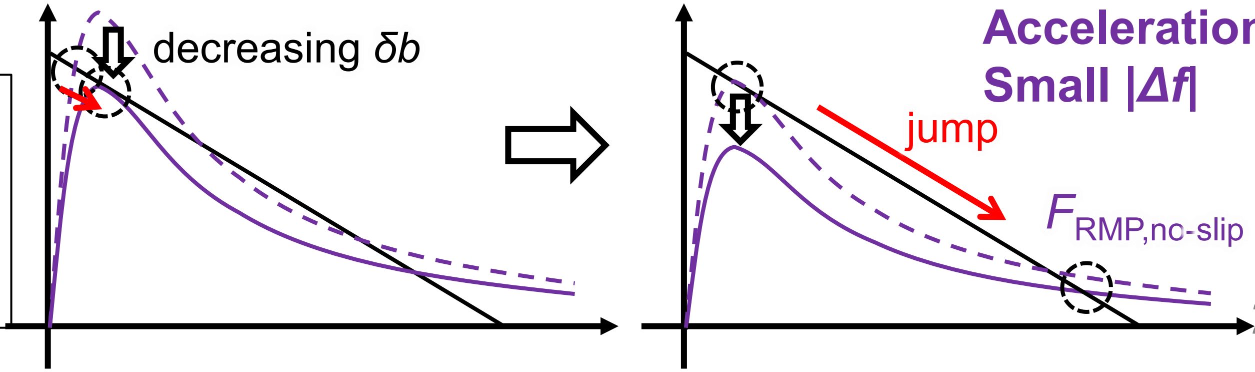
- The δb–f trajectory during the **frequency-decreasing phase** is consistent with the conventional F_{RMP} model.
- The unexplained nature of the frequency-increasing phase suggests that a new model is required for its interpretation.
- ***F_{RMP}* no-slip model**:
  - A small frequency difference with the external RMP leads to strong RMP shielding.



→ The frequency jump observed during the frequency-increasing phase can be qualitatively explained by the F_{RMP} no-slip model. [FEC2025]

$$F_{\mathrm{RMP,slip}} \equiv \delta b \delta b_{\mathrm{RMP}} \frac{\omega \tau_{\mathrm{v}}}{\sqrt{1+\omega^2 \tau_{\mathrm{v}}^2}} \quad (\text{large } |\Delta f|)$$

$$F_{\mathrm{RMP,no-slip}} \equiv \delta b \delta b_{\mathrm{RMP}} \frac{\omega \tau_{\mathrm{v}}}{1+\omega^2 \tau_{\mathrm{v}}^2} \quad (\text{small } |\Delta f|)$$



Short Summary
Torque balance model incorporating RMP penetration

- The δb–f relationship can be derived from the torque balance model (Fitzpatrick, 1993).
- External RMPs driven by eddy currents induced by MHD instabilities may co-rotate with the plasma,
  → resulting in a possible **“no-slip” state**.

τ_v: a function of *T*, *n*, and shape factor
δb_{RMP}: external RMP amplitude
ω_0: rotation frequency determined by viscosity, and it depends on *n*, *T*, shape factor, and gradient

Braking *J*×*B*	$F_{RMP,slip}$	$F_{RMP,no\text{-}slip}$	F_{rw}
Perturbed *B*	Ext. RMP with large $\|\Delta f\|$	Ext. RMP with small $\|\Delta f\|$	Eddy current
Perturbed *j*	Instability	Instability	Instability

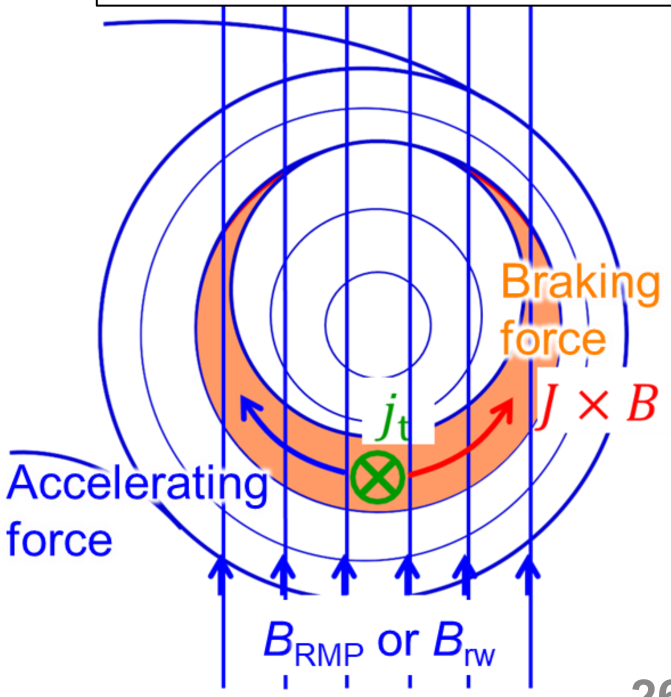
Driving force (NC viscosity) $F_{VC} \equiv \mu(\omega_0 - \omega)$

Braking force

$$F_{RMP,slip} \equiv \delta b \delta b_{RMP} \frac{\omega \tau_v}{\sqrt{1+\omega^2 \tau_v^2}} \quad (\text{large } |\Delta f|)$$

$$F_{RMP,no-slip} \equiv \delta b \delta b_{RMP} \frac{\omega \tau_v}{1+\omega^2 \tau_v^2} \quad (\text{small } |\Delta f|)$$

$$F_{rw} \equiv \delta b^2 \frac{\omega \tau_v}{1+\omega^2 \tau_v^2} \quad (\text{small } |\Delta f|)$$



AI-Assisted Prediction of Abrupt MHD Events

Abrupt event with International Collaboration

- Understanding and predicting **abrupt plasma phenomena** is critically important for advancing fusion research.
- In LHD, various abrupt events such as the Energetic-ion-driven Interchange Mode (EIC) and **Core Density Collapse (CDC)** have been observed.
  [EIC: Du et al., PRL, 2015], [CDC: Ohdachi et al., Nuclear Fusion, 2017]
- To better understand the fast dynamics of CDC, international collaborative research is underway:
  - Rotational transform profile measurements during CDC are being conducted in collaboration with IPP, Germany
  - Pressure profile evolution during CDC is being investigated using a high-repetition Thomson scattering system (**fast TS**) with University of Wisconsin–Madison

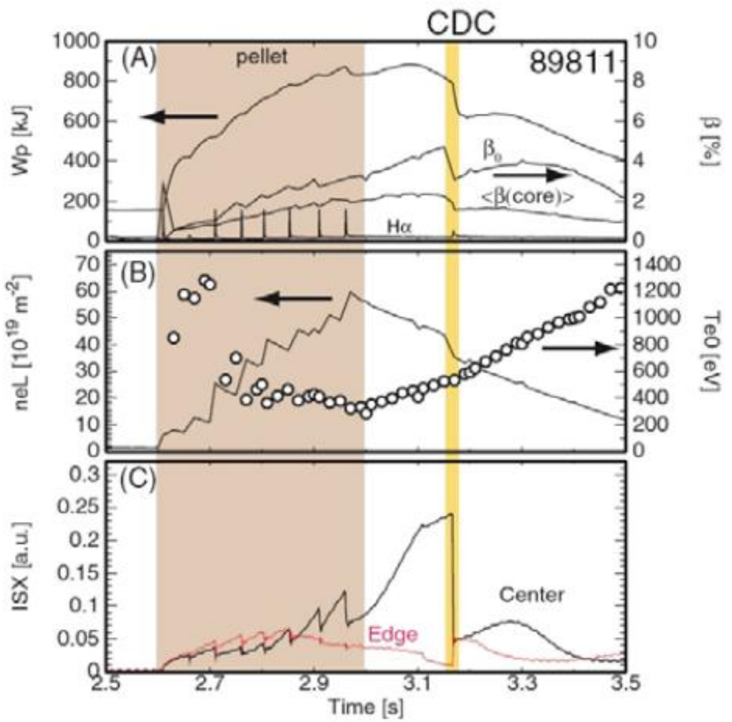
  ※A formal collaboration agreement has been signed with the UW-M

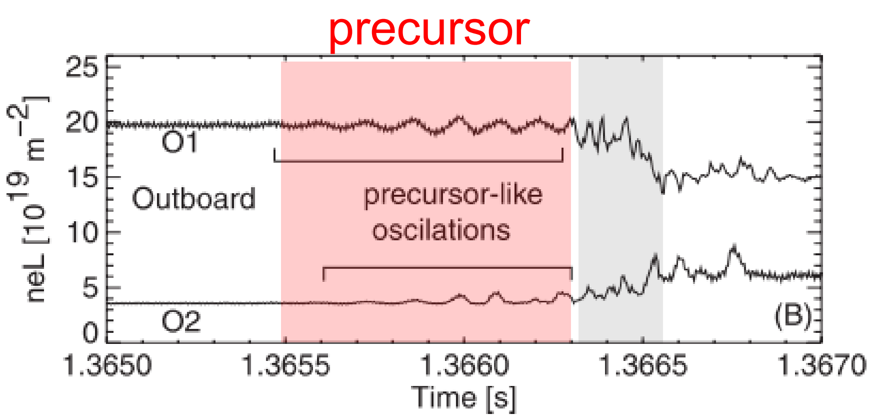
→ Due to the short measurement time of fast TS, advance event prediction and timely triggering are required

Abrupt event in LHD—Core Density Collapse—

- Injection of multiple pellets into LHD plasmas enables the formation of super central density plasmas
  - One of the operational scenarios aimed at achieving high-performance plasma conditions
- In such plasmas, core density collapse (CDC) events have been observed [S. Ohdachi et al., Nucl. Fusion, 2017]
  - The collapse proceeds very rapidly, typically within a few milliseconds
- Just before the collapse, precursor oscillations in the density signal are often observed
- However, due to variations in waveform patterns, simple threshold-based detection is difficult

→ A machine learning-based method has been developed for detecting precursor oscillations

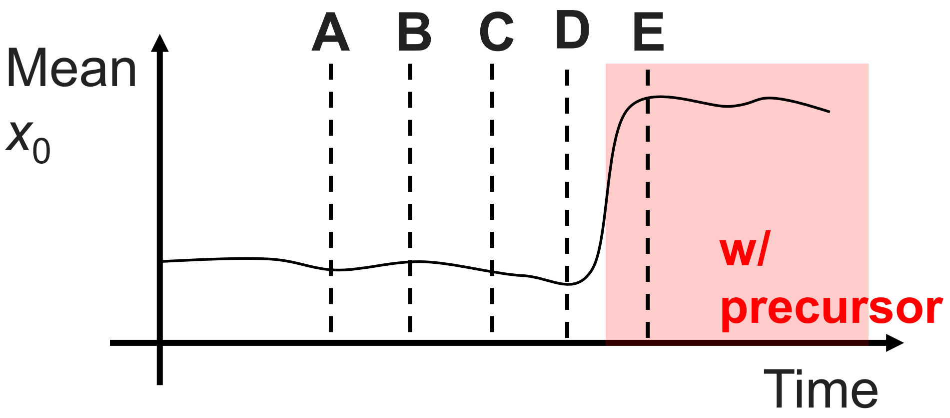




Anomaly detection using Isolation Forest

- For unsupervised, fast, and lightweight anomaly detection, the Isolation Forest is employed
  - Data are split based on randomly selected features and thresholds to construct decision trees
  - Anomalies are more easily isolated

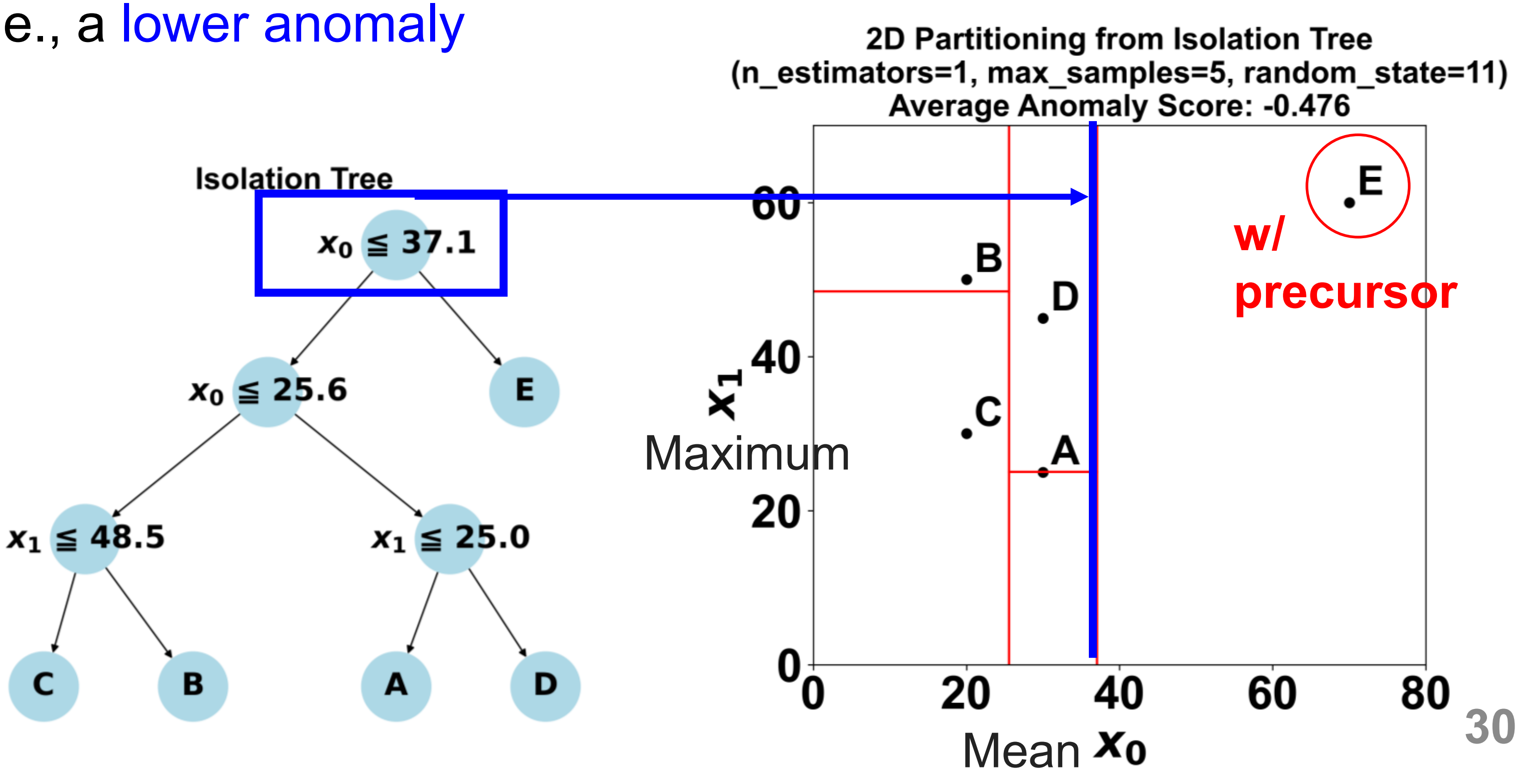
  →A shorter path to the leaf (i.e., a lower anomaly score) indicates anomaly



  - The data are classified as anomalous or normal based on a threshold comparison

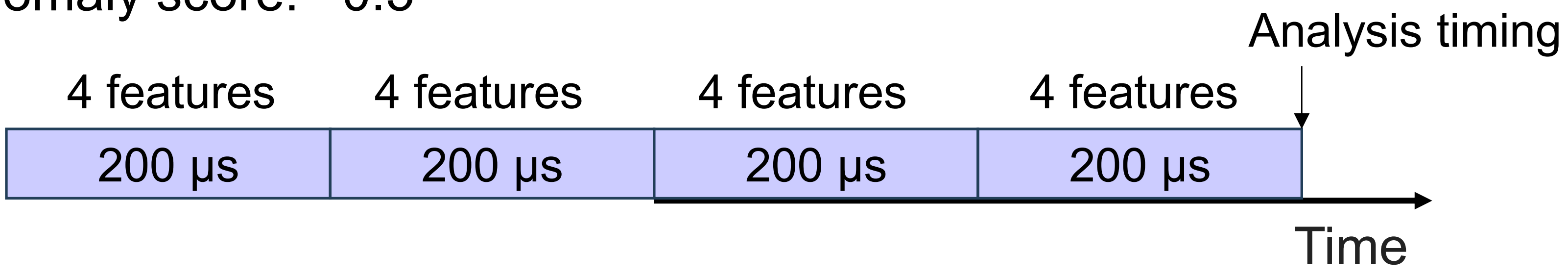
Anomaly score $-2^{\frac{E}{C}}$

- The average path length E across all isolation trees



Parameter Settings for Isolation Forest

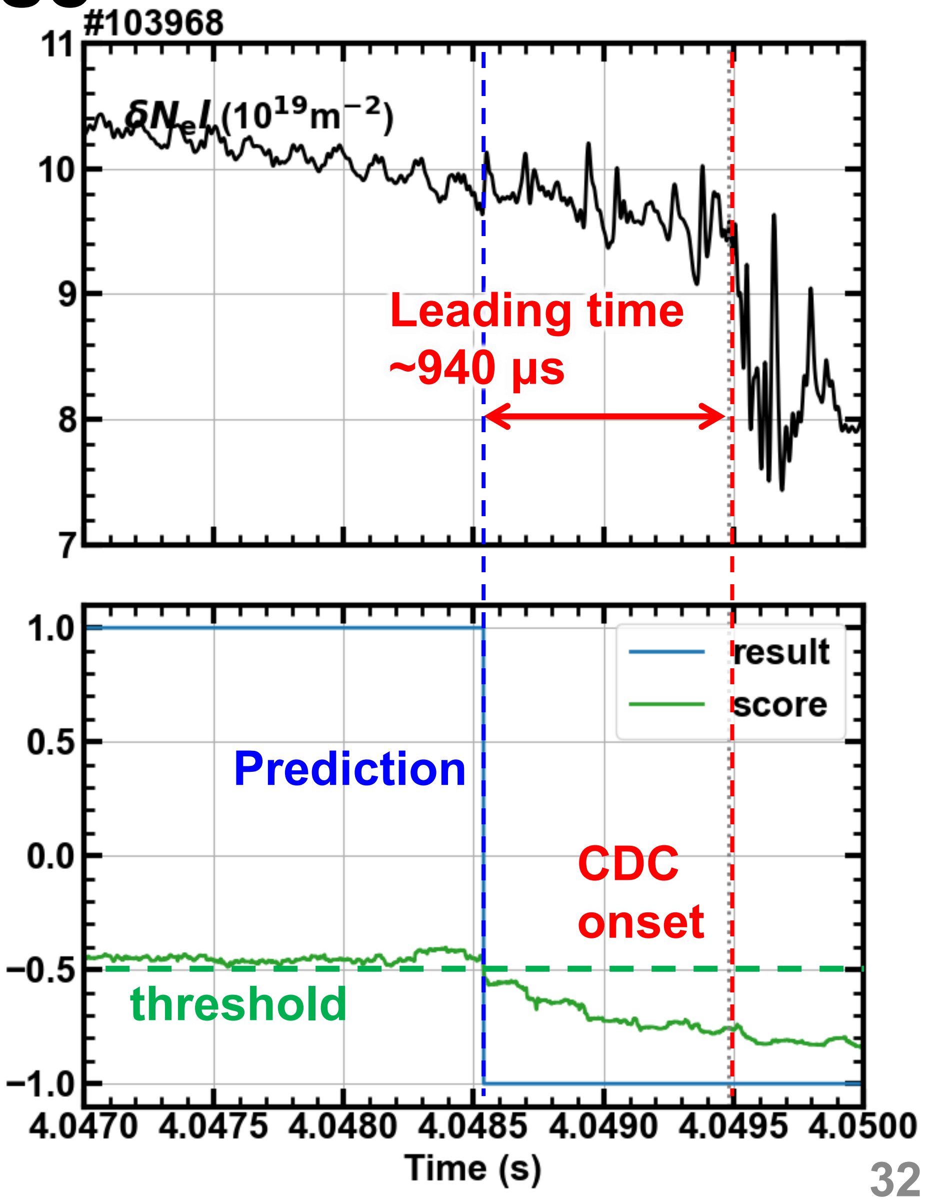
- Use electron density signals at 1 MS/s
- 16 features in total
  - Four basic features are considered: mean, maximum, minimum, and peak-to-peak value
  - A window of 800 μs is divided into four segments, and features are calculated for each segment
  - Selected features, window length and the number of segments are optimized
- Number of weak learners (decision trees): 100
  - Too many trees may lead to overfitting and high computational cost, while too few may reduce accuracy.
- Number of samples per tree (sub-dataset size): 1024
- Threshold for the anomaly score: –0.5



Successful prediction several hundred microseconds before the collapse

- Leave-One-Out Cross Validation (LOOCV) was performed using 10 CDC discharges
  - nine for training and one for testing
- CDC onsets were successfully predicted on average about 300 μs, with the earliest prediction occurring up to 960 μs in advance

→ The leading time is within the ~200 μs delay of fast TS in LHD



CDC onset:
The time derivative of the electron density exceeded the threshold within 1 ms.

Real-time trigger device with microcontroller implementation

- The algorithm was implemented on a microcontroller to develop a trigger-generation device
- The microcontroller platform, MIMXRT1170-EVKB
  - a high-speed clock (up to 1 GHz), large memory resources, and support for real-time processing
  - Accepts analog input and provides digital output (TTL) signals to issue diagnostic triggers.
- Analog signals are digitized at 1 MHz using the microcontroller's built-in A/D converter
- Anomaly scores are computed every 10 μs
- The model is trained offline in Python using Isolation Forest. In real time, anomaly scores are computed in C by comparing extracted features with a preset threshold

→ Planned for LHD validation in late 2025, the system targets real-time prediction and diagnostic triggering

MIMXRT1170-EVKB manufactured by NXP Semiconductors

Summary

- This presentation highlights recent MHD research in LHD to encourage collaborative studies within the helical device community.

1. **Stabilization of resistive interchange modes by external RMPs**
2. **Island dynamics based on Parity transitions in MHD mode structure**
3. **Frequency dynamics and δb–f hysteresis analysis**
4. **AI-assisted prediction of abrupt events (e.g., CDC)**

- **LHD experimental proposals are open from June 2–13, 2025**
    - The experiments will be conducted from mid-September to the end of December 2025