Off-Axis Fishbone-like Instability and Excitation of Resistive Wall Mode in JT-60U and DIII-D

by

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with

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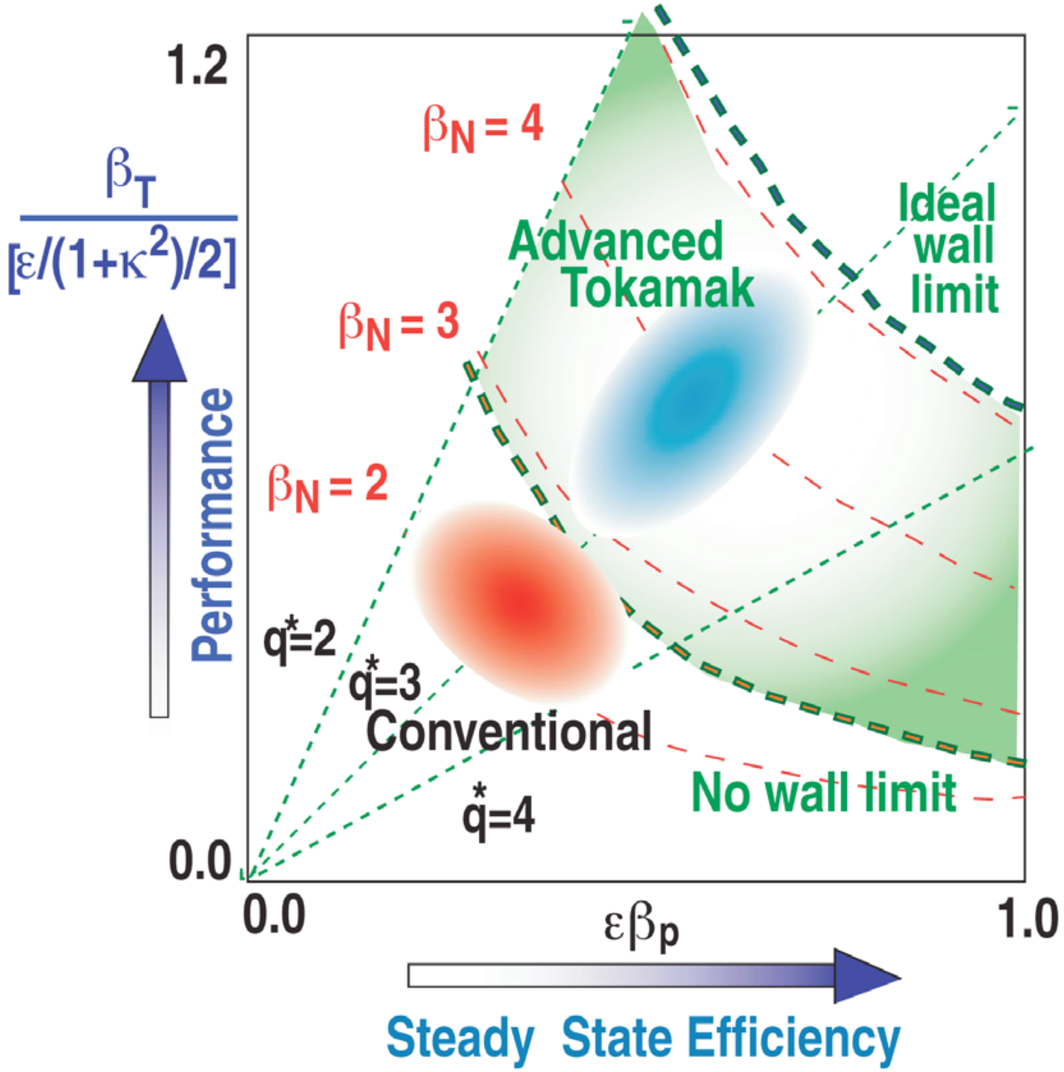
Presented at the
52nd Annual Meeting of
the APS Division of Plasma Physics
Chicago, Illinois

November 8-12, 2010

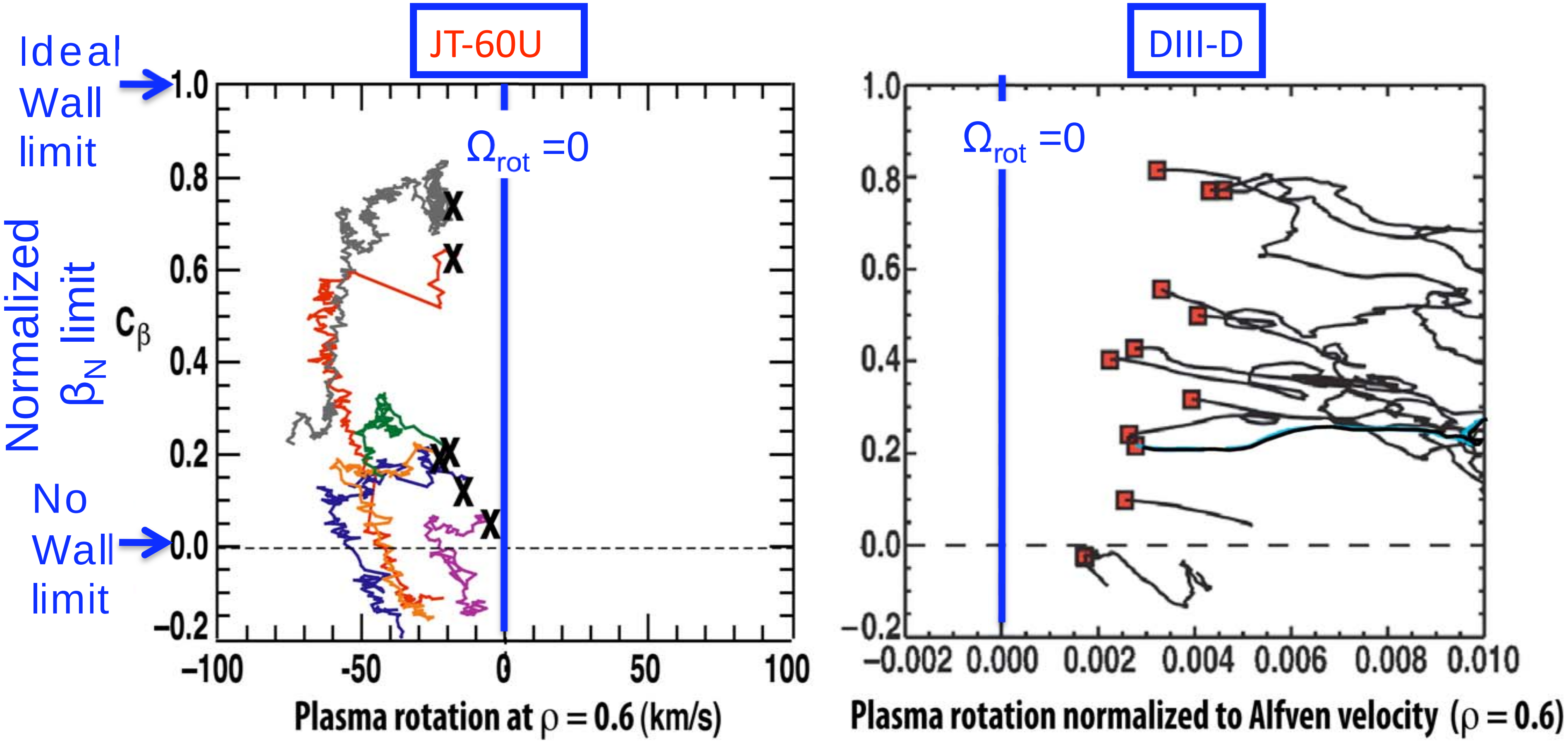
Tokamak-reactors Have Been Looking for High β_N Regime



Exploration in high β_N

- Well above no wall limit
- Resistive wall mode (**RWM**) suppressed
- **Reactor-relevant low rotation plasmas**

JT-60U and DIII-D Successfully Accessed High β_N Regime



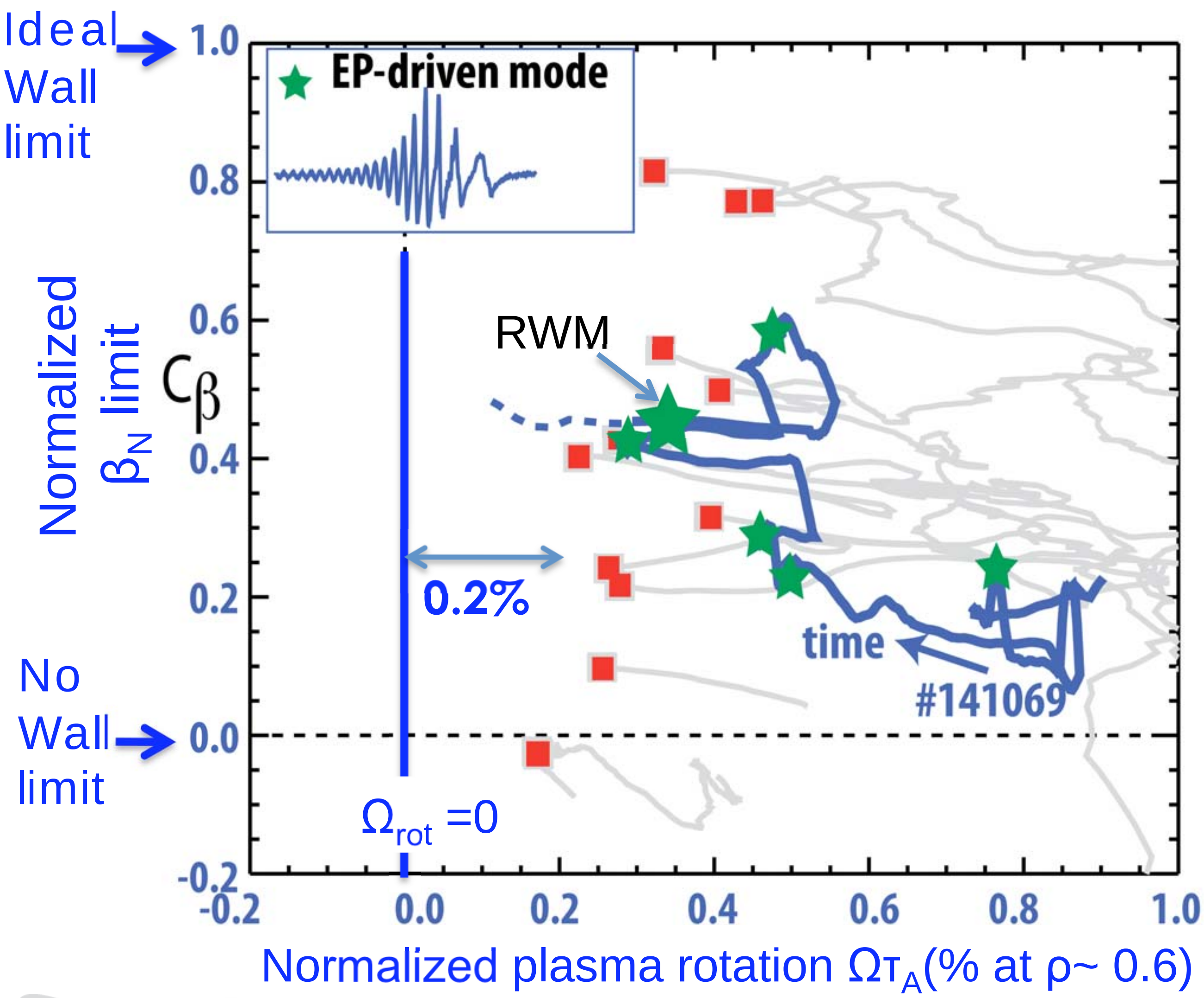
M. Takechi et al.,
Phys. Rev. Lett (2007)

E Strait, et al.,
Phys. Plasmas (2007)

- **However, MHD instabilities prevented long-duration high β_N discharge**

Energetic Particle (EP) Driven Modes Seem to Terminate Many Discharges at High b and Low Rotation

DIII-D

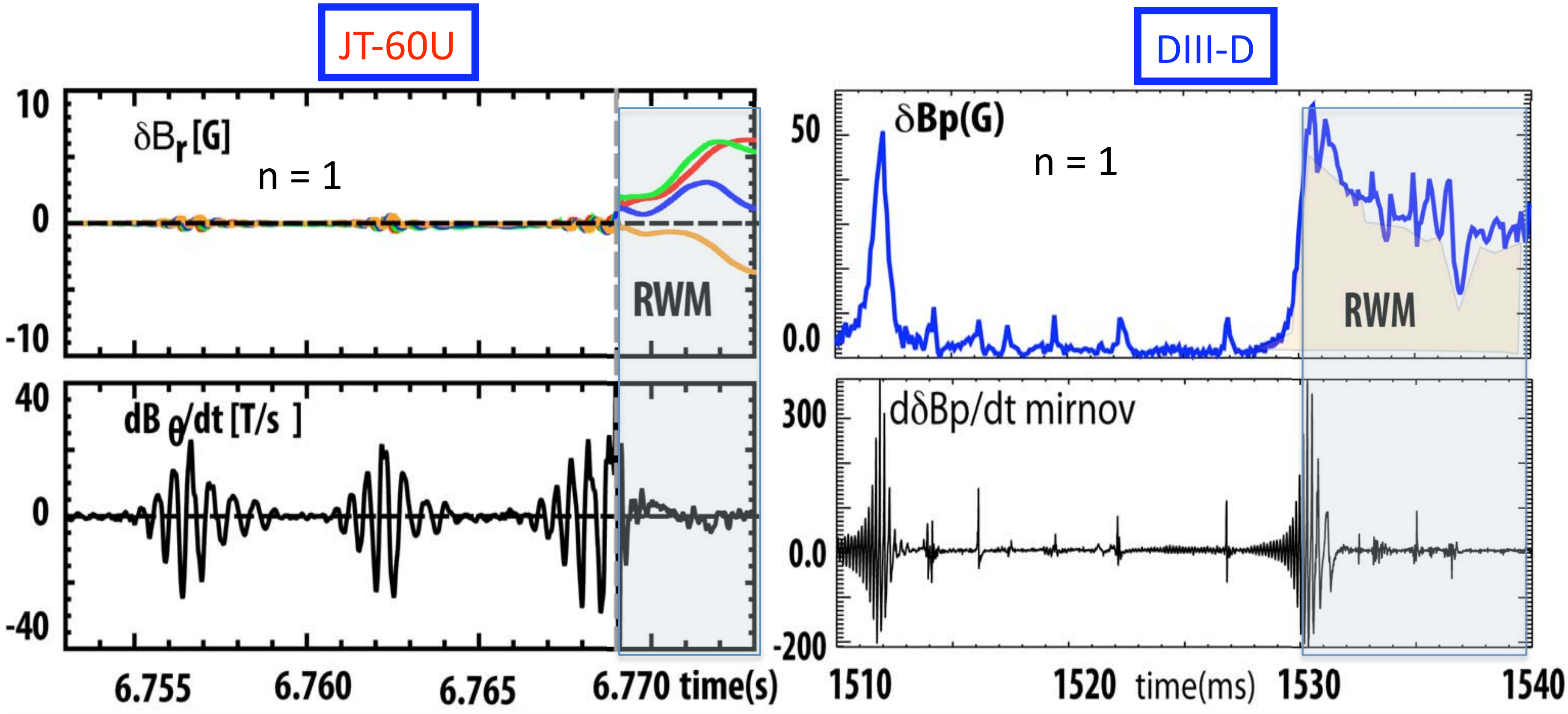


Low rotation plasma

$\Delta(\Omega\,\tau_A) \sim 0.2\%$ equivalent to $\Delta V\phi \sim 10$ km/s

is critical

The Characteristics of These Instabilities are Similar in JT-60U and DIII-D



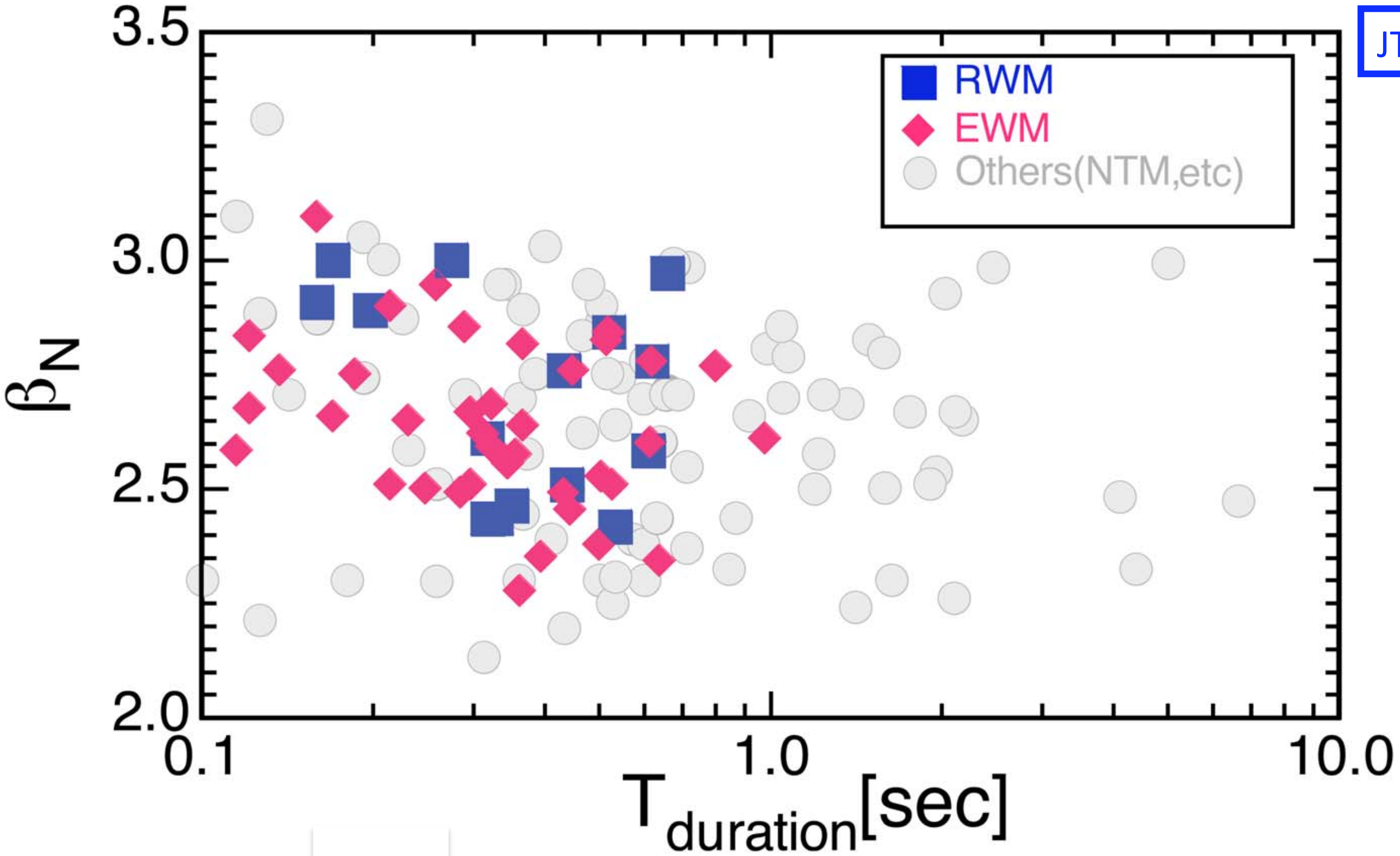
"Energetic particle-driven Wall Mode (EWM)" in JT-60U: G. Matsunaga, et al., PRL (2009)

"Off-axis fishbone-driven" RWM in DIII-D: M. Okabayashi. et al., Nucl. Fusion (2009)

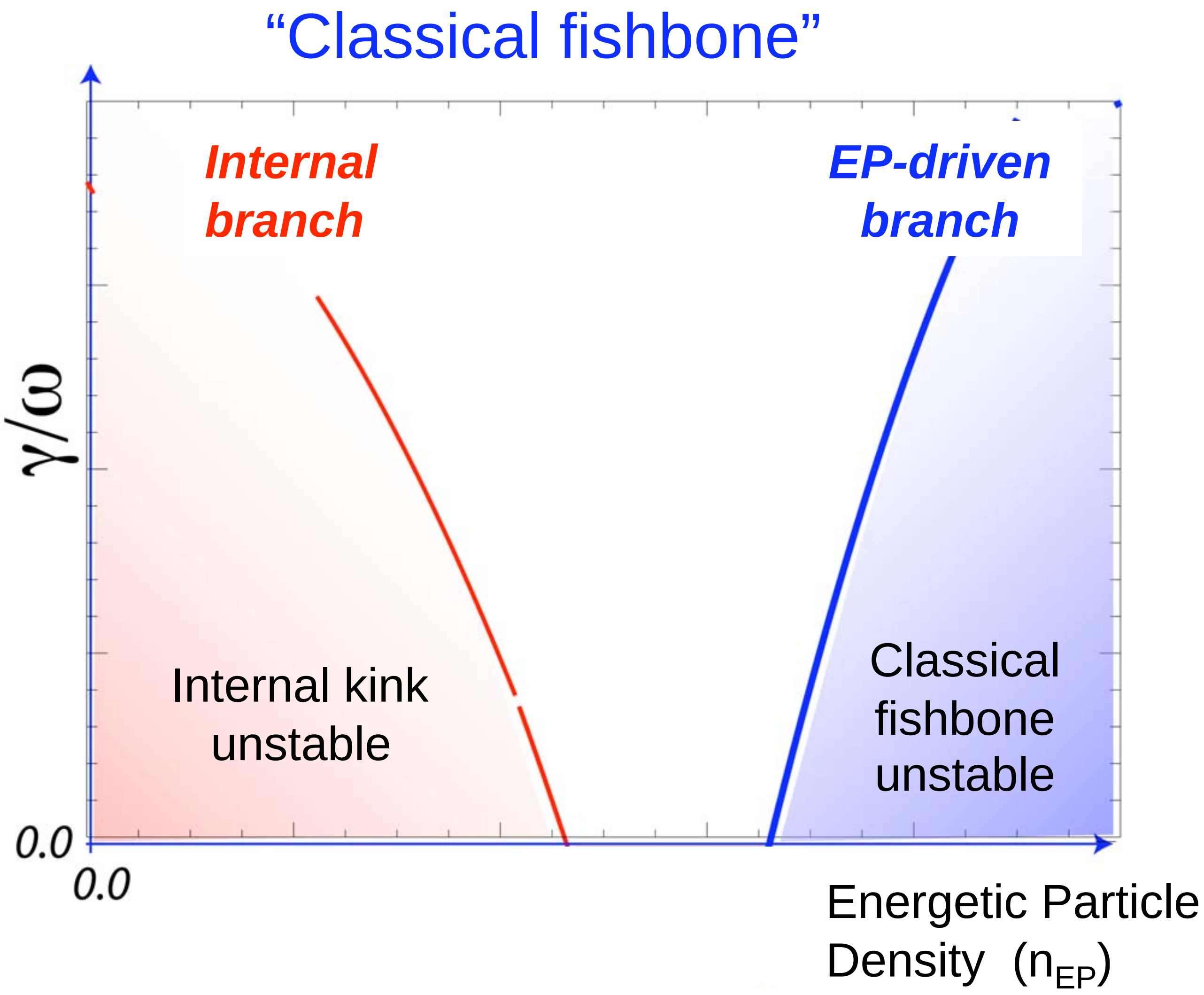
- We simply use **"Off-axis-Fishbone" Mode (OFM)**

Early EP-driven Mode Onset was a Serious Obstacle for Long-duration High β_N Discharges in JT-60U

JT-60U

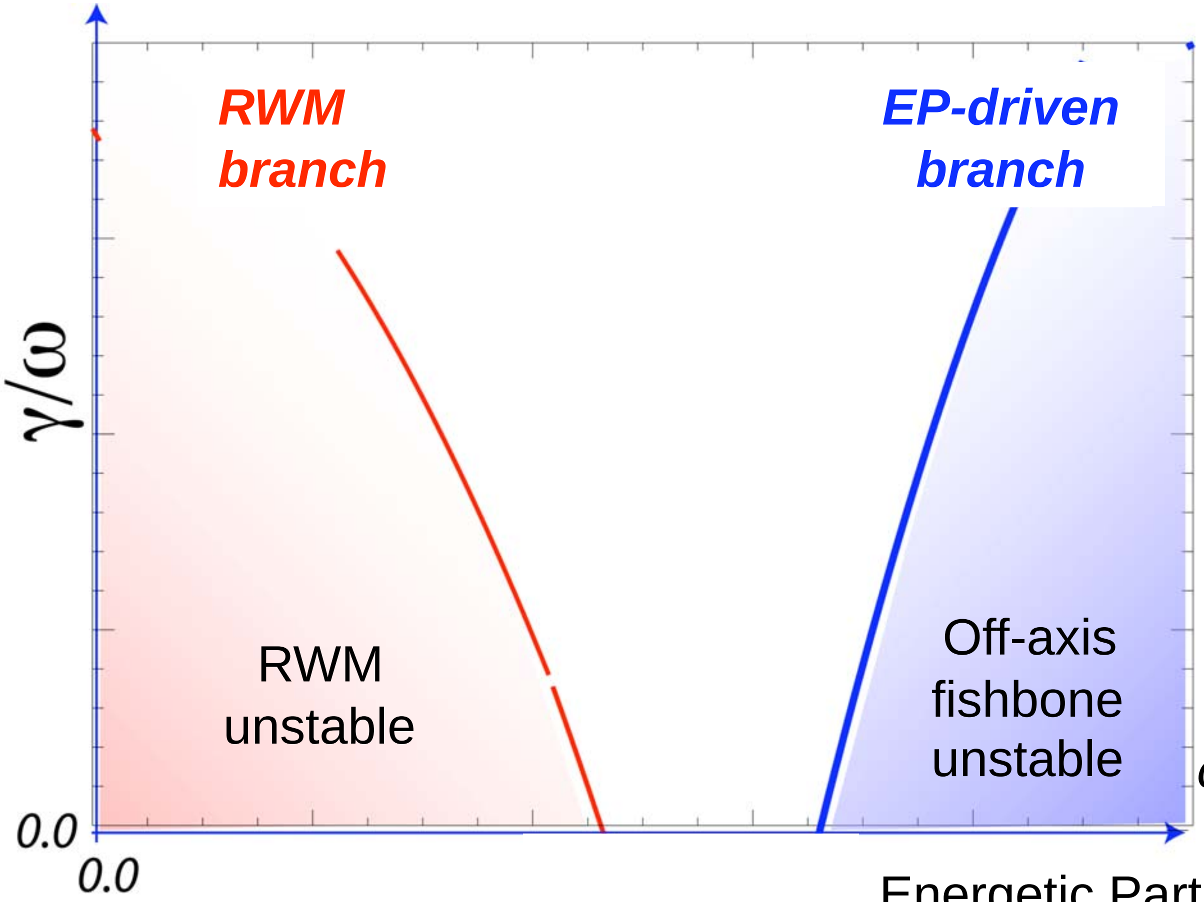


Classical Fishbone Provides a Paradigm for New EP-driven Mode



EP-driven Mode in Wall-stabilized High β_N Plasmas

- **Internal kink -> External kink -> RWM**

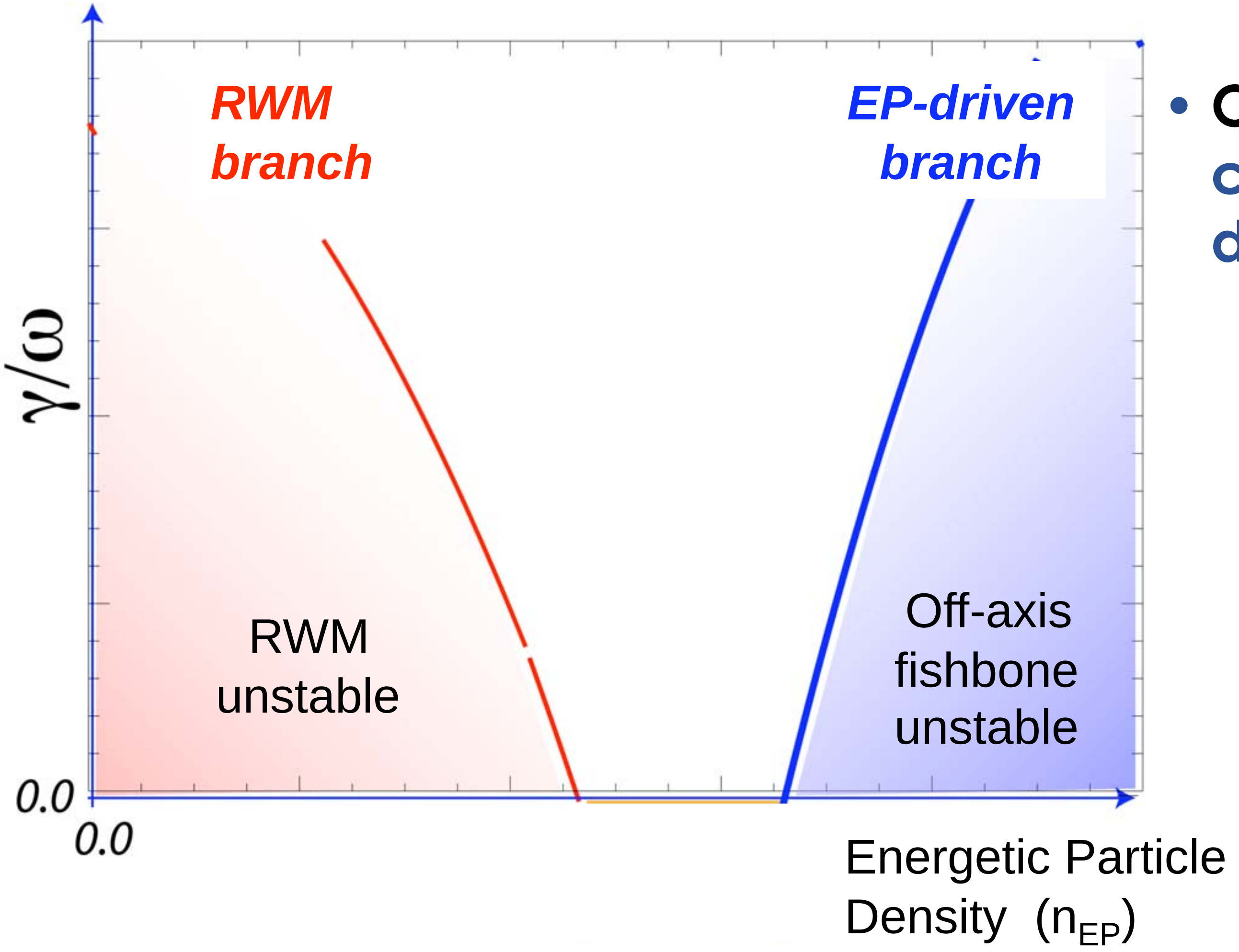


Energetic Particle Density (n_{EP})

- **RWM Stability** provided by
  - Resistive wall
  - Plasma rotation
  - Kinetic effects
    - Thermal and
    - **EP precession drift**

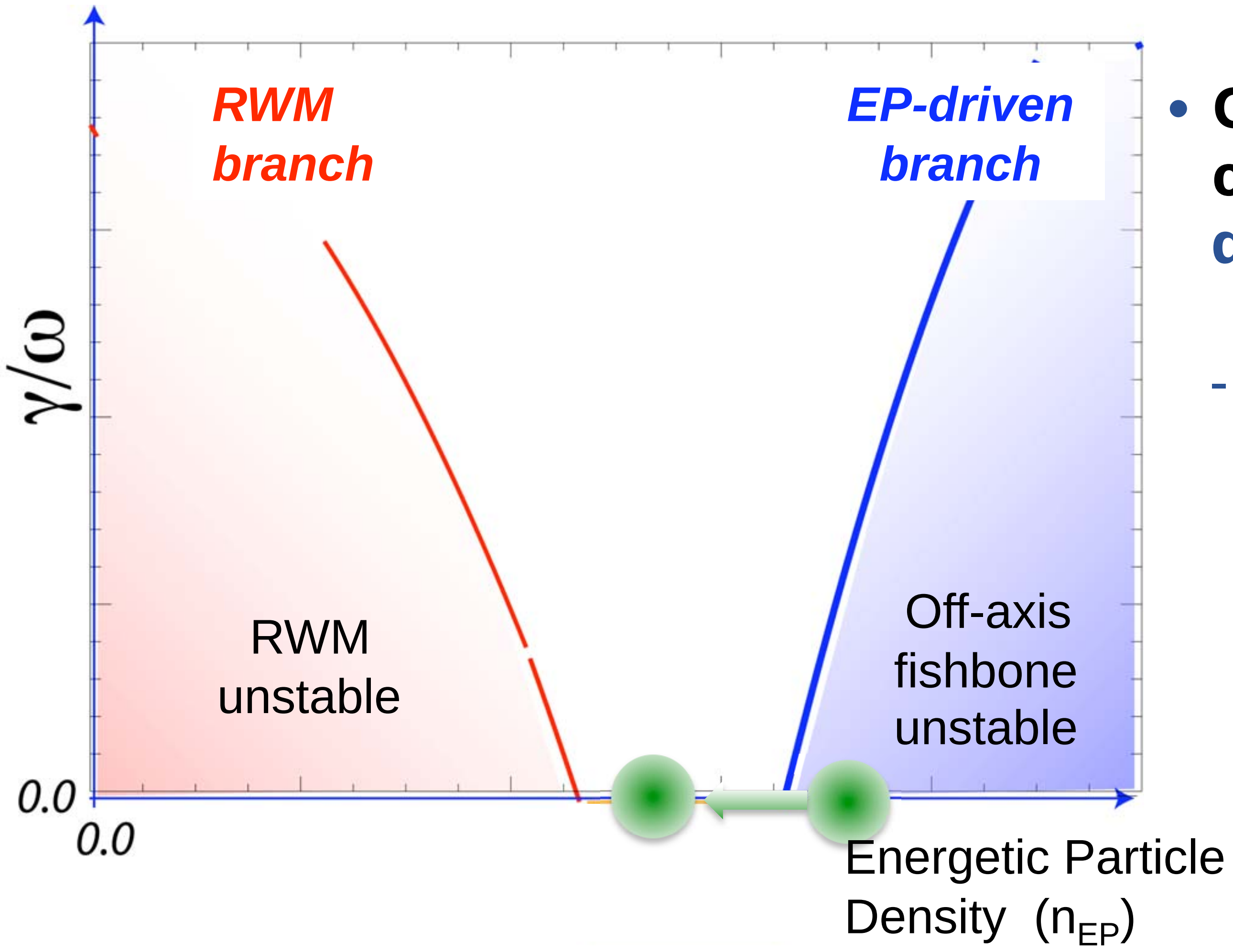
$$\delta W_{\text{kinetic}} \sim \int dV \frac{(\omega - ....)}{(\omega - \omega_{D.EP} - \omega_{rot} + ...)}$$

Hypothesis: Transiently-driven EP Mode Excites RWMs



- **Off-axis fishbone** can have two destabilizing effects

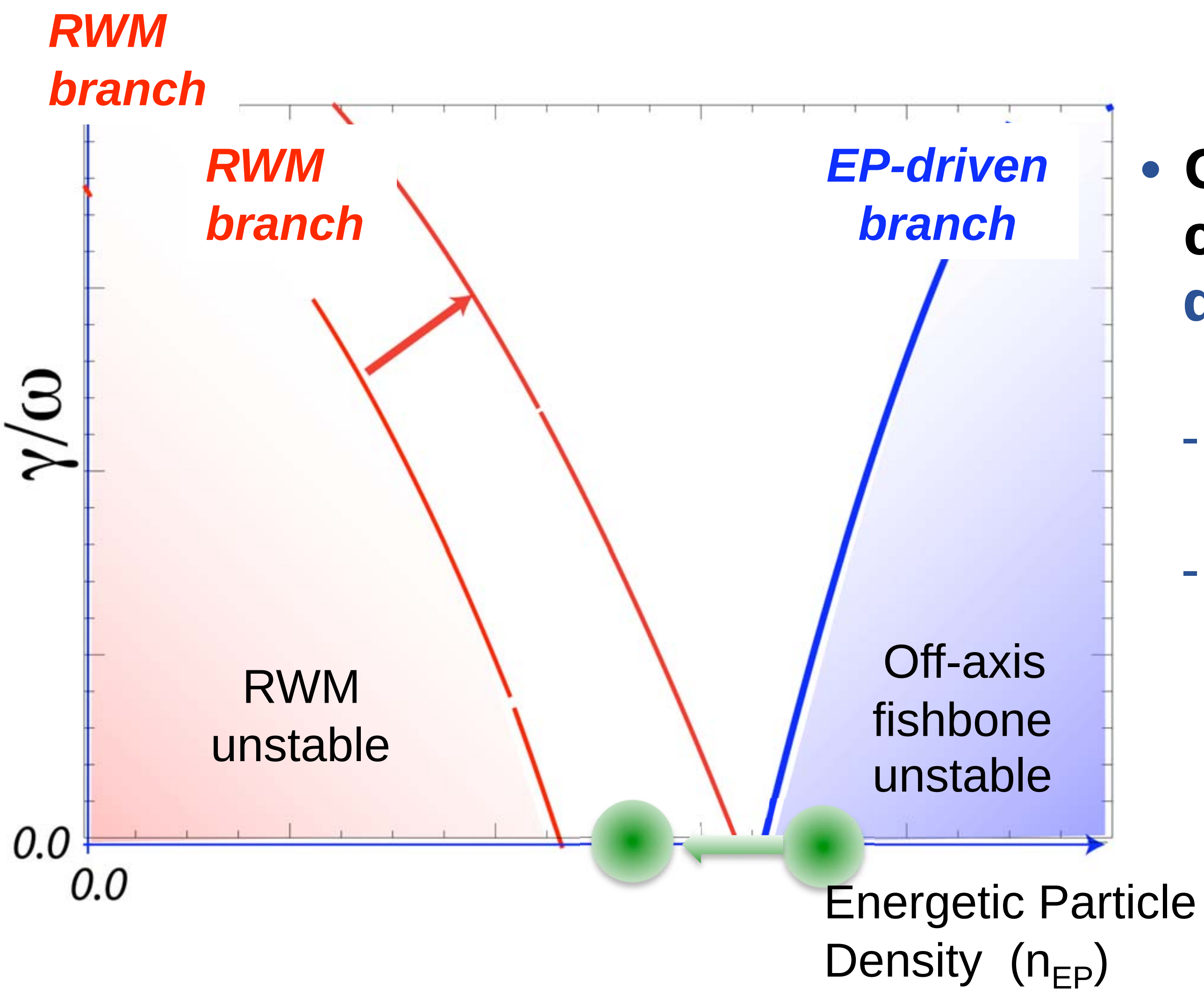
Hypothesis: Transiently-driven EP Mode Excites RWMs



- **Off-axis fishbone can have two destabilizing effects**

  - Reduces EP density

Hypothesis: Transiently-driven EP Mode Excites RWMs



- **Off-axis fishbone can have two destabilizing effects**
  - Reduces EP density
  - Reduces plasma rotation

Outline

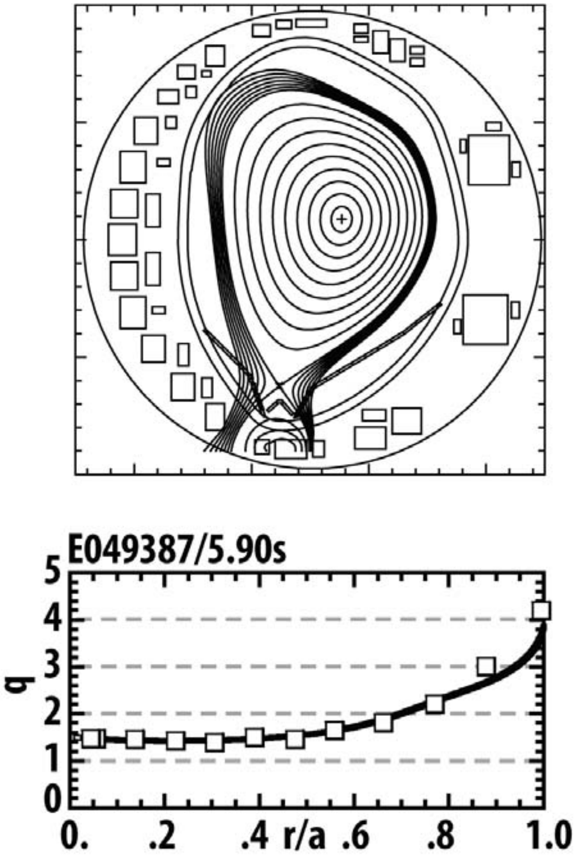
- **Energetic Particle (EP)-driven "Energetic Particle Wall Mode(JT-60U) and "Off-axis-Fishbone Mode (DIII-D)" can trigger RWM in JT-60U and DIII-D, preventing the high β_N operation**

  - During the burst, EP density n_{EP} decreases
    plasma rotation Ω_{rot} decreases
    → reducing the EP kinetic effect

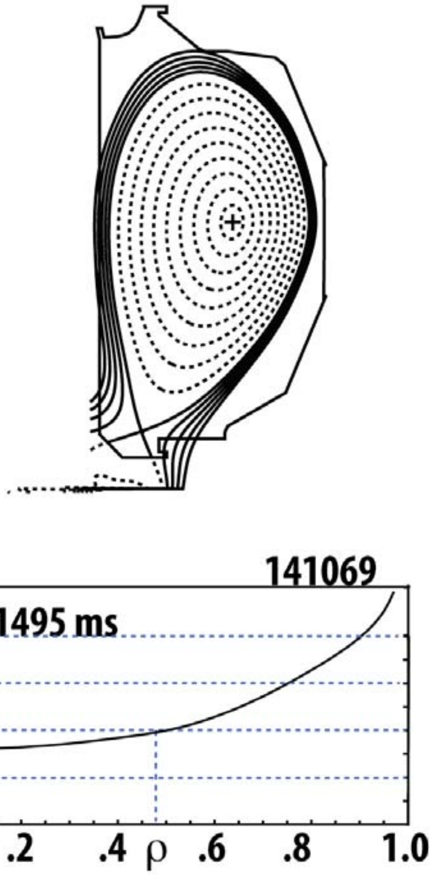
- **EP-driven mode Characteristics:**
  - Similar in JT-60U / DIII-D,
    including non-linear mode distortion
  - EP loss coincided with the increase of mode distortion

- **MARS-K (RWM stability analysis) demonstrates the role of EPs**

The Off-axis Fishbone-like Mode has been Explored with Parameters Similar in JT-60U and DIII-D: q_0 well above Unity

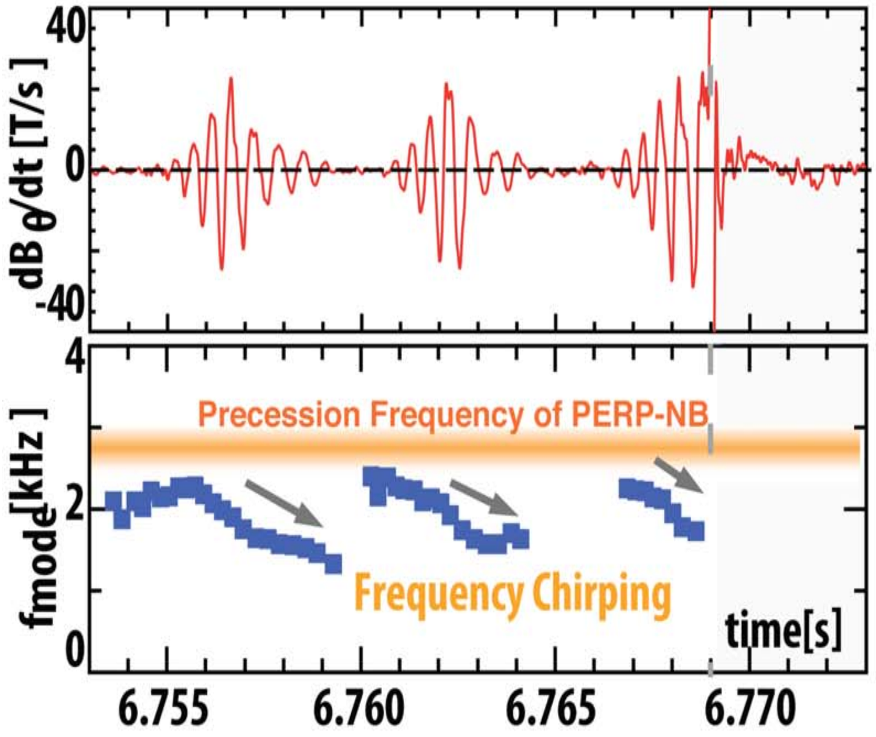


JT-60U		DIII-D
2.4	βn,no-wall	2.1
3.2	βn.ideal-wall	2.6
3.0	βn (exp)	2.3
0.9	Ip (MA)	1.0
1.5	Bt (T)	1.7

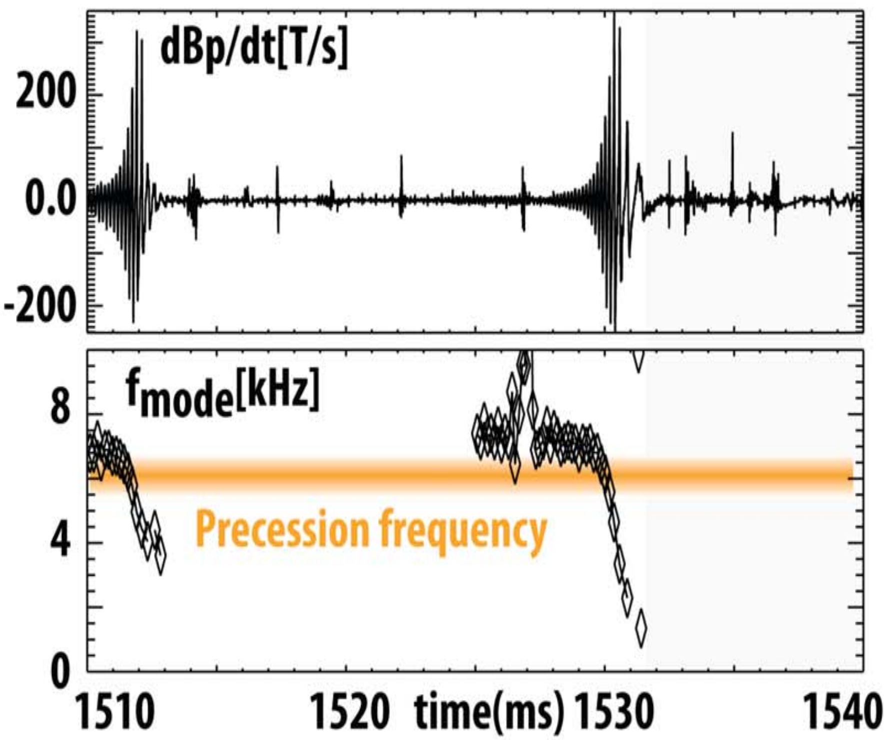


Frequency Behavior Suggests that these Bursting MHD Modes are EP-driven

JT-60U

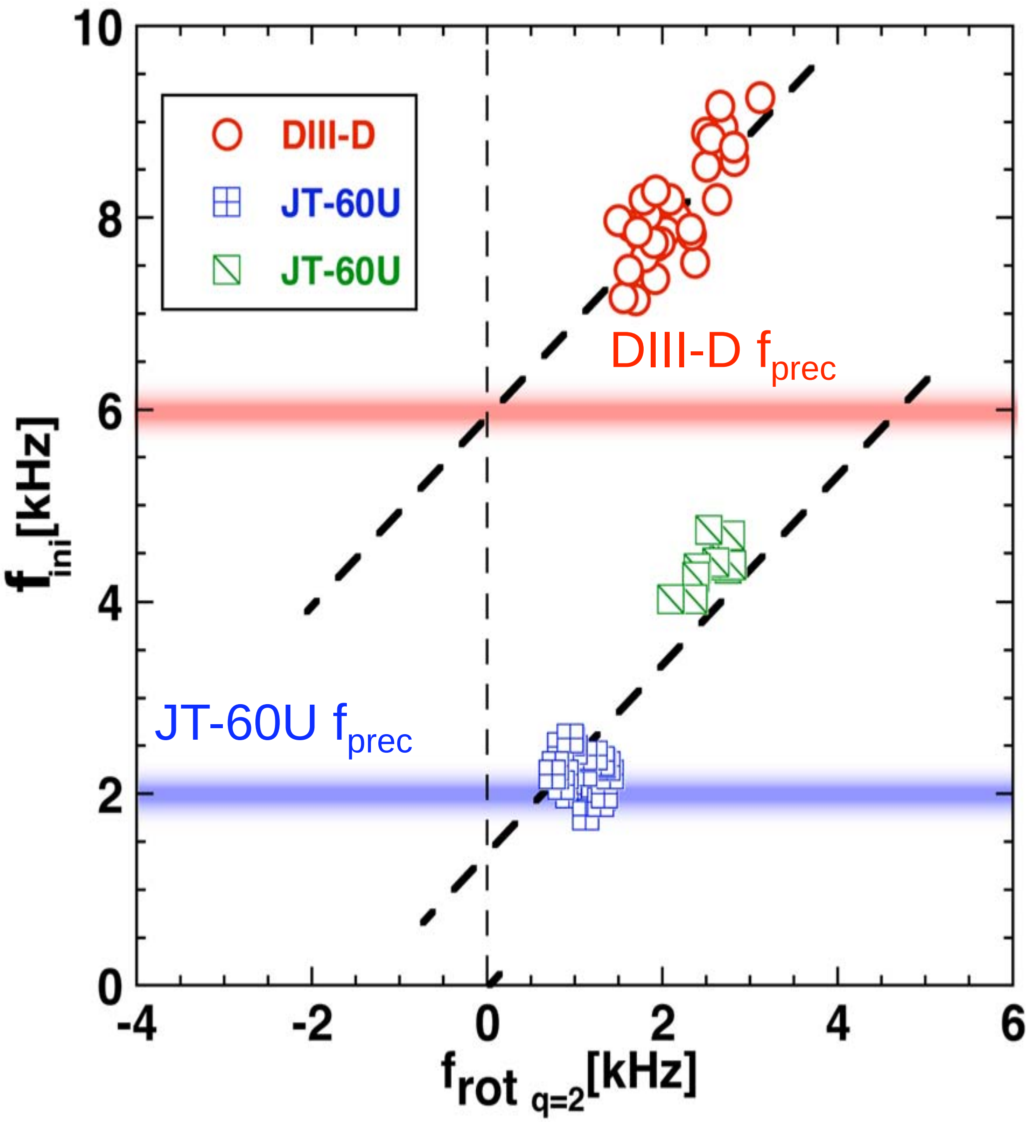


DIII-D



- **The initial frequency is close** to precession frequency of trapped Eps
- Mirnov frequency **chirping down** to very low frequency ≤ 1 kHz
- Mode is localized around q=2 [Matsunaga, PRL 2009]

The Bursting Mode Resonates with the EP Precession Drift like Classical Fishbone



JT-60U/DIII-D

- **Initial frequency**
  (at the onset of burst)

$$f_{init} = f_{prec} + f_{rot}$$

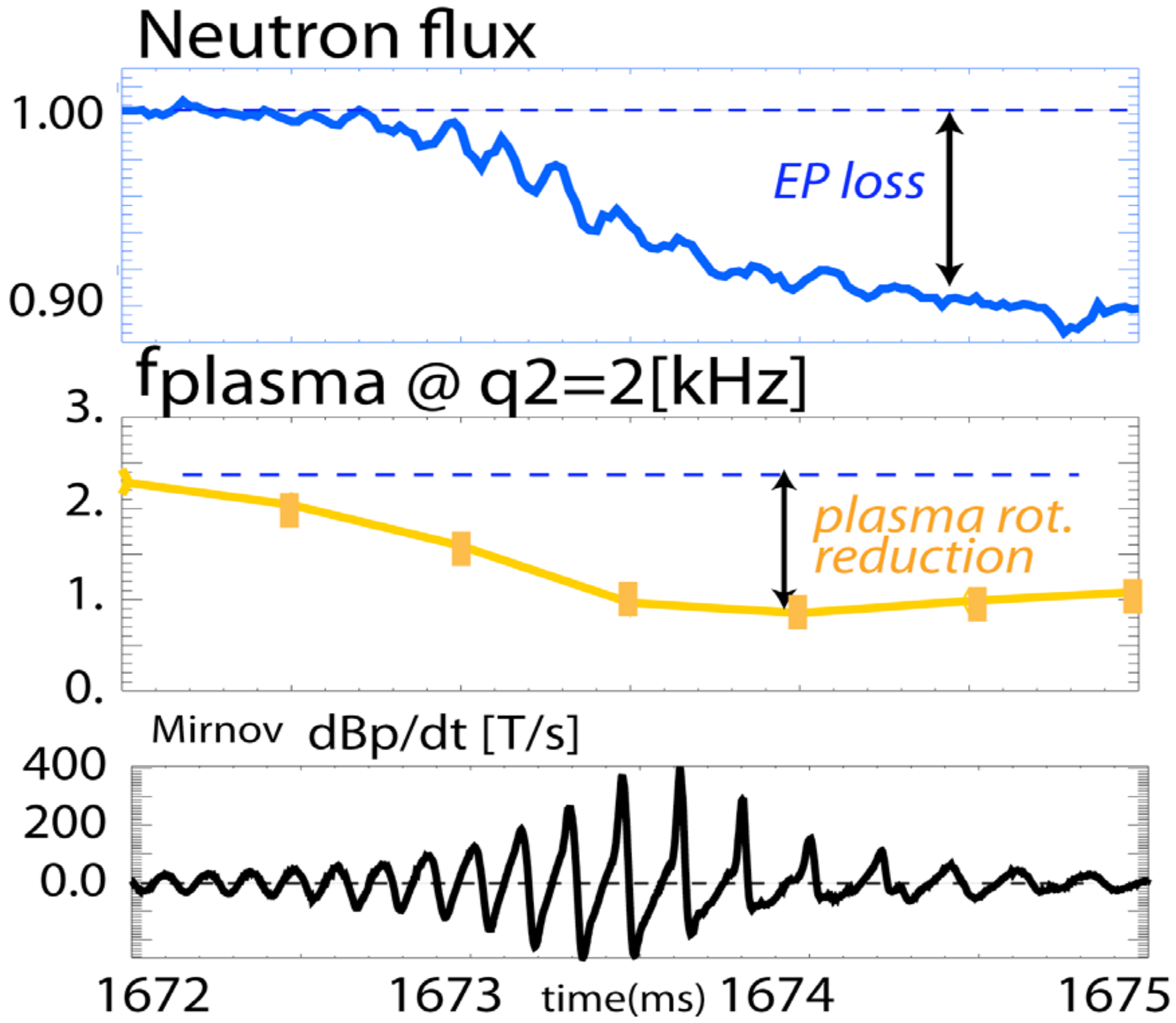
$$f_{prec} = \sim 6 \text{ kHz (DIII-D, 70keV)}$$
$$= \sim 2 \text{ kHz (JT-60U,85 keV)}$$

(without electric field)

  – *Precession frequency of trapped EPs calculated With Orbit Following Monte-Carlo (OFMC) Code*

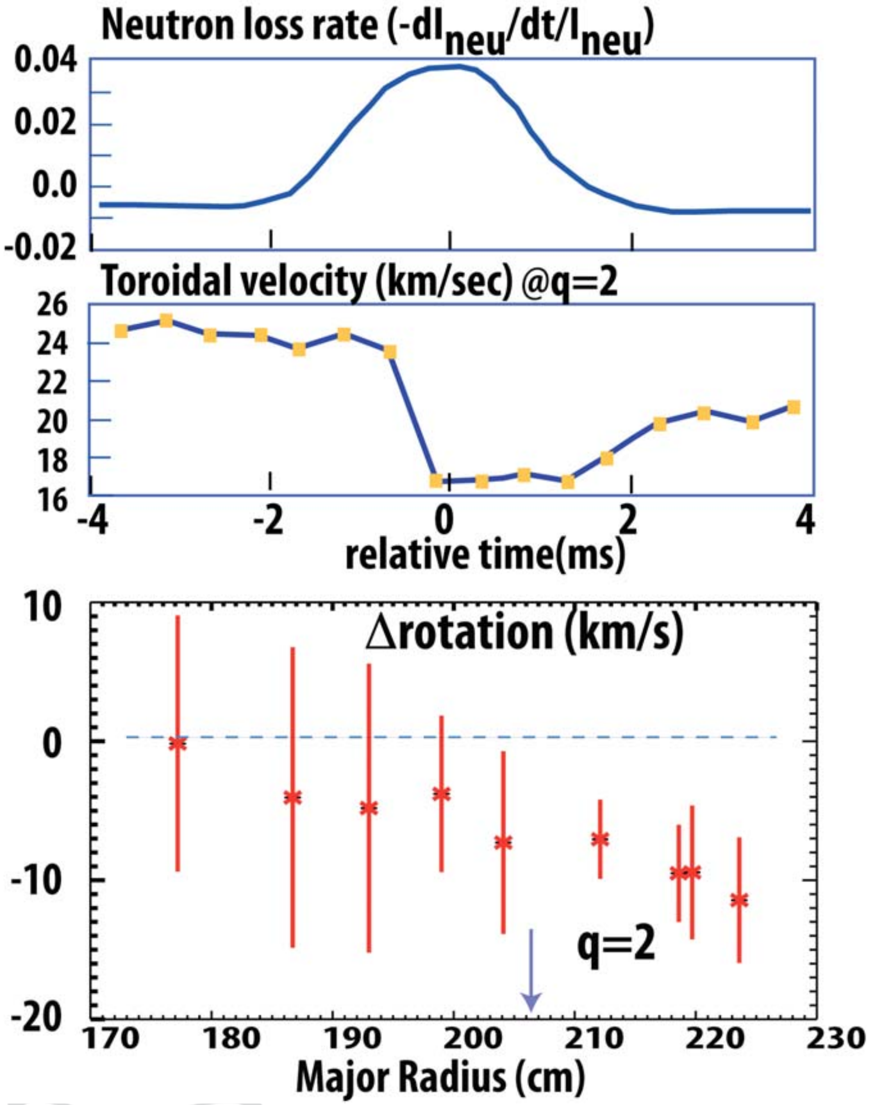
Off-axis fishbone mode affects key parameters for the RWM Stabilization mechanisms

DIII-D



- **Neutron emission reducing**
  → losing EP
- **Plasma Rotation reduction**

EP Losses Act like a Torque Impulse $\Rightarrow$Toroidal Rotation Reduction



DIII-D

- **Total fast-ion loss rate** inferred from slope of neutrons: $-d(I_{neu}/dt)/I_{neu}$

  $\Delta I_{neu}/I_{neu}$ **~10% -> $\Delta n_{EP}/n_{EP}$ ~ 9 - 10%**

  (based on TRANSP analysis)
- Larger Reduction occurs at $R \geq R_{q=2}$
- **EP losses** cause sudden

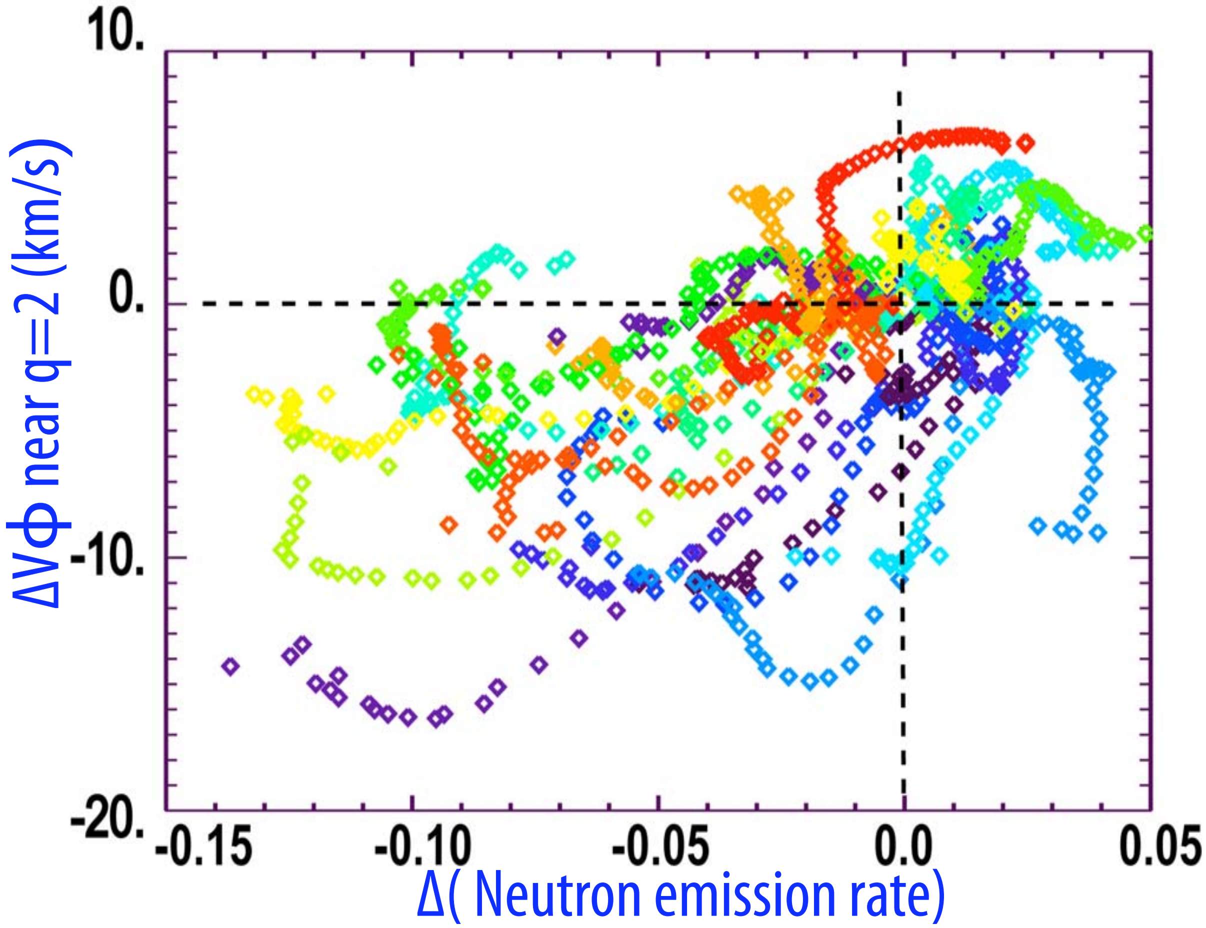
  Non-ambipolar Er field buildup

  (similar to blip of NBI, ripple EP loss)
- CER acquired in 0.5 ms sampling
- Conditionally average 8 similar bursts

  (deGrassie PoP 2006)

Decrease in Rotation is Correlated with Decrease in Neutron Rate

DIII-D



- Drop after OFM events

  - $\Delta n_{EP}/n_{EP}$ ~ 5 - 10%

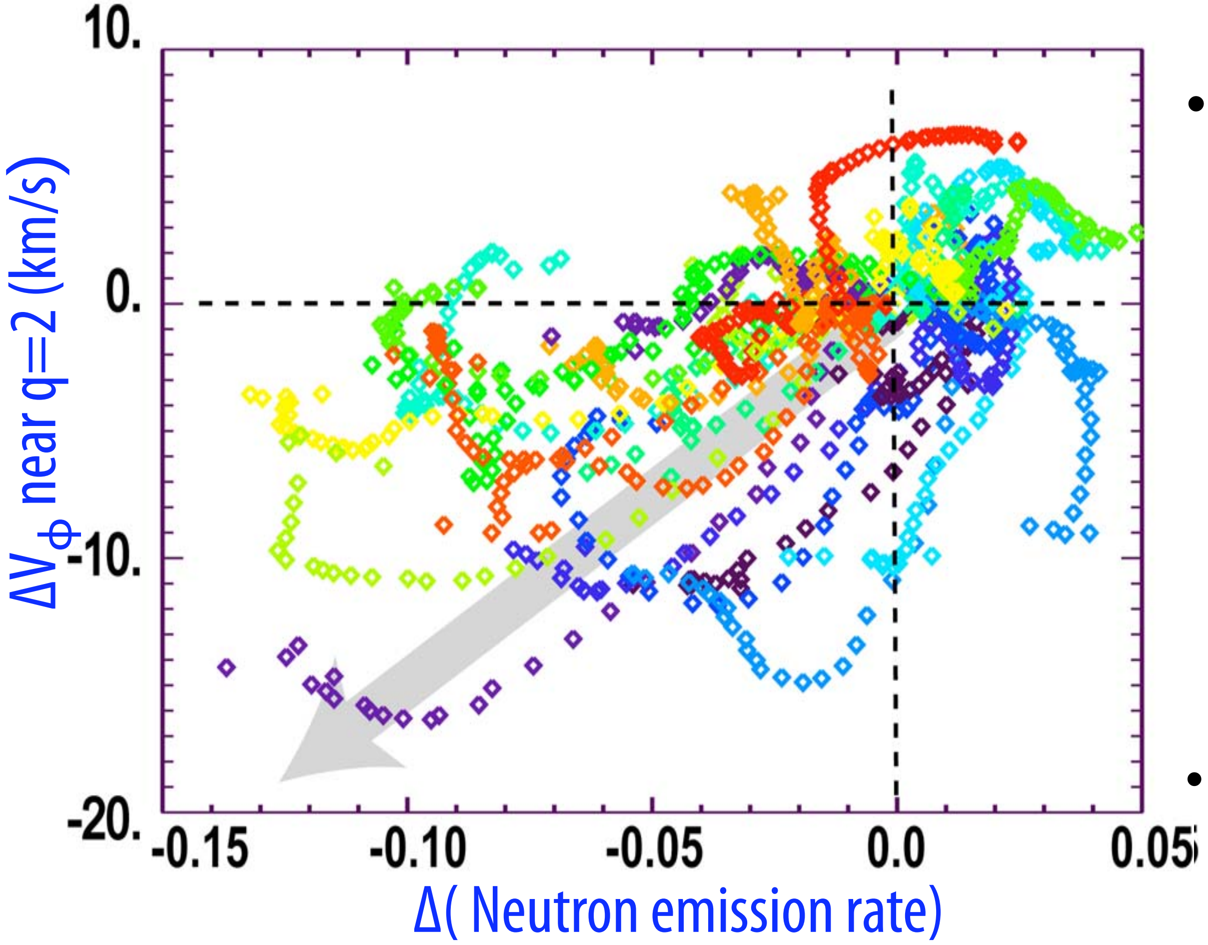
  - $\Delta V\phi$ ~ -10 km/s

  are common

~ 40 events of OFM 141086/141092/1500-2000ms

Decrease in Rotation is Correlated with Decrease in Neutron Rate

DIII-D



- **Non-ambipolar Er buildup** ,assuming EP angular momentum conserved

$$\Delta V_\phi \sim -r_{EP.shift}\left(\frac{eB_p}{M_i}\right)\left(\frac{\Delta n_{EP}}{n_i}\right)$$

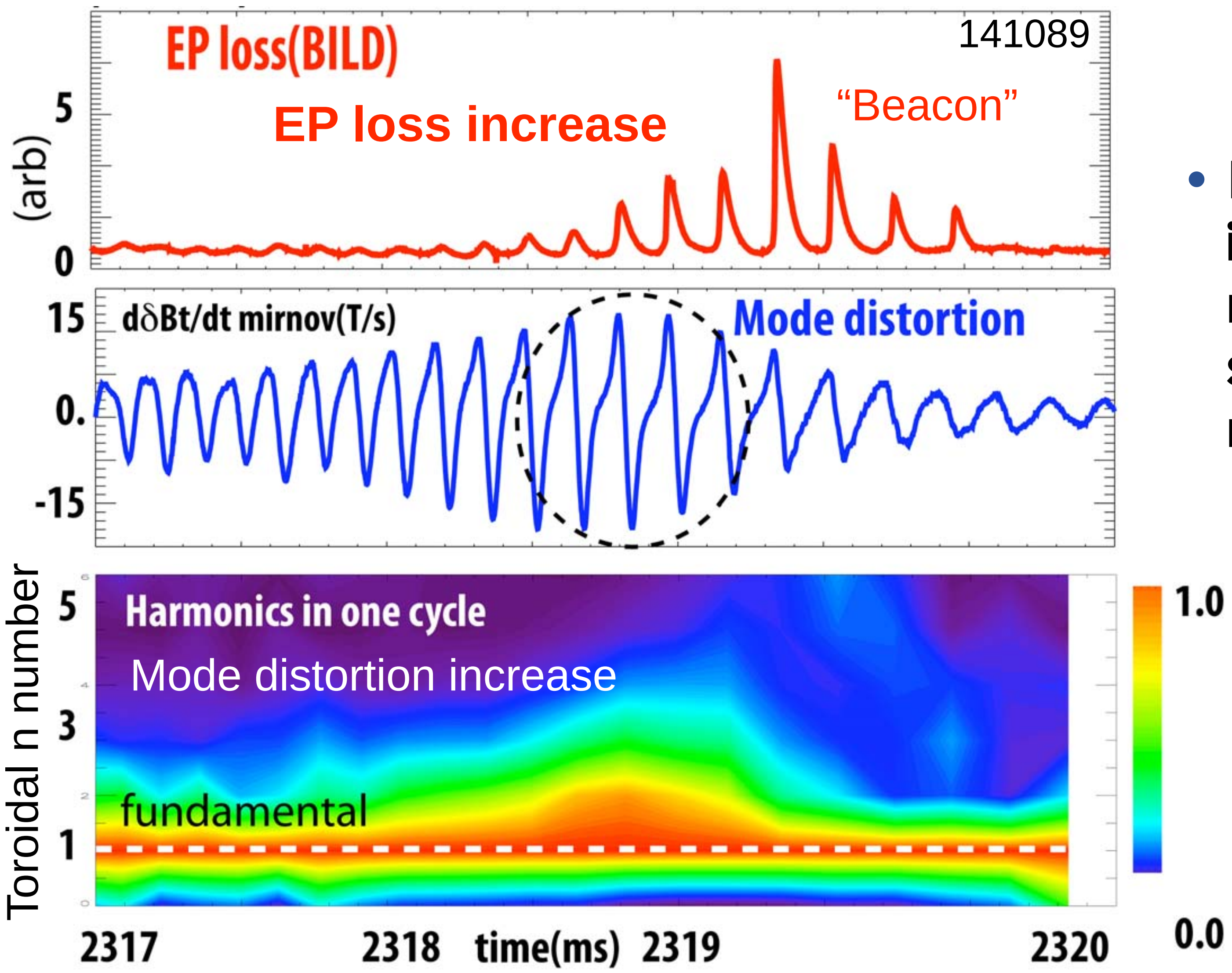
EP radial drift during burst **~ 15-20 cm (mode radial size)**

- The **Δn_{EP}** can be the key for the RWM stabilization In low rotation plasmas

~ 40 events of OFM 141086/141092/1500-2000ms

EP Losses Increase Coincides With The Mode Distortion

DIII-D

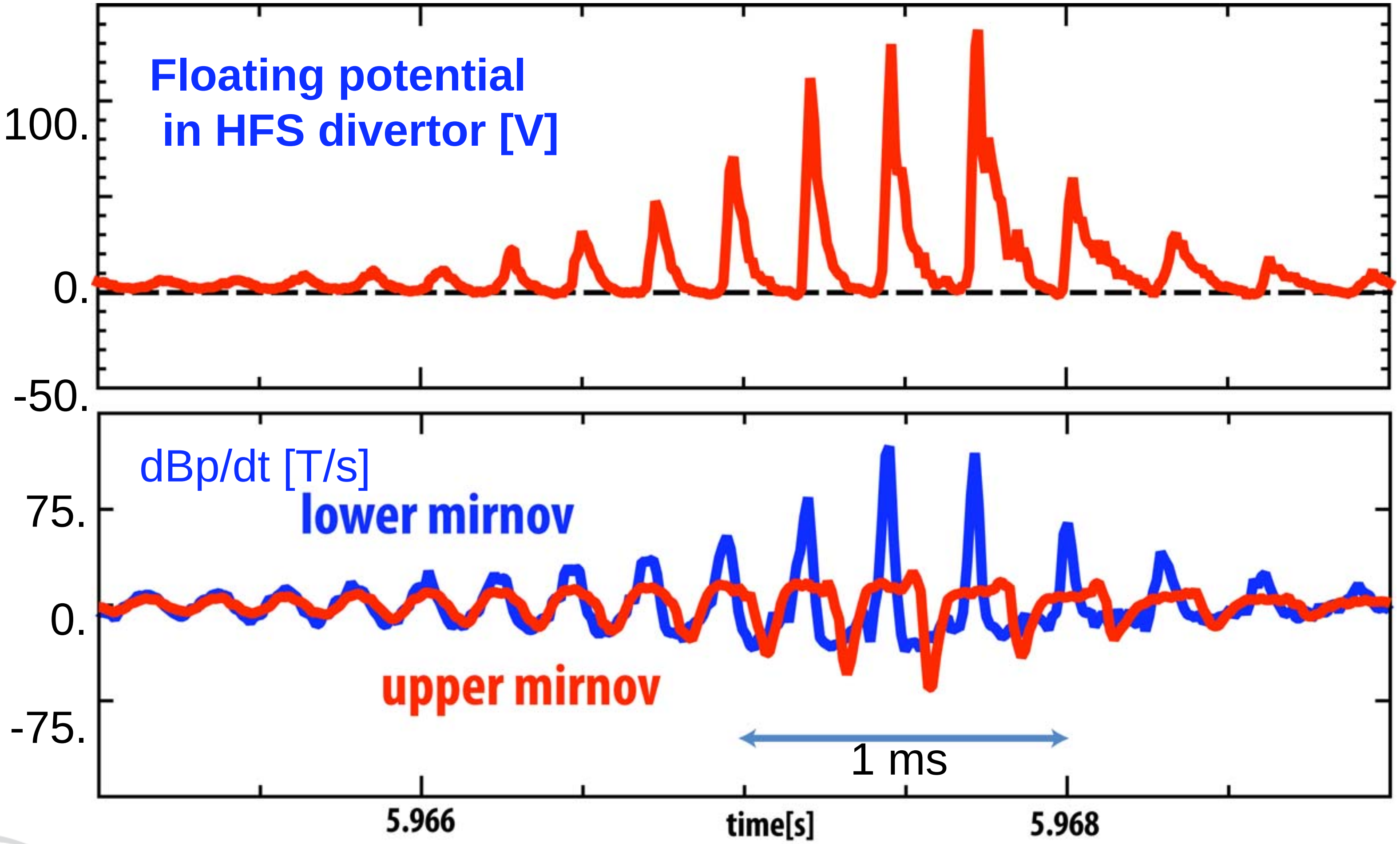


- **EP loss occurs in "beacon" manner synchronized with mode phasing**

Floating Potential in the Divertor Shows Positive Spikes with Higher Mode Distortion in JT-60U

- **Positive spikes imply possible EP losses**

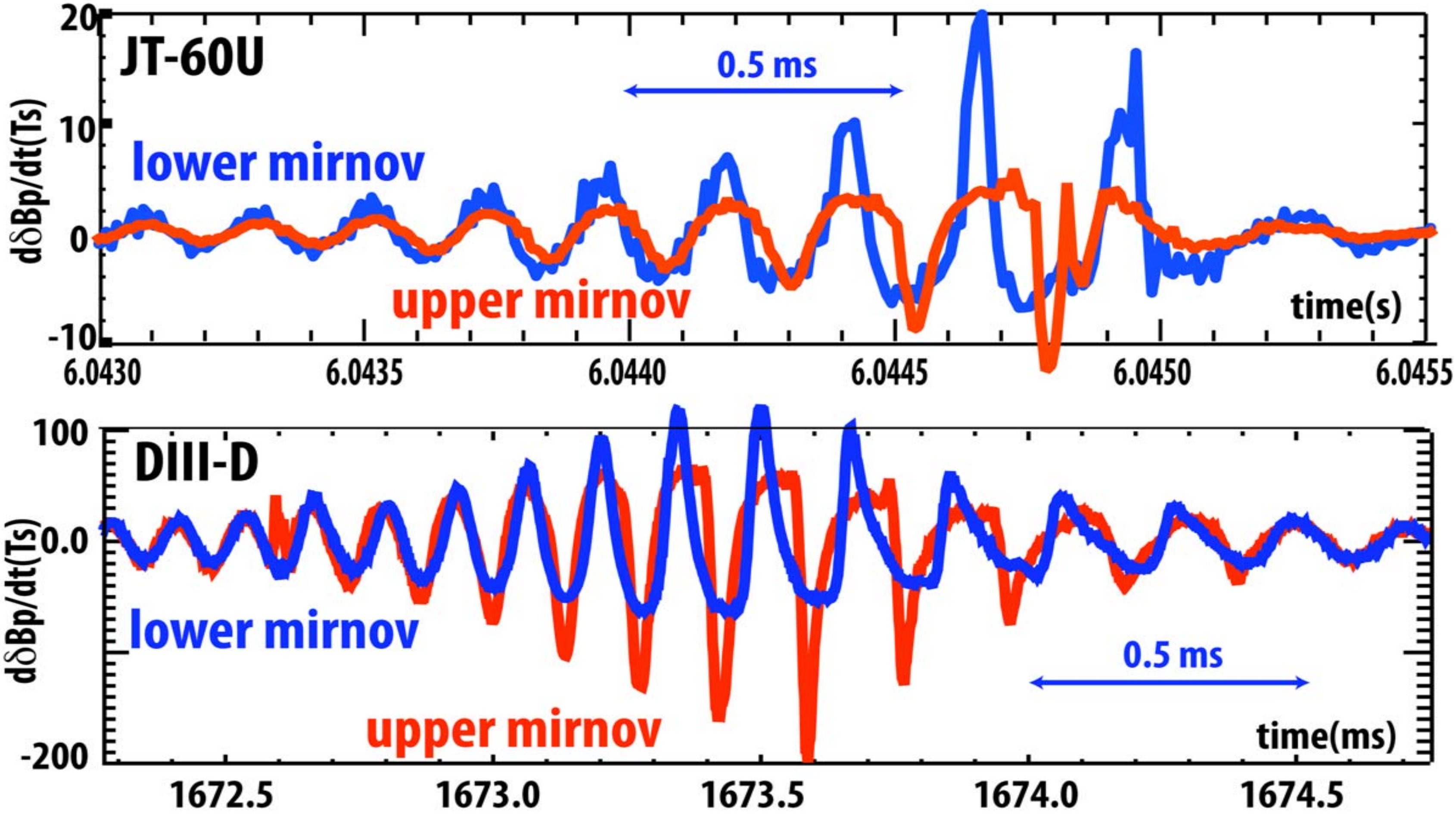
JT-60U



Mode Distortion in JT-60U / DIII-D Shows Similar Poloidal Mode Structure

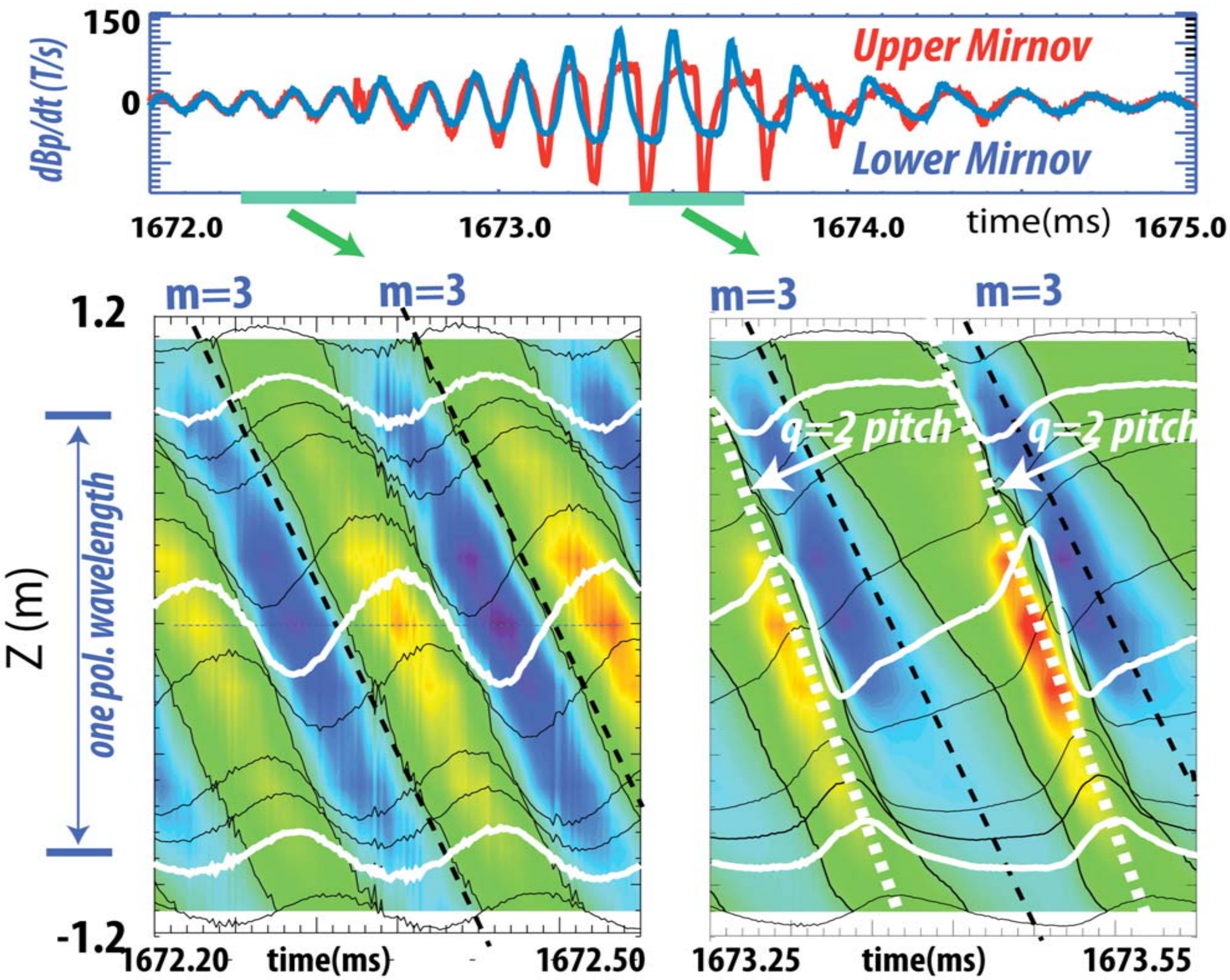
- **Loops are separated by ~ one pol. wave length of m=3**

JT-60U/DIII-D



The Mode Distortion Follows the q=2 Pitch
- Poloidal Mode Structure

DIII-D



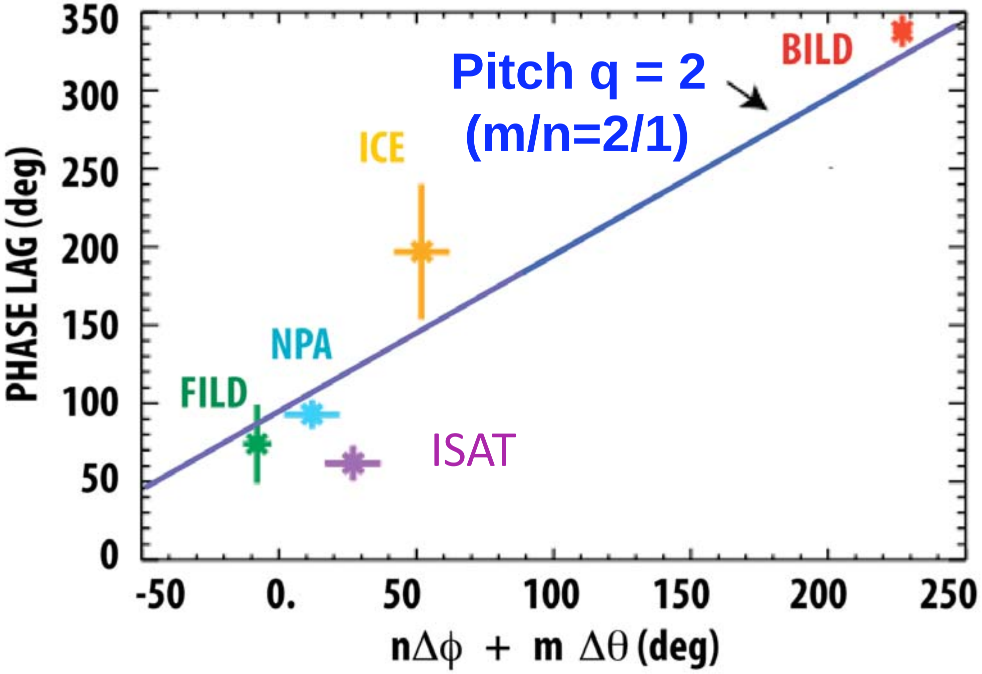
- **Localized-distortion analysis**

↓

- **Mode distortion**
  - pitch q=2
  - toroidal width ~ 30 deg
  - located around m=3 amplitude maximum at outer midplane

EP Losses “Beacon” Shows q=2 Pitch Dependence

DIII-D

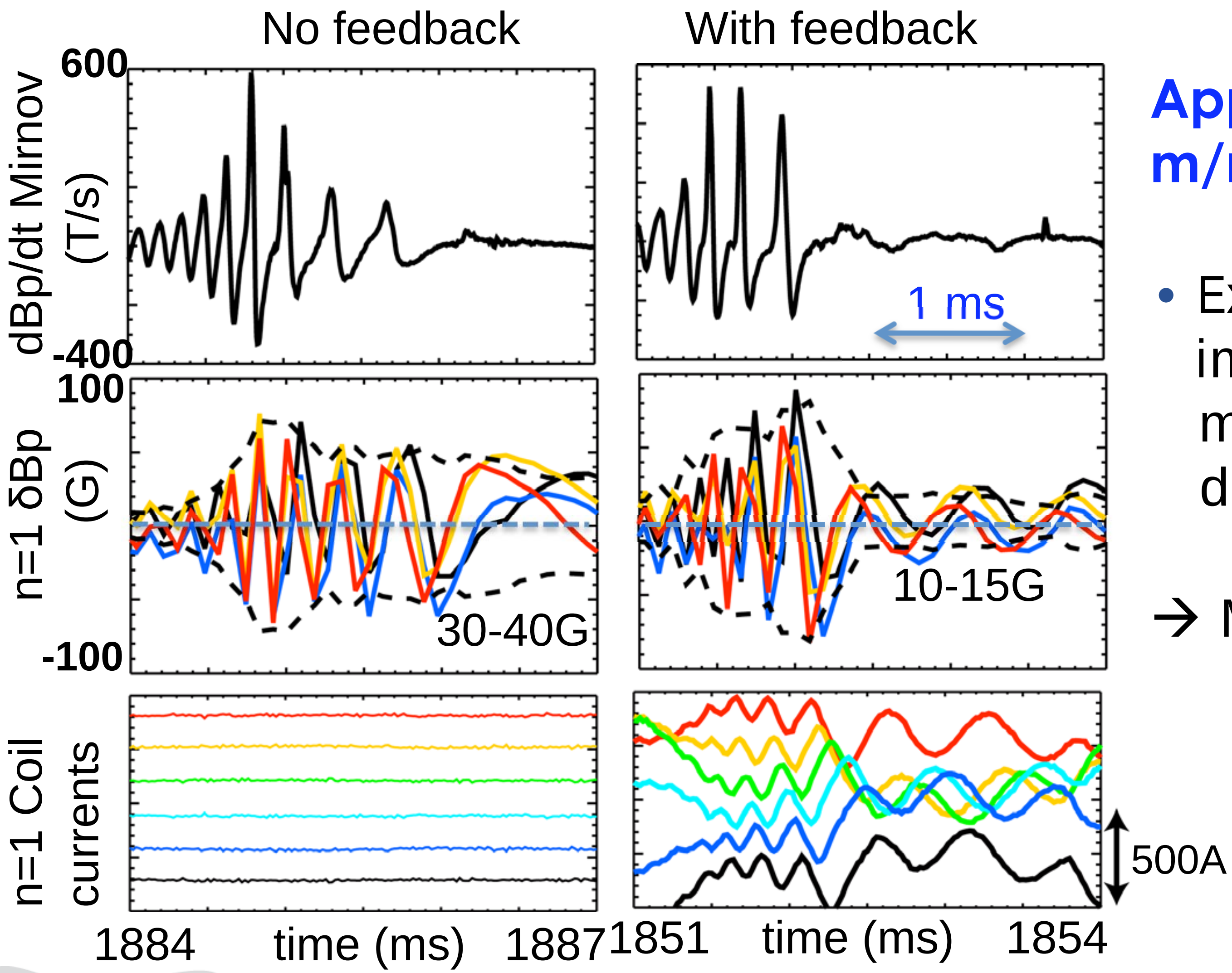


- **PHASELAG:**
  phase delay of the signal peaking of EP diagnostic to a peak of a fixed mirnov loop

- **EP diagnostics located at various off-midplane (θ) and toroidal location (Φ) :**
- **Ion cyclotron emission ICE)**
- **Beam ion loss detector (BILD)**
- **Neutral particle analyzer (NPA)**
- **Fast ion loss detector (FILD)**
- **Langmuir probe (ISAT)**
  - Numerical simulation is in progress

The n=1 Mode is the External Kink Character, based on the Response to the Applied n=1 field through Feedback

DIII-D



Applied field: m/n=3/1

- External field impacted the mode development

→ Mode is **External kink character in wall-stabilized plasmas**

Rapid Drop of Ω_{rot} and n_{EP} Provides a Unique Approach to Assess the Marginality

- **MARS-K** (RWM stability code including EP effects) [Y. Liu 2010 PPCF]
  - **with self-consistent approach: unstable without EP** (eigen function calculated consistently)
  - with perturbative approach: unstable (first order δW approximation)
  - growth rate

$$\gamma \sim \frac{\delta W_\infty + \delta W_k}{\delta W_b + \delta W_k} \qquad \delta W_k = \int dV(\xi \cdot \nabla \overset{=}{p})$$

$$\int dV \left[\frac{(\omega - \omega_{rot} + \omega_{*i}.....}{\omega - \omega_{rot} - <\omega_{prec.}> + ...} \right]$$

  - kinetic effect:

$$\delta W_k = \alpha_k (c_{EP}\delta W_{EP} + c_{thermal}\delta W_{thermal})$$

α_k: kinetic contribution factor

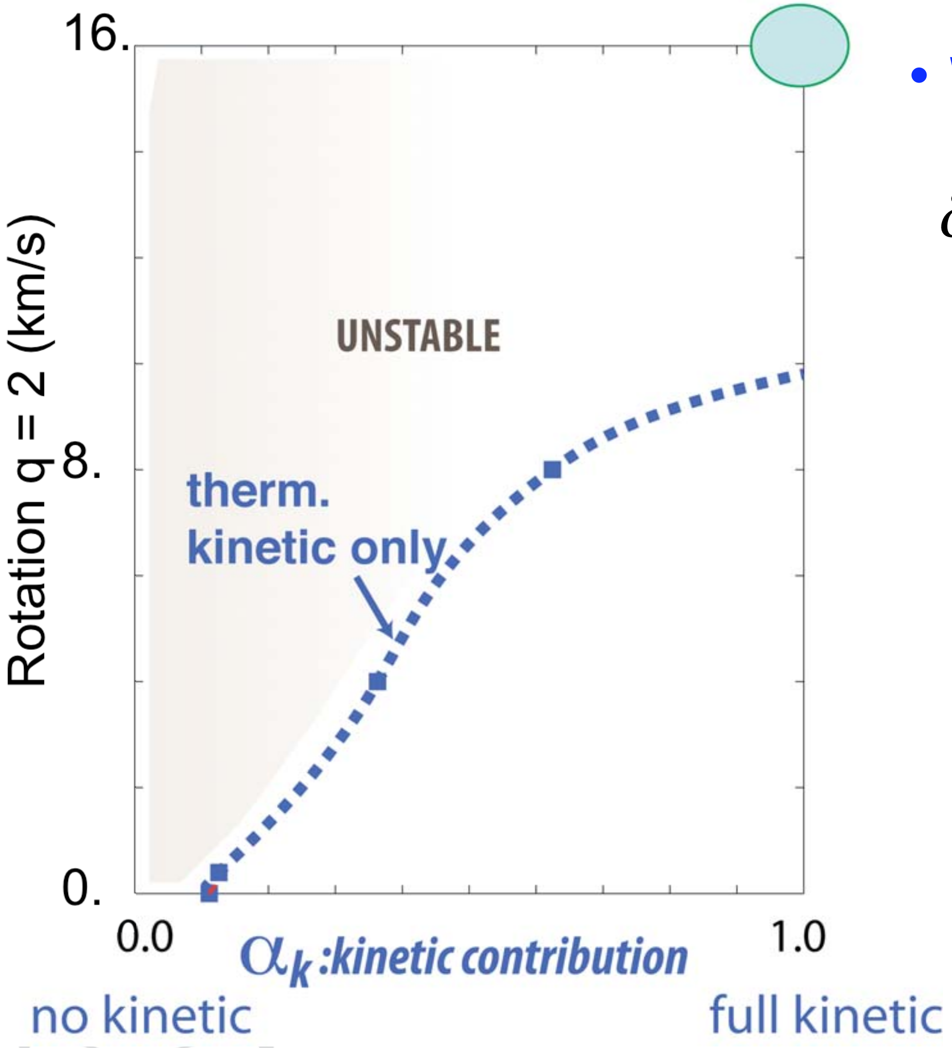
- at present:
  - EP: isotropic distribution

Yueqiang Liu

Experimental Condition:
Unstable by Thermal Kinetic Only

DIII-D

EXPs (rotation V_ϕ = 16 km/s at q=2)



- **Without EP, thermal-kinetic-only unstable**

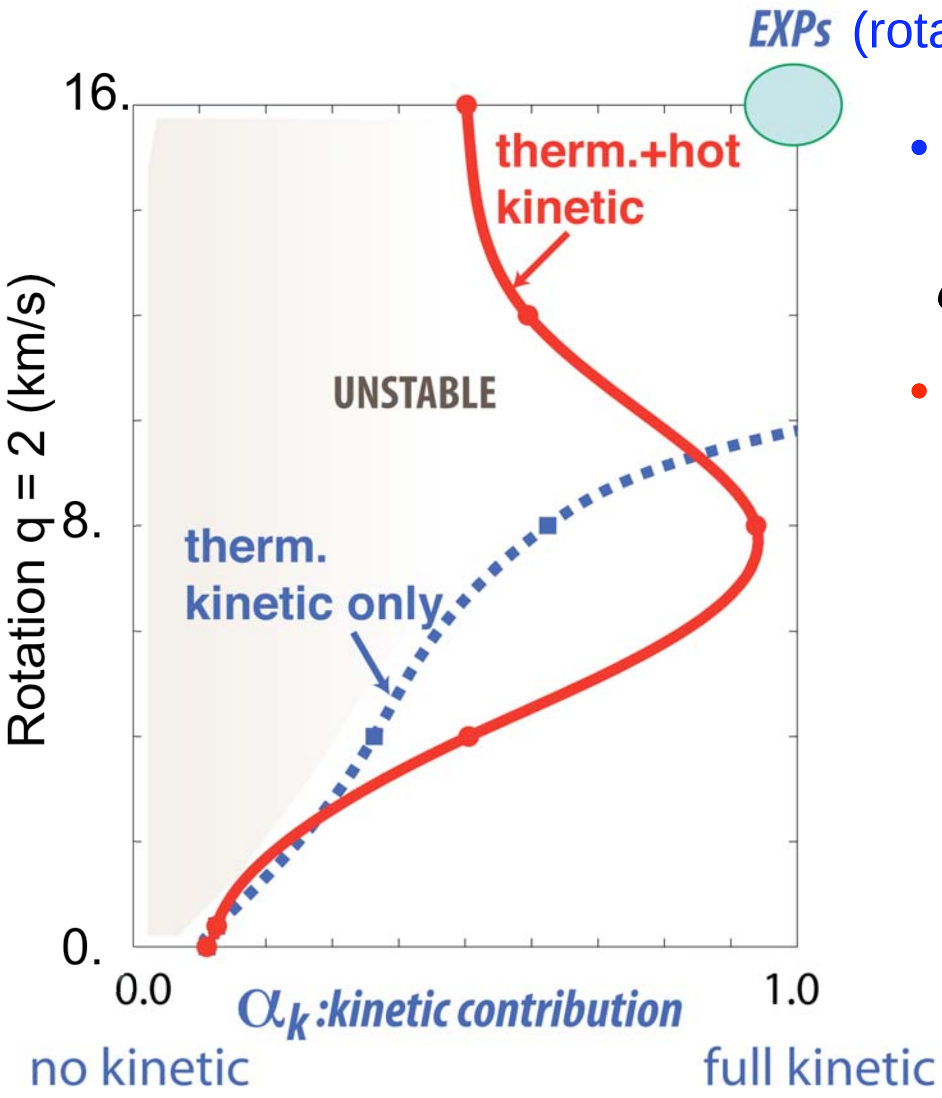
$$\delta W_k = \alpha_k (\cancel{c_{EP}} \delta W_{EP} + c_{thermal} \delta W_{thermal})$$

(MARS-K with self-consistent approach)

Yueqiang Liu

Experimental Condition:
Stable by Including EP Kinetic

DIII-D



(rotation V_ϕ = 16 km/s at q=2)

- **Without EP, thermal-kinetic-only unstable**

$$\delta W_k = \alpha_k(\cancel{c_{EP}}\delta W_{EP} + c_{thermal}\delta W_{thermal})$$

- **With EP-kinetic included. Exp. condition is predicted stable**

$$\delta W_k = \alpha_k(c_{EP}\delta W_{EP} + c_{thermal}\delta W_{thermal})$$

(MARS-K with self-consistent approach)

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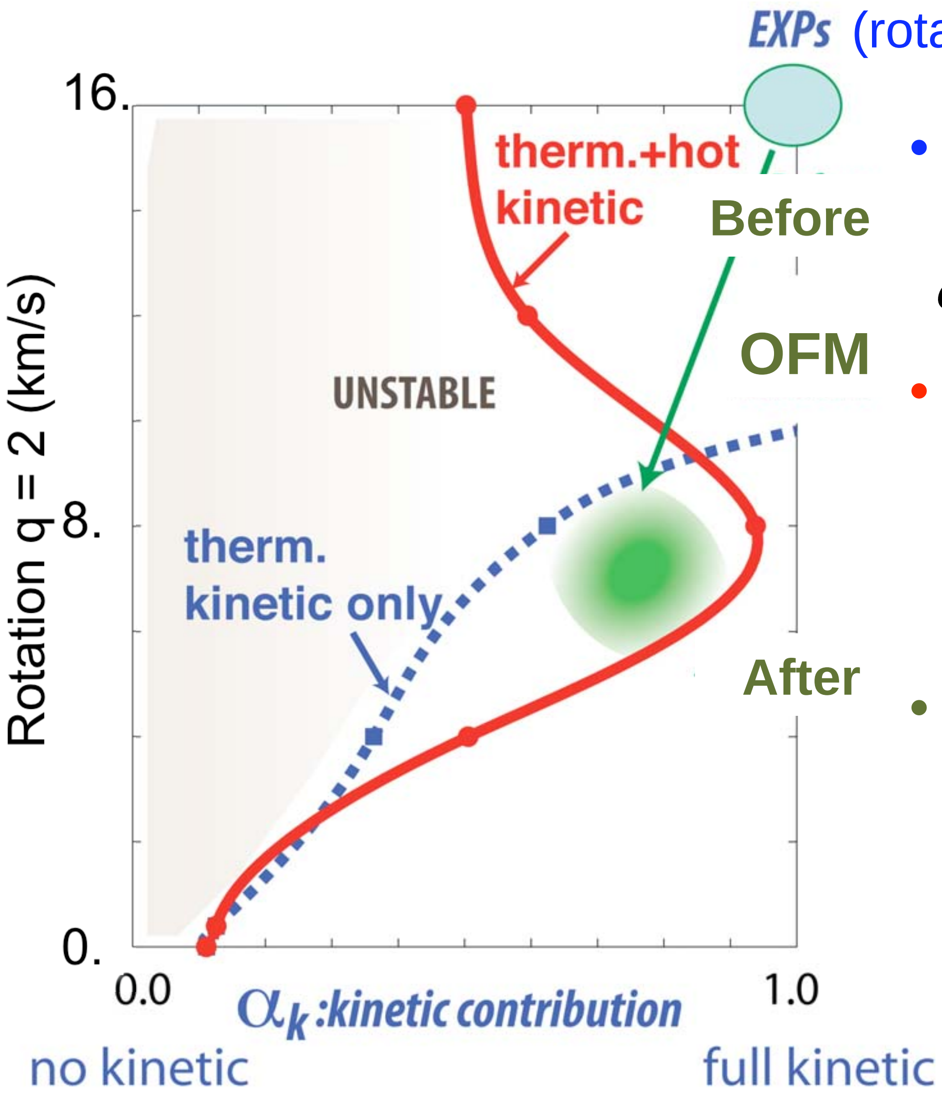
EP Loss by Off-axis-fishbone May Lead to RWM Onset

DIII-D



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- **With EP-kinetic included. Exp. condition is stable**

$$\delta W_k = \alpha_k(c_{EP}\delta W_{EP} + c_{thermal}\delta W_{thermal})$$

- **After losing EP ~10% and rotational stabilization~ 10km/s, the condition could become unstable**

(MARS-K with self-consistent approach)

Yueqiang Liu

SUMMARY:
Off-axis Fishbone Mode Characteristics:

- **Both "Energetic particle-driven Wall Mode (EWM)" in JT-60U and "Off-axis fishbone-driven" RWM in DIII-D have shown:**

  - **The initial phase** is like classical **fishbone:**
  - Evolves with strong **non-linear mode distortion**

- Mode distortion coincides with **the rapid increase of EP losses**
  - Follows **the q=2 pitch** same as the EP losses

- **External kink character**
  - strong response to the additional **n=1 external field** through feedback

→**A new branch of EP driven mode exists with external kink character in wall-stabilized plasmas**

The theoretical work is in progress. Further experiments are required to clarify EP loss process in the EP-driven mode

SUMMARY:
Impact on the RWM Stabilization:

- **Both "Energetic particle-driven Wall Mode (EWM)" in JT-60U and "Off-axis fishbone-driven" RWM in DIII-D can trigger RWM**.

- **EP density drops** ~10% and **Plasma rotation drops**~10 km/s in a burst

- **Significant** for the RWM stability in **low rotation plasmas**, which heavily relies on kinetic effects produced by the EP and the plasma rotation

- Rapid drop of n_{EP} and Ω_{rot} provides a **unique approach** to assess the RWM stability
  - MARS-K indicates **EP** contribution to RWM stabilization

→**EP** becomes a crucial factor for **high β_N MHD stabilization** toward **steady state reactor operation**

Mechanism of RWM onset is to be clarified, and control of EP-driven mode is also needed for high β_N operation