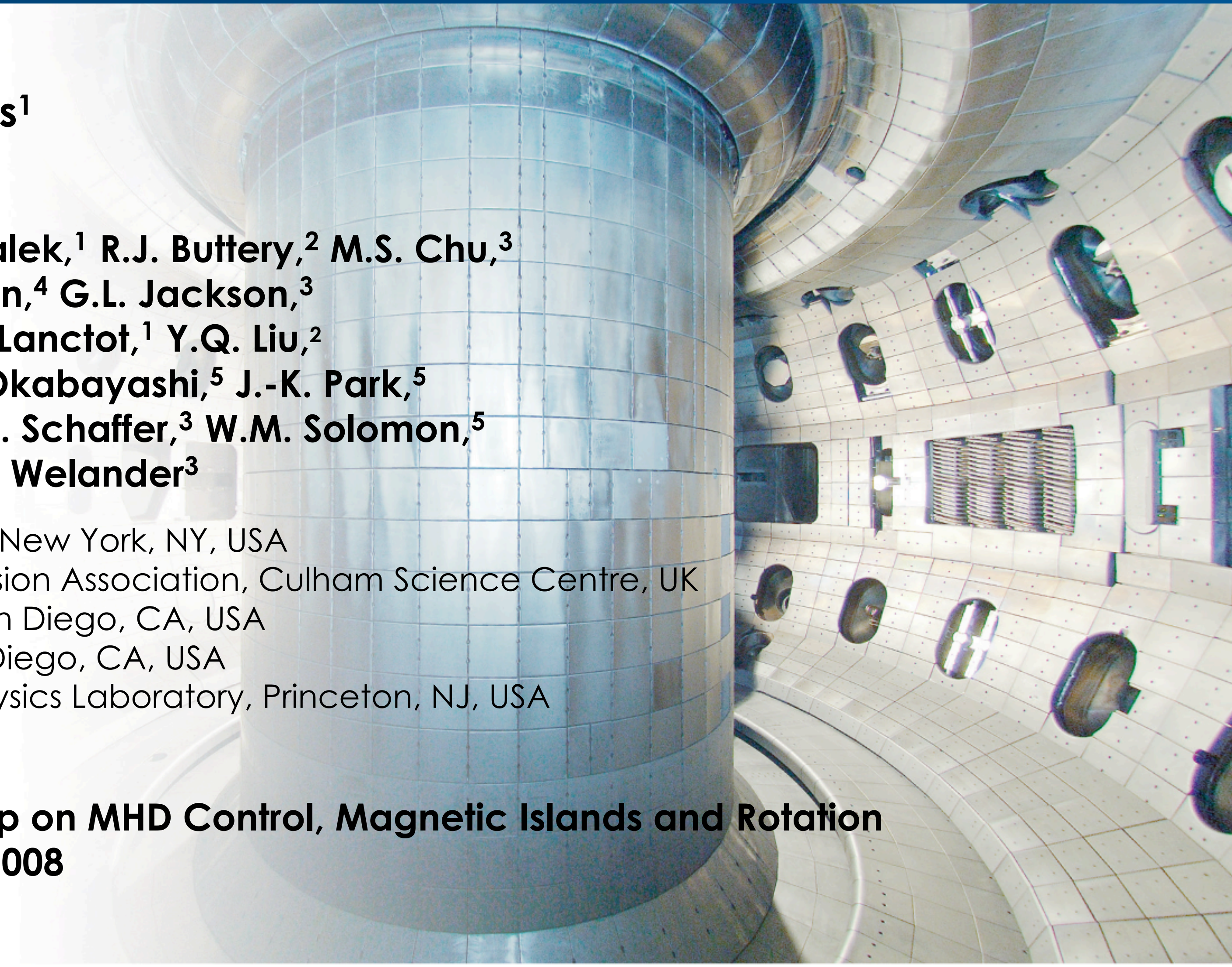
Interaction of Resistive Wall Mode Stability, Error Fields and Plasma Rotation



By

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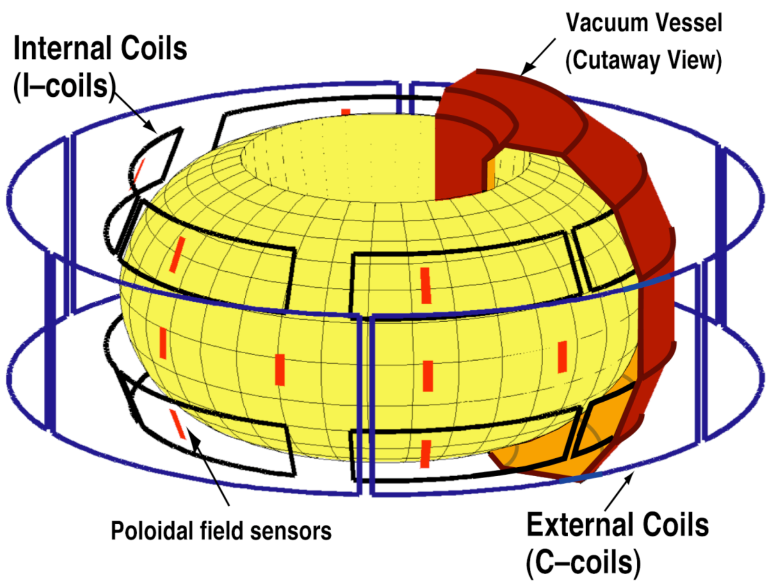
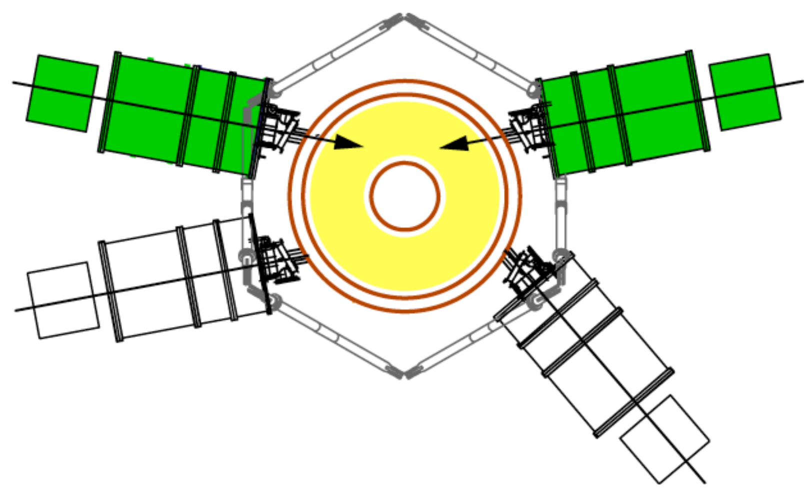
Columbia University

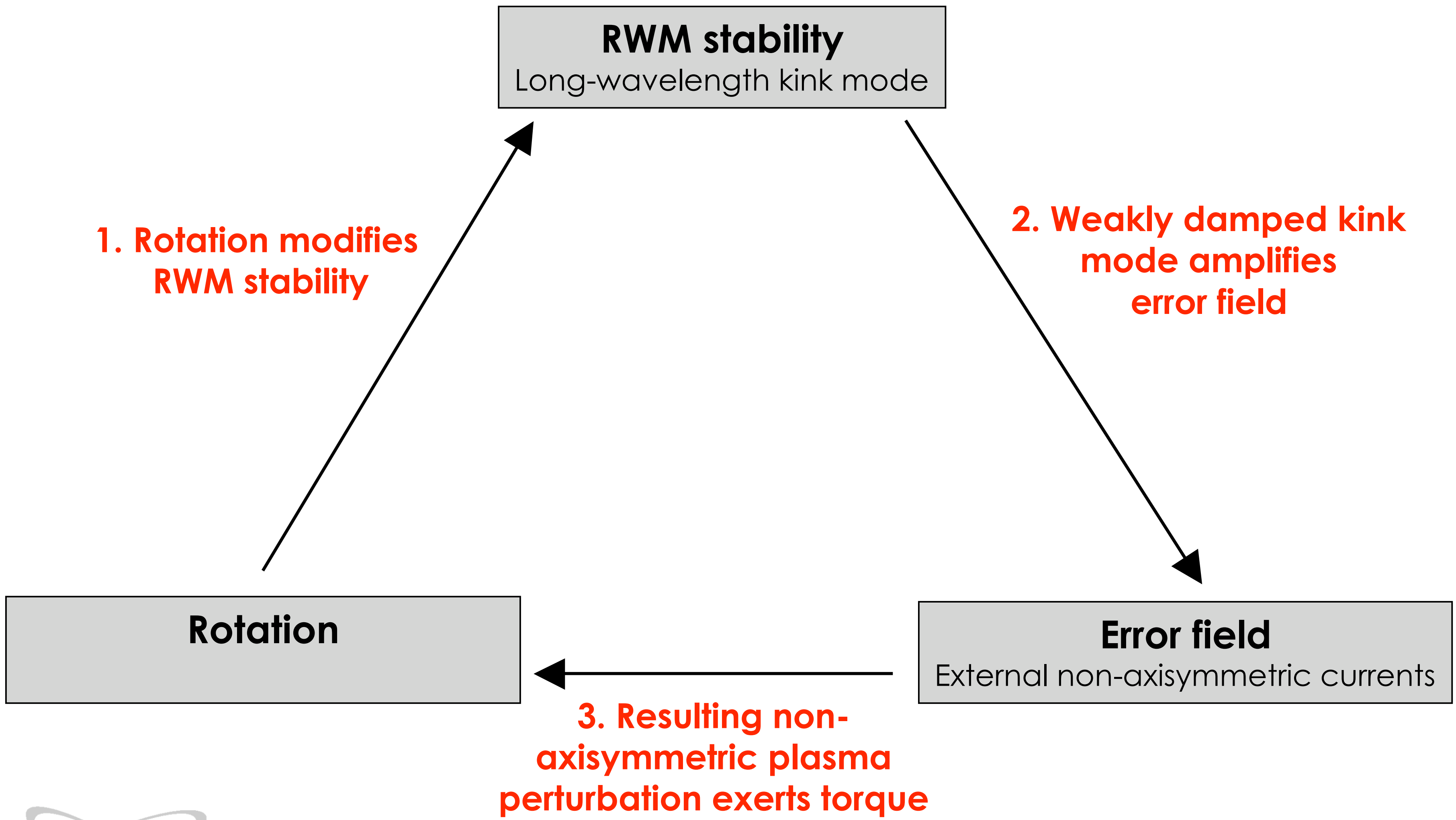
DIII-D is well suited to study the interaction of RWM stability, error fields and plasma rotation

- **Nearby vacuum vessel leads to significant gain in β_N through wall-stabilization**
- **Two sets of non-axisymmetric coils can correct intrinsic error field and apply well-known external perturbations δB^{ext}**
- **Magnetic probes measure perturbed field δB including the plasma response δB^{plas}**
- **Simultaneous co- and counter neutral beam injection (NBI) decouples torque from heating power**





Interaction of RWM stability, error fields and plasma rotation



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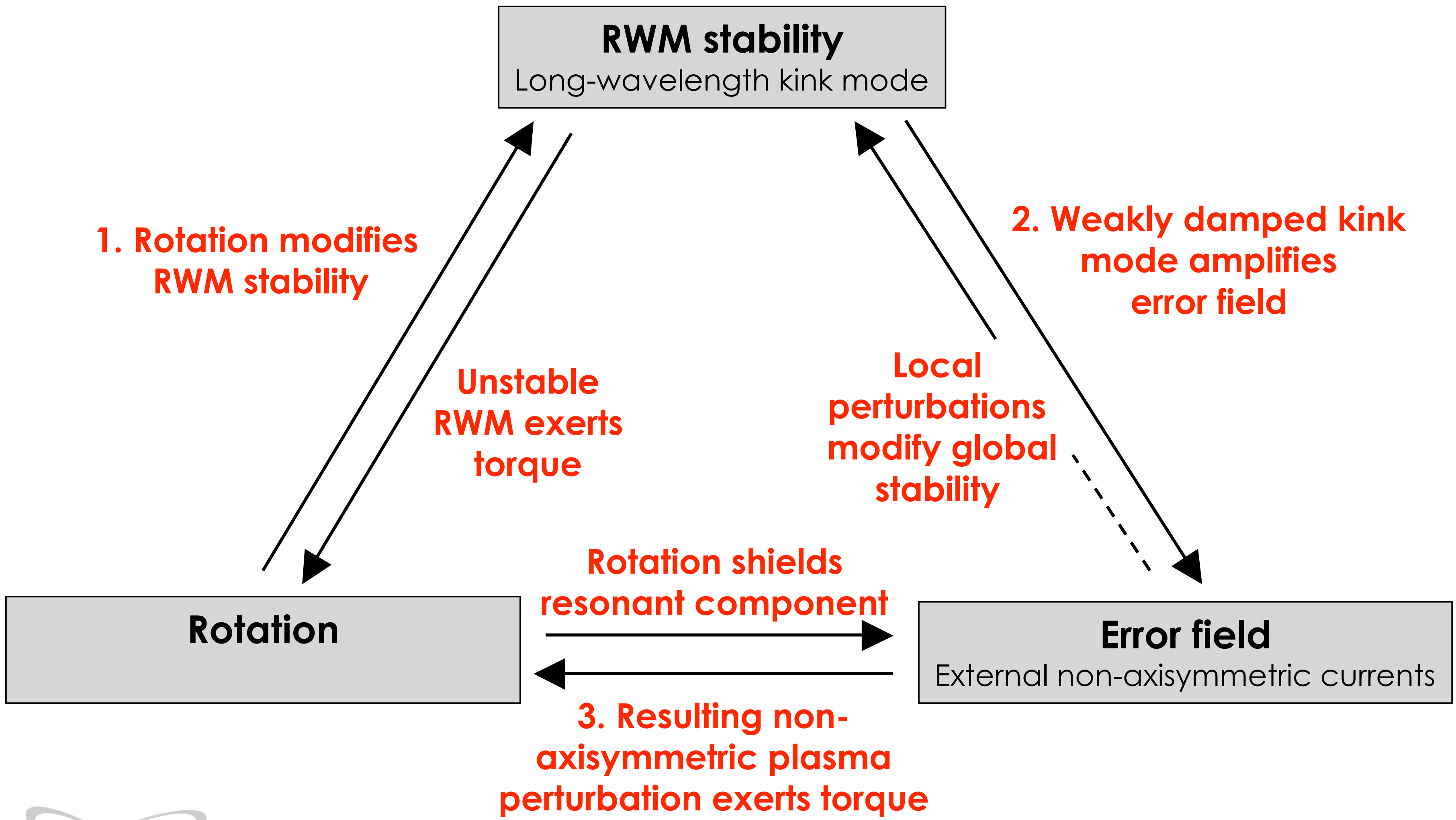
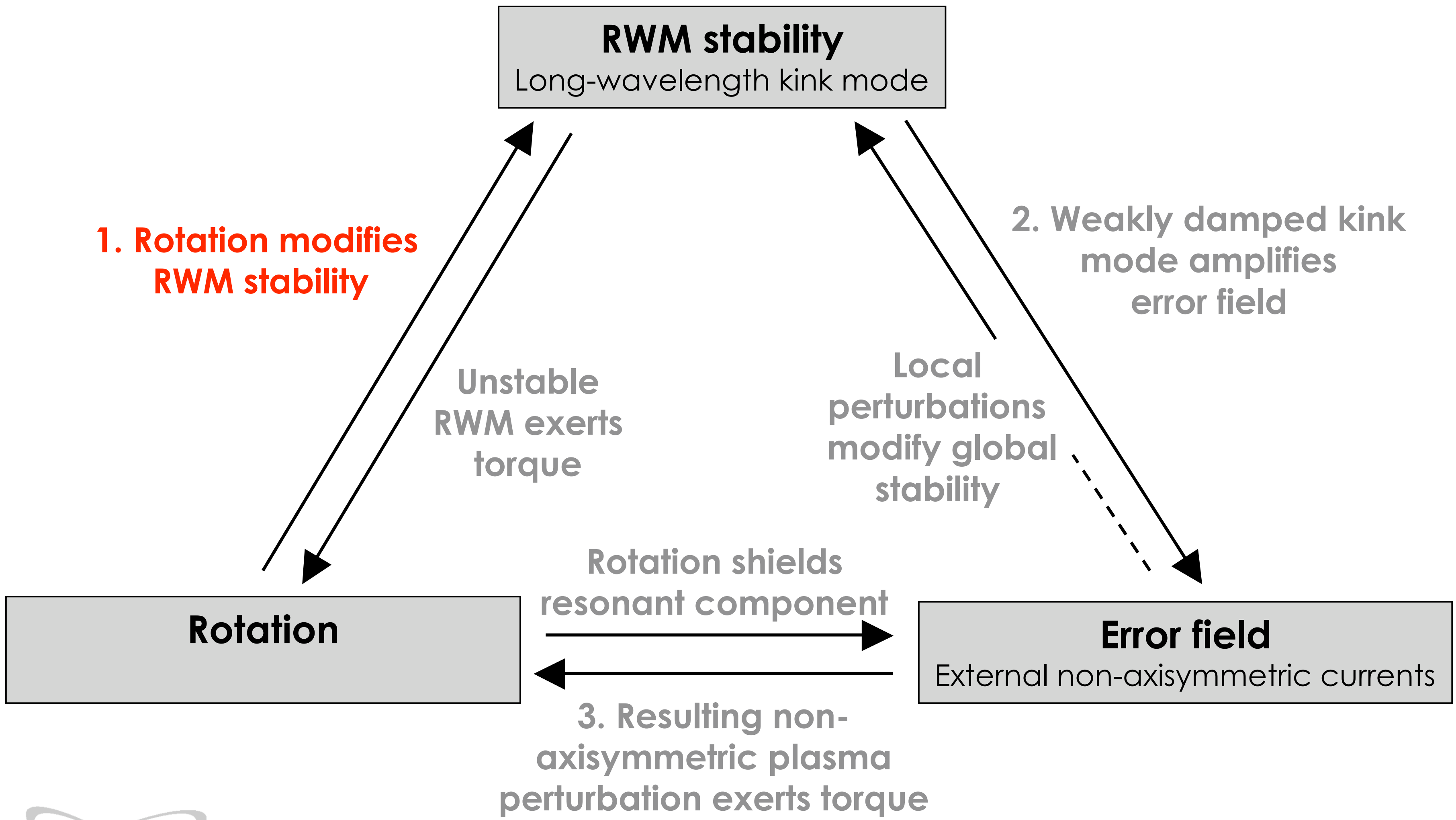


Interaction of RWM stability, error fields and plasma rotation



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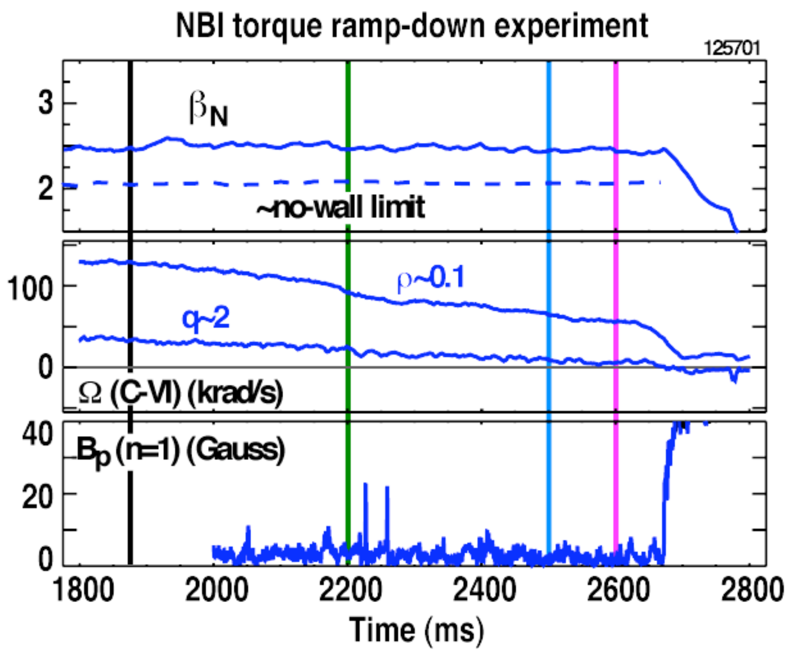
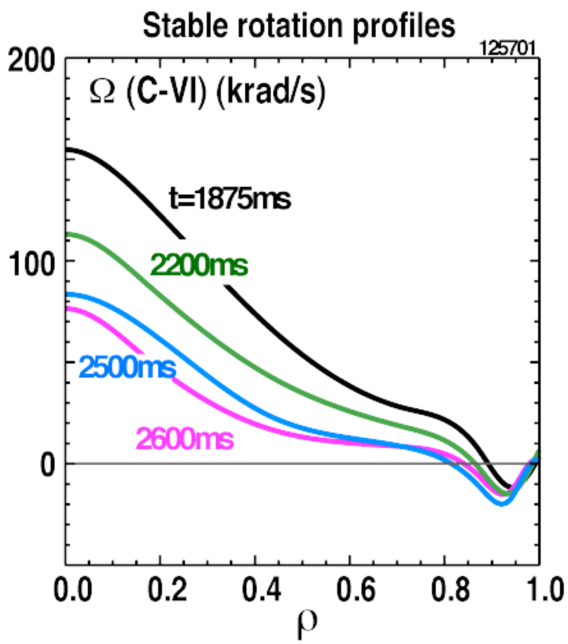
RWM remains stable over a wide range of plasma rotation profiles

- **Good error field correction is essential to maintain wall-stabilization down to very low plasma rotation** [H. Reimerdes, et al, *Phys. Rev. Lett.* (2007)]
  - Rotation controlled by varying the NBI torque



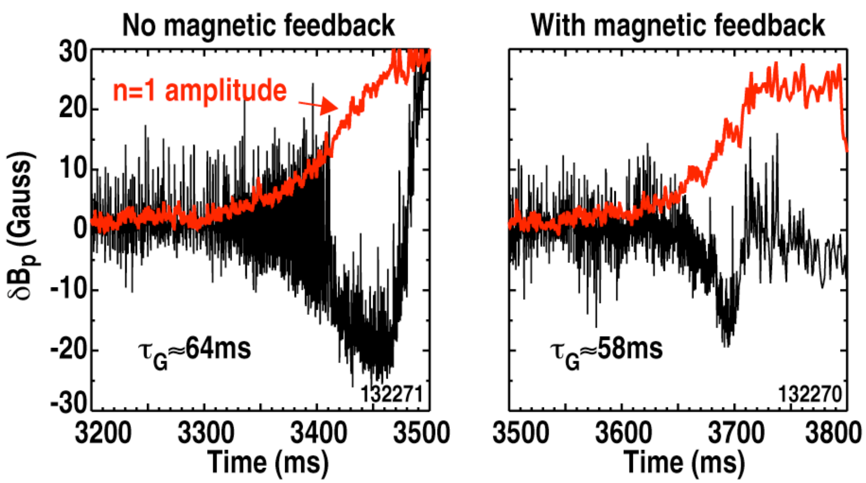


- **Operation limited by the onset of a rotating or locked growing *n*=1 mode**

Rotation threshold in wall-stabilized discharges is NOT imposed by an unstable RWM

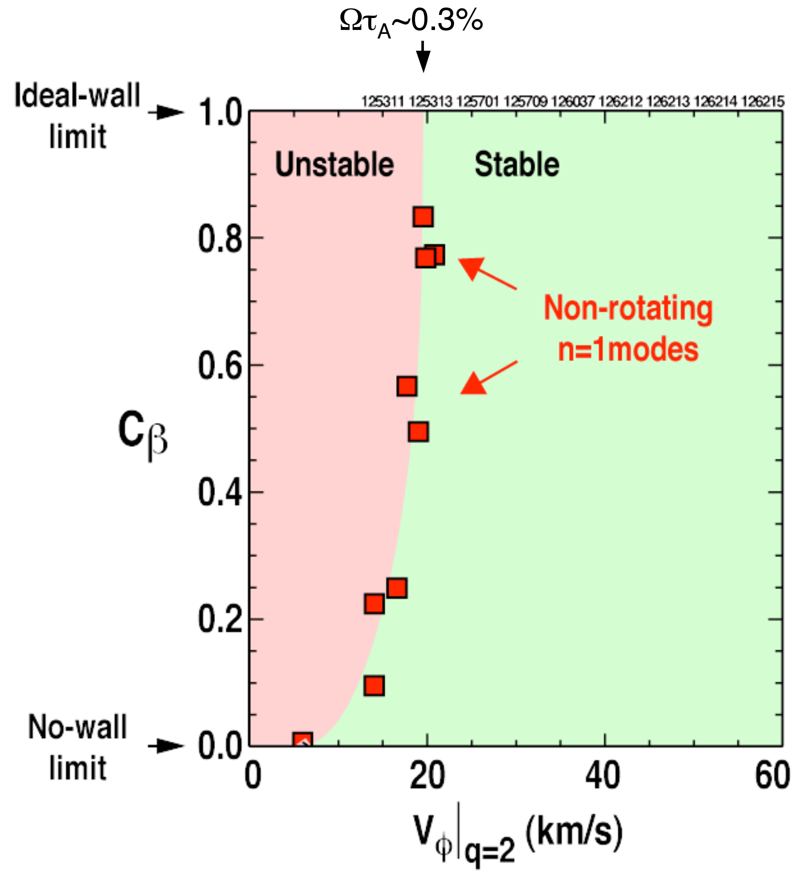
- **Rotation at the *n*=1 mode onset has only a weak β dependence**

  [E.J. Strait, et al, *Phys. Plasmas* (2007)]



  – Growth on resistive rather than wall time-scale (τ_W~3ms)

  – Mode unaffected by feedback

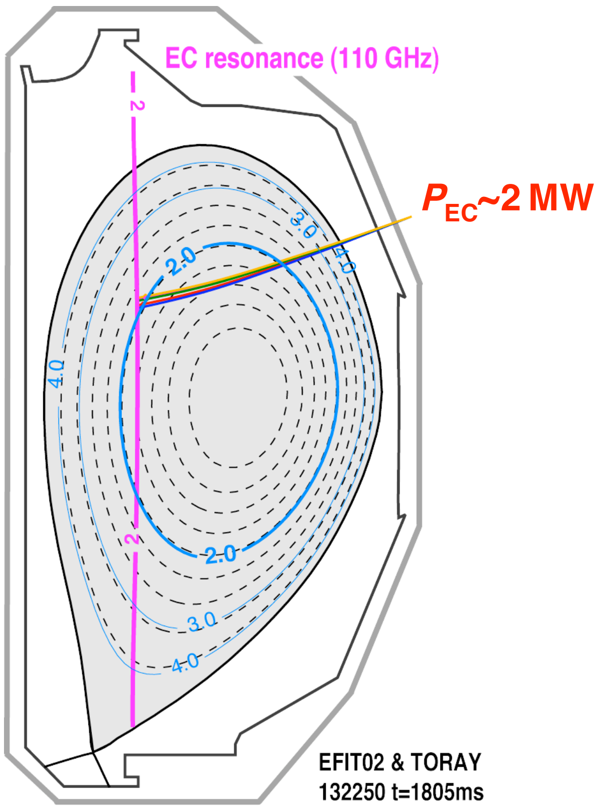


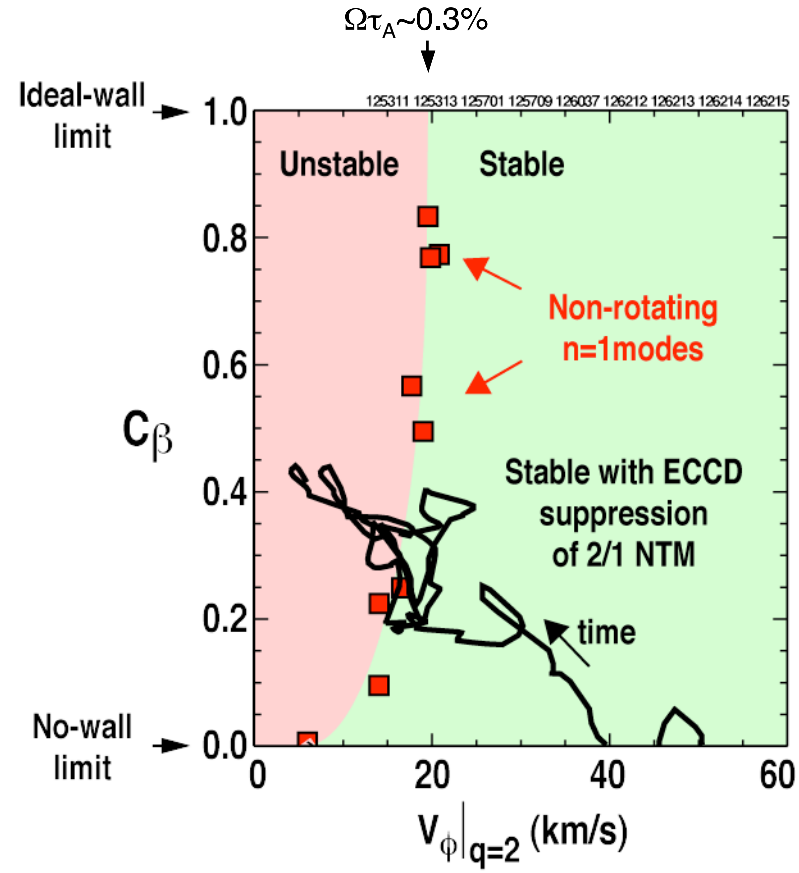
➔ Perturbation evolution consistent with a locked growing 2/1 NTM

  – Critical β_N reduced at low rotation [R. Buttery, et al., *Phys. Plasmas* (2008)]

NTM suppression can extend operating regime even below the previously reported rotation threshold

- **Apply preemptive ECCD *at q*=2 surface to suppress 2/1 NTM**
  [R. Prater, et al., *Nucl. Fusion* (2007)]

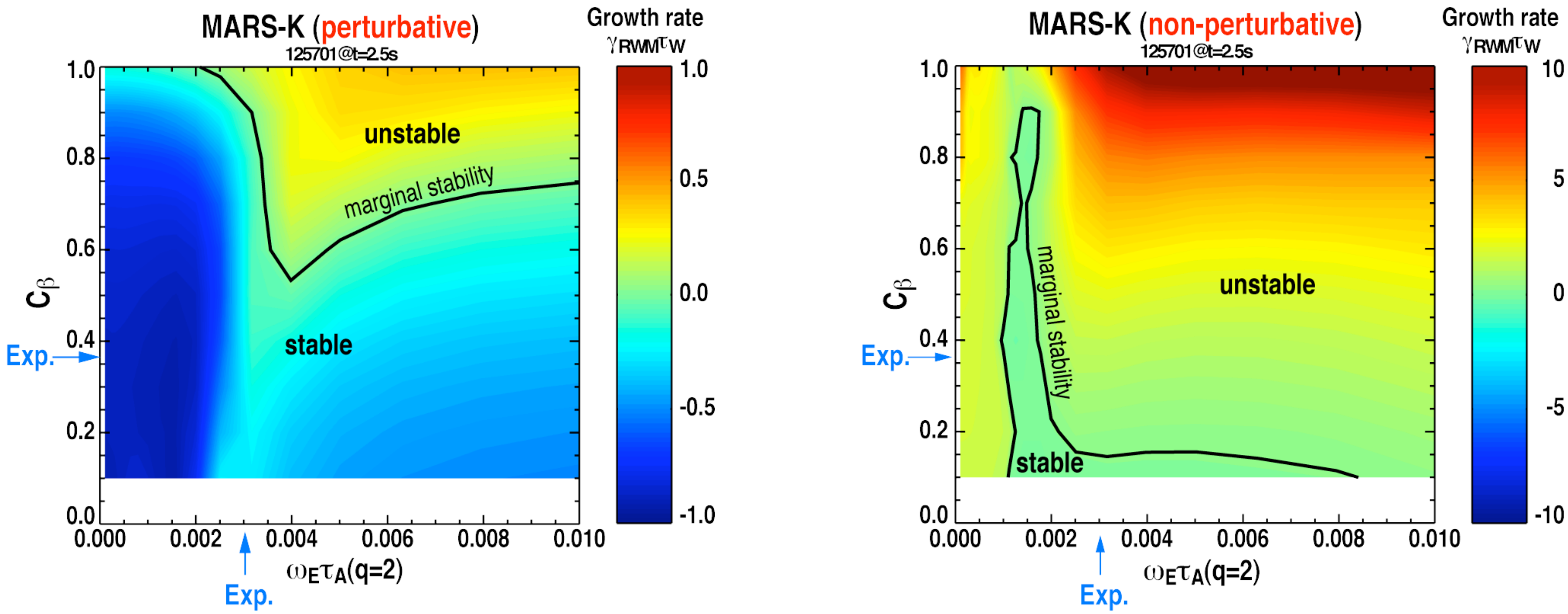




- **Operational constraints limit $C_\beta \leq 0.5$**

New MARS-K code compares perturbative and non-perturbative formulation of kinetic damping

- **MARS-K: Perturbative and non-perturbative formulation of kinetic damping including particle bounce (ω_b) and precession drift (ω_d) frequencies of thermal particles** [Y.Q. Liu, et al., IAEA 2008]
- **Calculate RWM growth rate for stable DIII-D plasma 125701@t=2.5s**



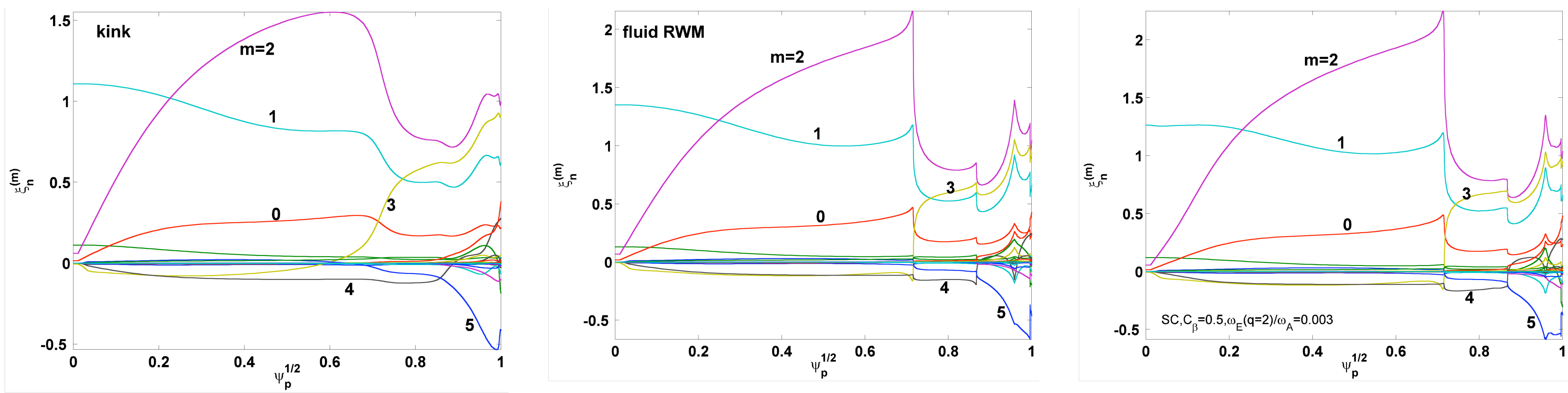
→ **Non-perturbative formulation significantly reduces kinetic stabilization**

[Figures from Y.Q. Liu, et al, APS 2008]

Change in stability caused by new RWM branches rather than a change of the mode structure

- **Key-features of <u>non-perturbative</u> approach:**
  - Mode structure can deviate from the ideal MHD *n*=1 kink mode
  - Mode rotation frequency can be non-zero (i.e. comparable to ω_b, ω_d)
- **Compare poloidal Fourier harmonics for normal displacement between:**

No-wall kink | Fluid RWM | Non-perturbative kinetic RWM



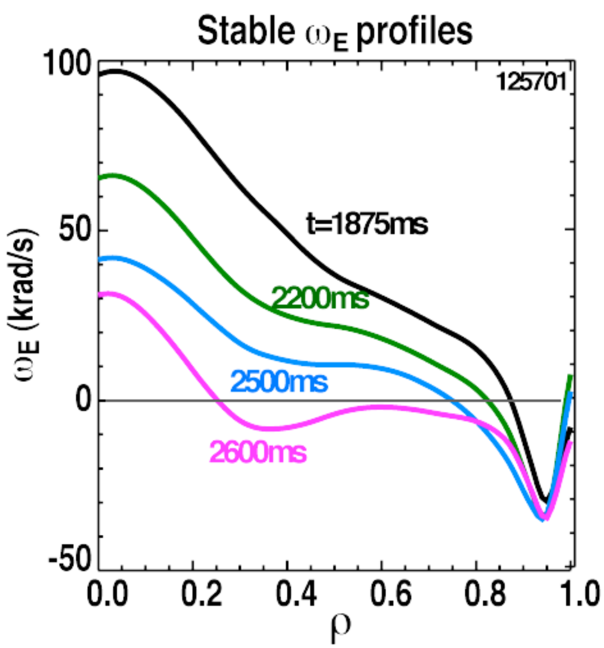
→ **No significant kinetic modification of RWM eigenfunction for DIII-D**

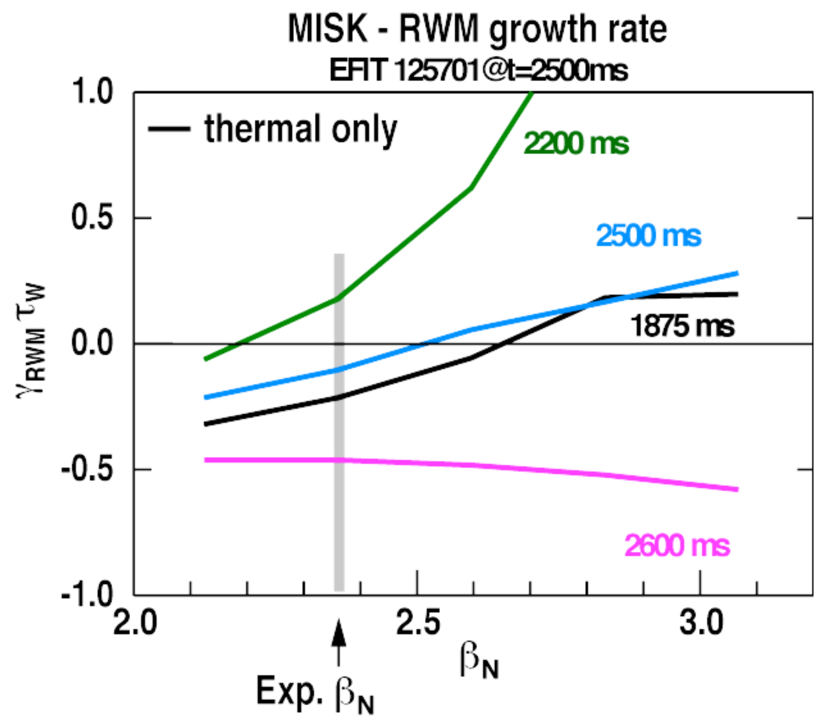
- **Non-linear eigenvalue formulation through kinetic integrals results in new (unstable) branches**

[Figures from Y.Q. Liu, et al, APS 2008]

Perturbative calculations using the MISK code indicate the importance of hot ions for the observed RWM stability

- **MISK: Perturbative formulation of kinetic damping based on the PEST mode structure** [Hu, Betti, *Phys. Rev. Lett.* (2004), Sabbagh, et al., IAEA FEC (2008)]





[Figures from J.W. Berkery, et al, APS 2008]

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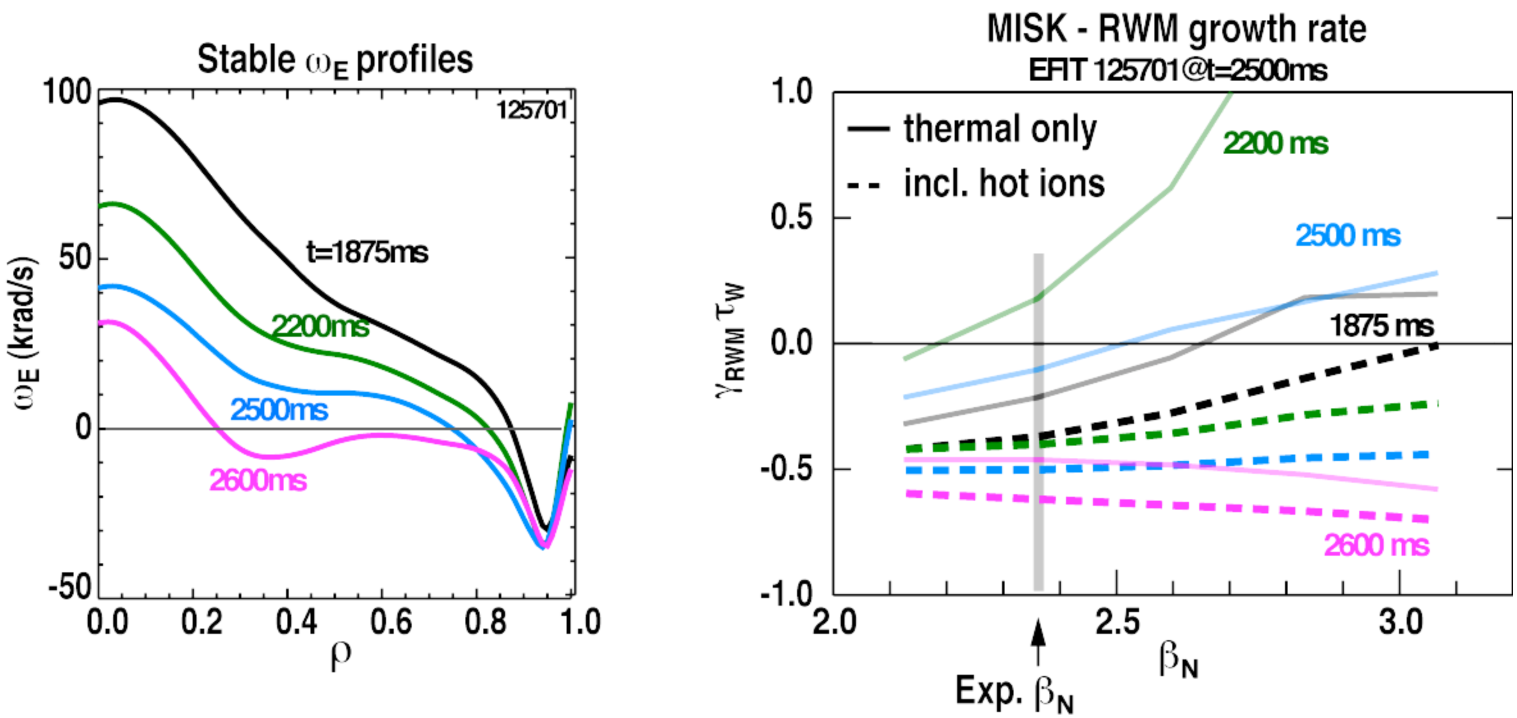
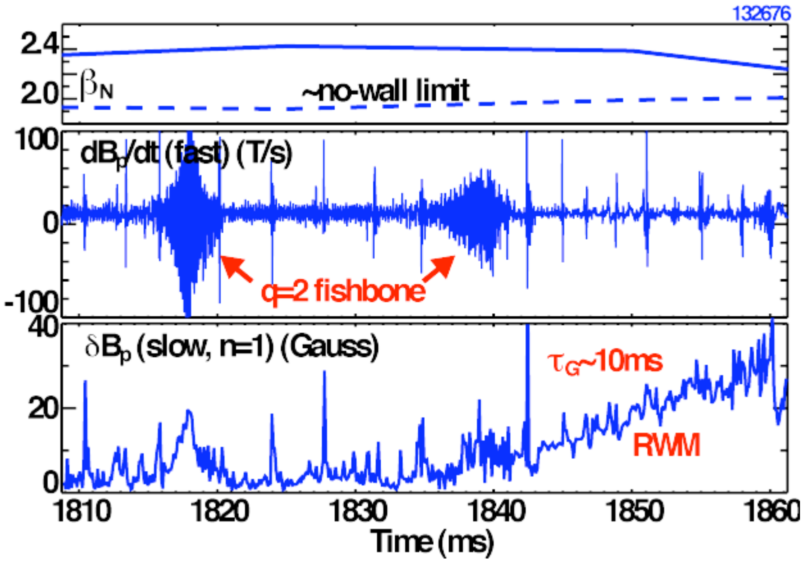


- **Kinetic effects sufficient to stabilize RWM over the entire range of observed rotation profiles**
  - Hot ions (~35% of total β) contribute significantly to the RWM stability

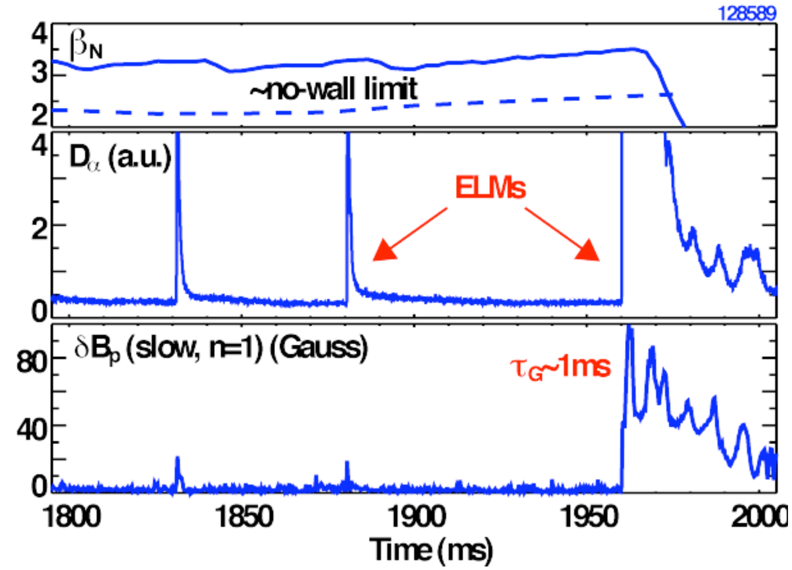
[Figures from J.W. Berkery, et al, APS 2008]

RWM can be triggered by localized instabilities such as q=2 fishbones and ELMs

- **Fishbone driven RWM observed at low density and slow rotation when q_{min}~2** [M.Okabayashi, et al., IAEA 2008]



- **ELM driven RWM can occur even at high rotation** [A.M. Garofalo, et al., *Phys. Plasmas* (2006)]

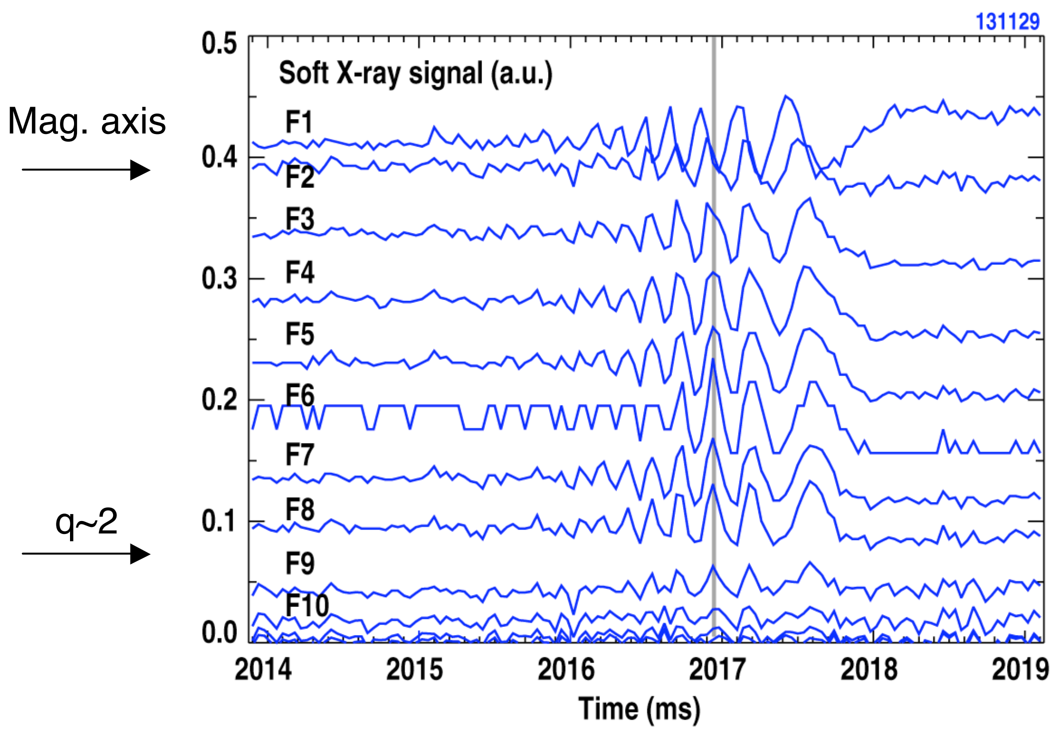


→ **Requires a non-linear destabilization mechanism**

Fishbone-driven RWM resembles "Energetic particle driven Wall Mode (EWM)" in JT-60U

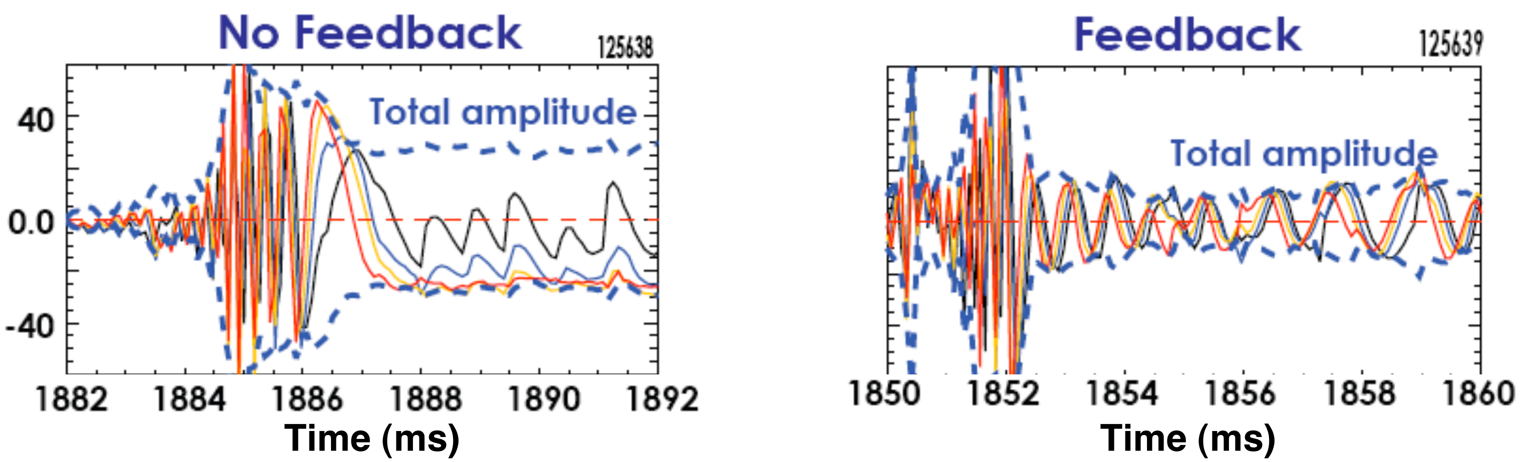
- **JT-60U observes EWM above no-wall limit** [G. Matsunaga, et al., IAEA 2008]
  - Directly induces RWM despite $\Omega > \Omega_{crit}$
  - Grows on wall time scales (1-2ms)
  - Globally spread kink-structure
  - Destabilized by perpendicular NBI (trapped particles)

- **DIII-D "q=2 fishbone" has similar global kink mode structure**
  - Growth time varies but can be as slow as wall time scales



Magnetic feedback can reduce the perturbation amplitude following a fishbone driven RWM

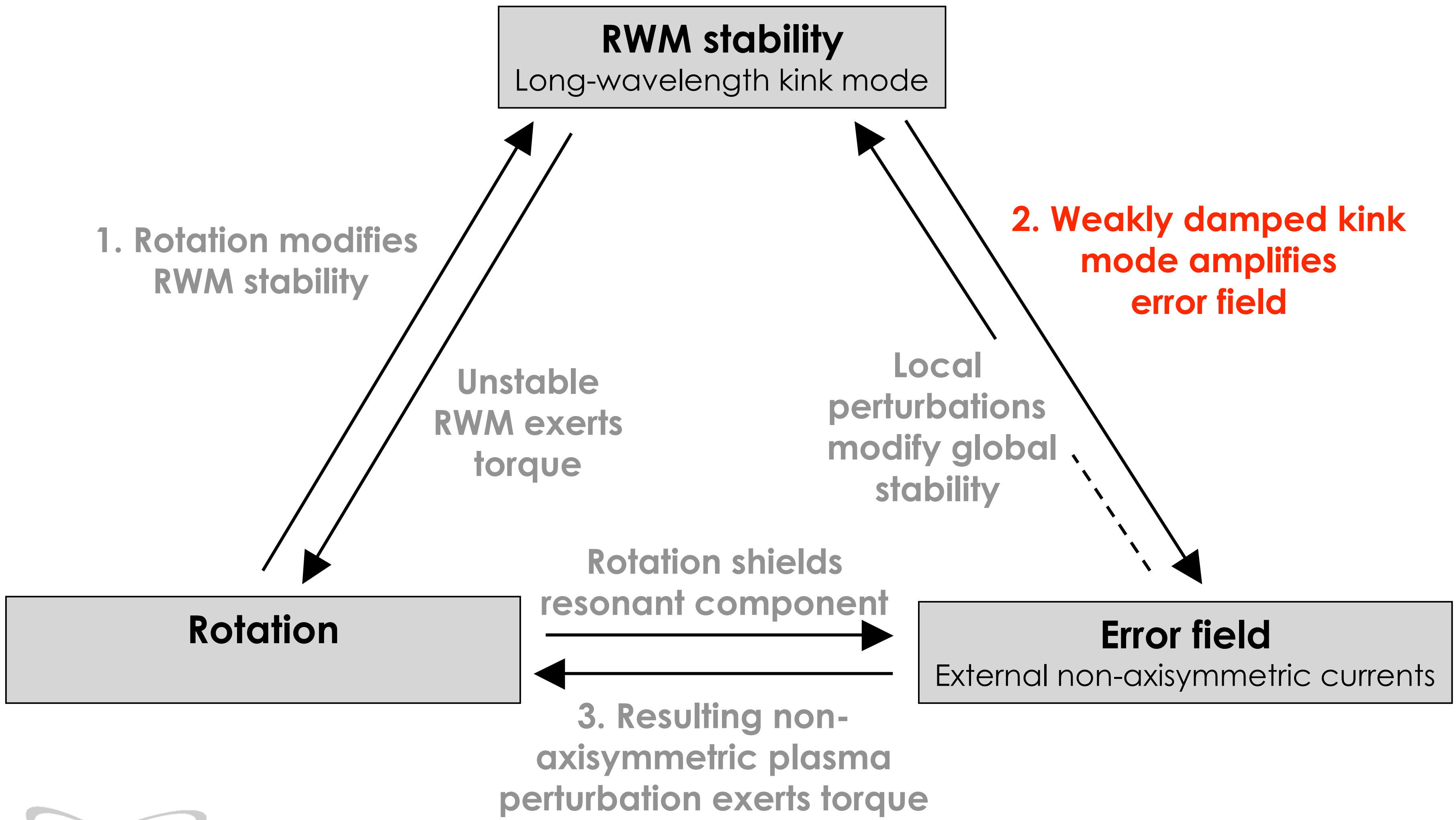
- **Apply RWM feedback in dicharges with fishbone-driven RWMs**



➔ **Finite amplitude rotating perturbation remains**

[Figures from M. Okabayashi, et al., IAEA 2008]

Interaction of RWM stability, error fields and plasma rotation



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Plasma amplifies externally applied *n*=1 field

- **Probe plasma with a static or slowly rotating *n*=1 field**
- **Obtain plasma response δB^{plas} from magnetic measurements by subtracting known vacuum coupling**
  - Plasma response increases linearly with applied current

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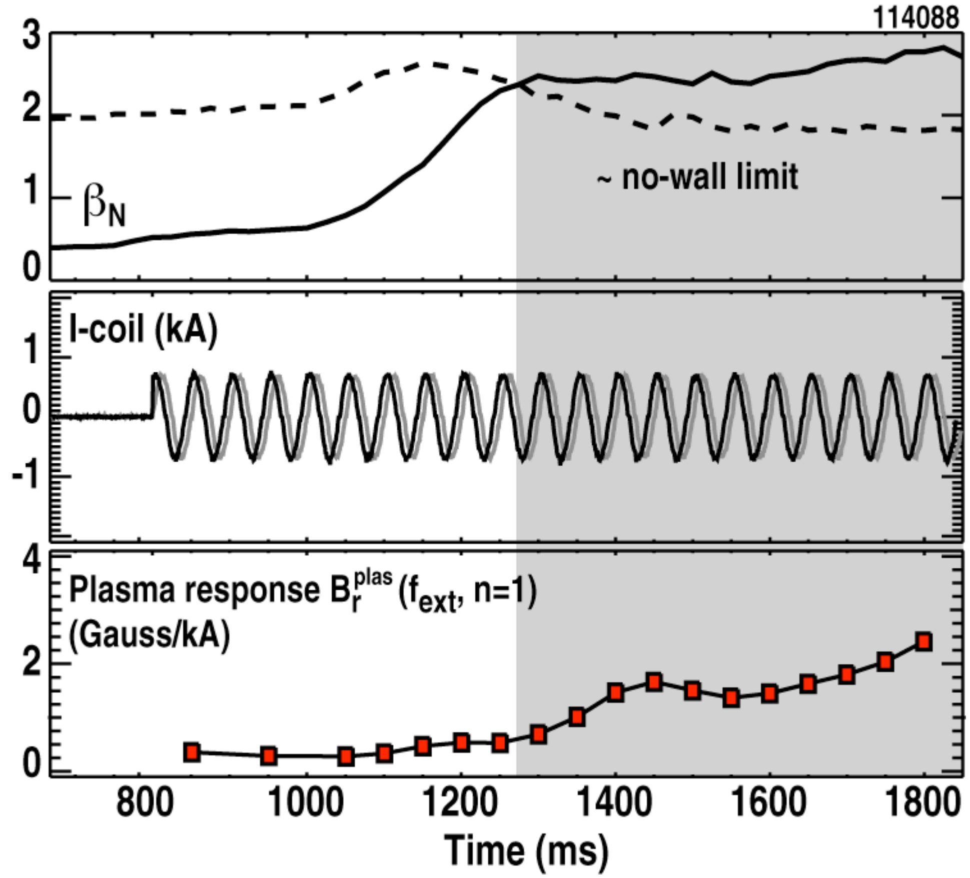
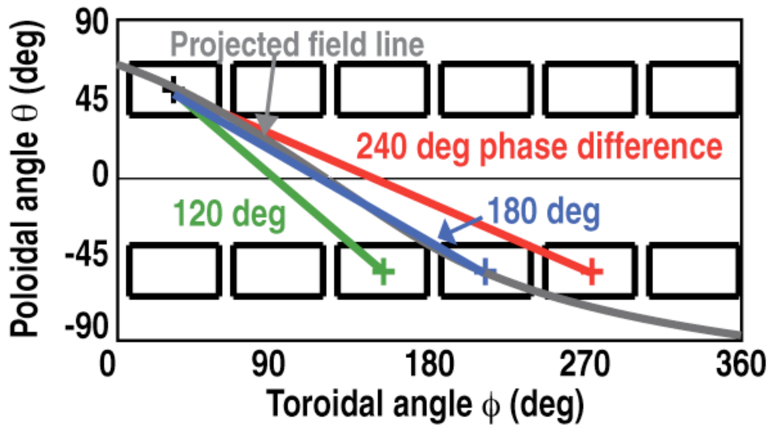
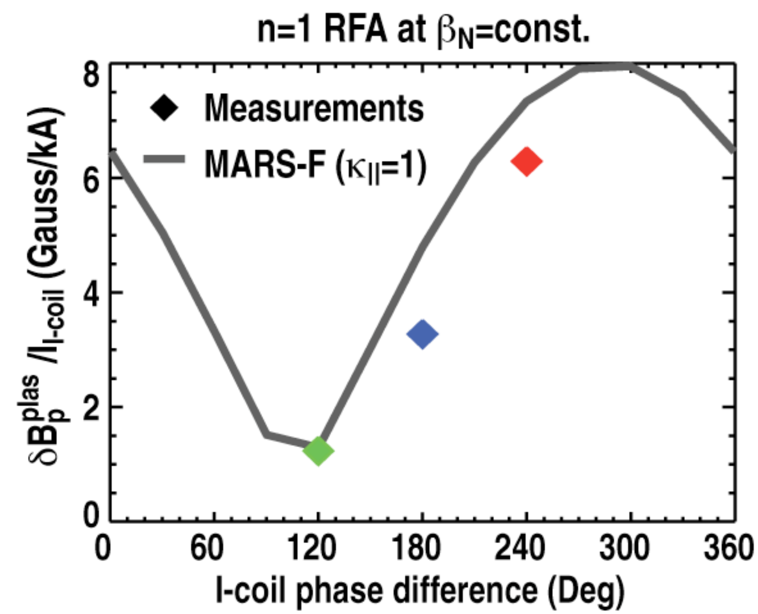
Described by resonant field amplification (RFA) of a weakly damped mode [A.H. Boozer, *Phys. Rev. Lett.* (2001)]



External field couples to a stable n=1 kink mode

- **RFA well described by a single stable RWM**
  - Response has a rigid structure [A.M. Garofalo, et al., *Phys. Plasmas* (2002)]
  - RFA frequency dependence consistent with single stable slowly rotating mode [H. Reimerdes, et al., *Phys. Rev. Lett.* (2004), A.C. Sontag, et al., *Nucl. Fusion* (2007)]
- **Vary the poloidal spectrum of the external I-coil field**





- **Measured dependence of RFA on I-coil phase difference in good agreement with MARS-F modeling (rotationally stabilized n=1 RWM)**

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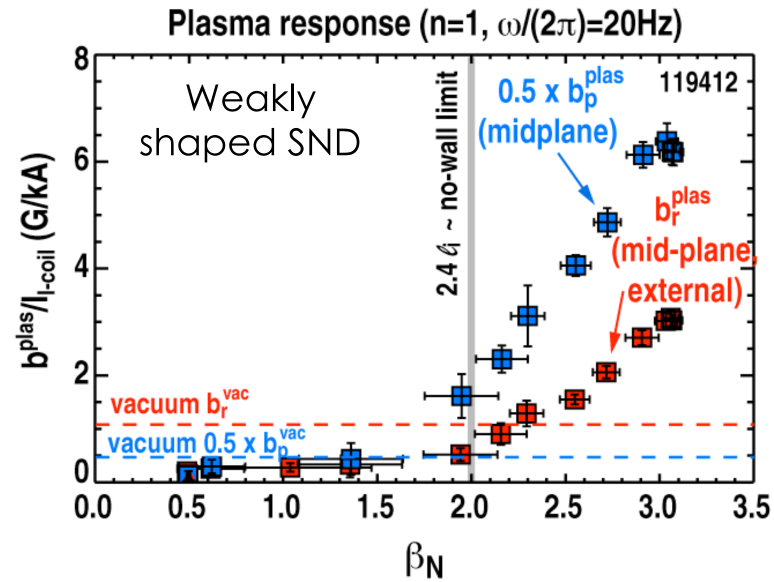
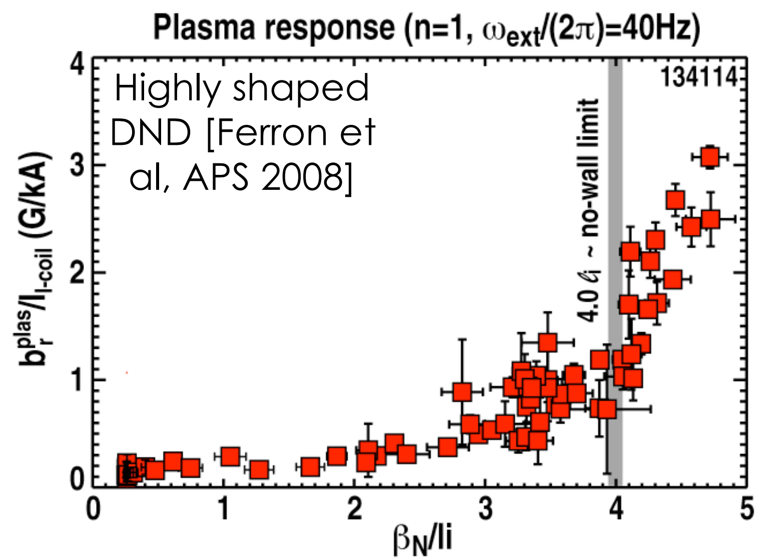
Resonant field amplification increases with beta

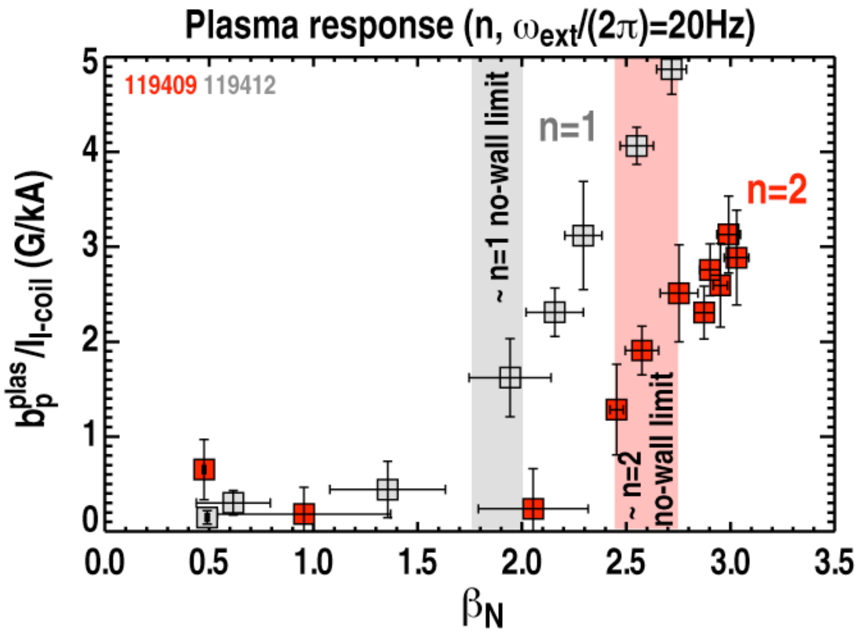
- **No or very weak RFA at low β_N (≤1)**
- **RFA increases with β_N**
  - Some scenarios show spikes or steps below $\beta_{N,no\text{-}wall}$
- **Increase of RFA with β_N accelerates in the vicinity of $\beta_{N,no\text{-}wall}$** [A.M. Garofalo, et al., *Phys. Plasmas* (2002)]
  - JET indicates an *RFA-threshold* at values of β_N 20% below $\beta_{N,no\text{-}wall}$ [M. Gryaznevich, et al., EPS 2008]
- **RFA can be used to test RWM stability models**
  - RFA above $\beta_{N,no\text{-}wall}$ is not consistent with soundwave or semikinetic damping models [H. Reimerdes, et al., *Nucl. Fusion* (2005)]



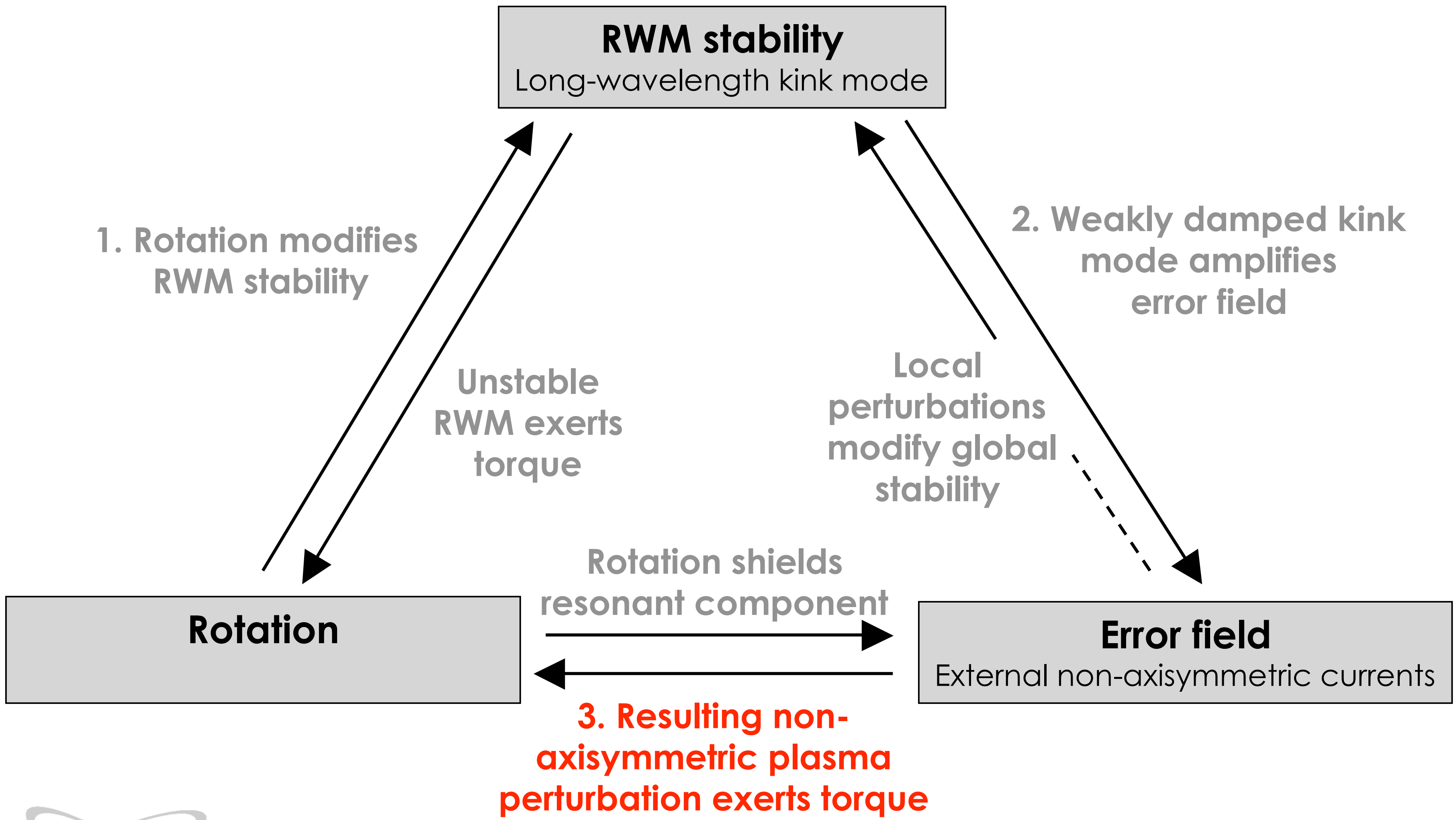


Higher *n* RFA (*n*=2) shows the same characteristic increase in the vicinity of the respective no-wall limit

- ***n*=2 RFA increases at significantly higher values of β_N than *n*=1 RFA in similar discharge**
  - Lower magnitude could be due to different coupling



Interaction of RWM stability, error fields and plasma rotation



Non-axisymmetric magnetic fields can stop the plasma rotation, drive locked modes and cause disruptions

- **External *n*=1 perturbations in the order of $\delta B^{ext}/B_T \sim 10^{-4}$ can be sufficient to stop the plasma rotation and drive a locked magnetic island**
  - Early high β experiments in DIII-D revealed a strong reduction of the error field tolerance with β [R.J. La Haye, et al., *Nucl. Fusion* (1992)]
  - However, β dependence has not been included in empirical scaling laws [ITER Physics Basis, *Nucl. Fusion* (1999)]

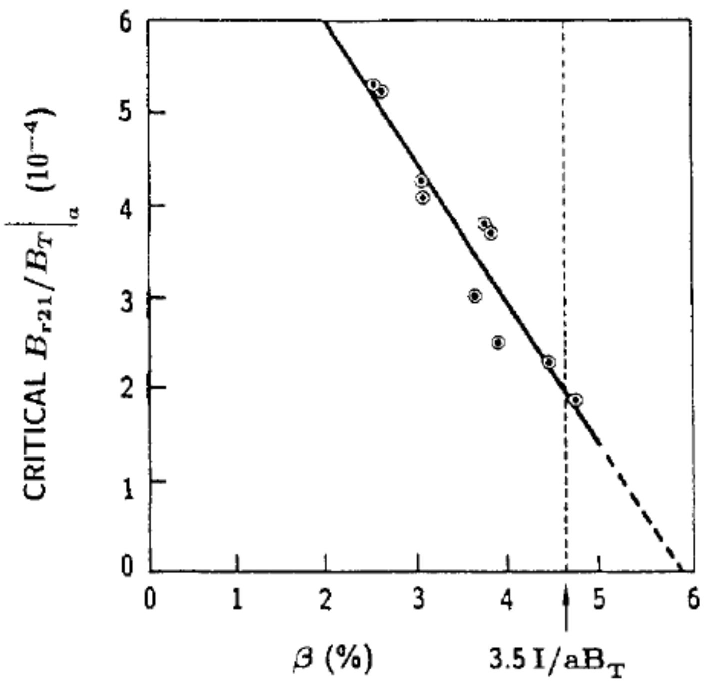


FIG. 10. Critical 2,1 relative error field for instability in H-mode plasmas as a function of beta (left or left/right beams).

Figure from La Haye, et al., Nucl. Fusion (1992]

Resonant magnetic braking torque can lead to a bifurcation of the plasma rotation

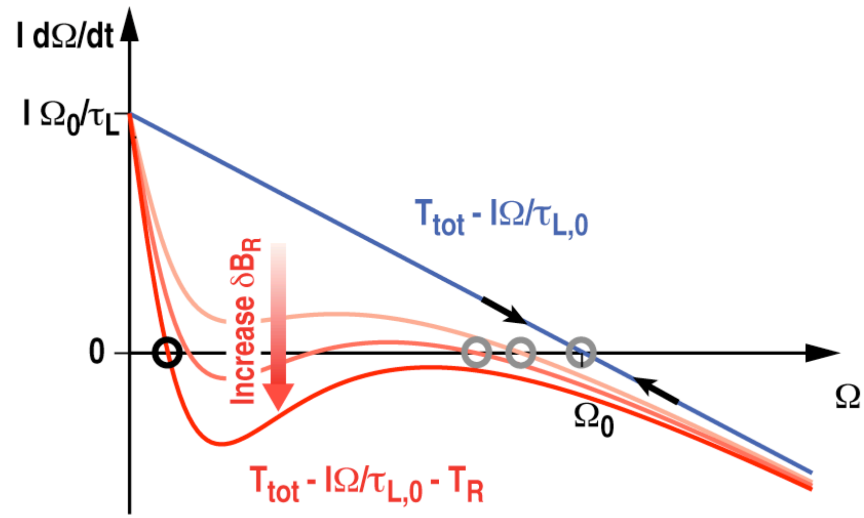
- **0D-model for plasma rotation**

$$I\frac{d\Omega}{dt} = T_{tot} - \frac{I\Omega}{\tau_{L,0}} - T_{MB}$$

with $\tau_{L,0}$ being the momentum confinement time without braking

- **Assume a resonant magnetic braking torque with $T_R \propto \Omega^{-1}$**
  [R. Fitzpatrick, *Nucl. Fusion* (1993)]

$$T_{MB} \rightarrow T_R = K_R\,\delta B_R^2\,\Omega^{-1}$$



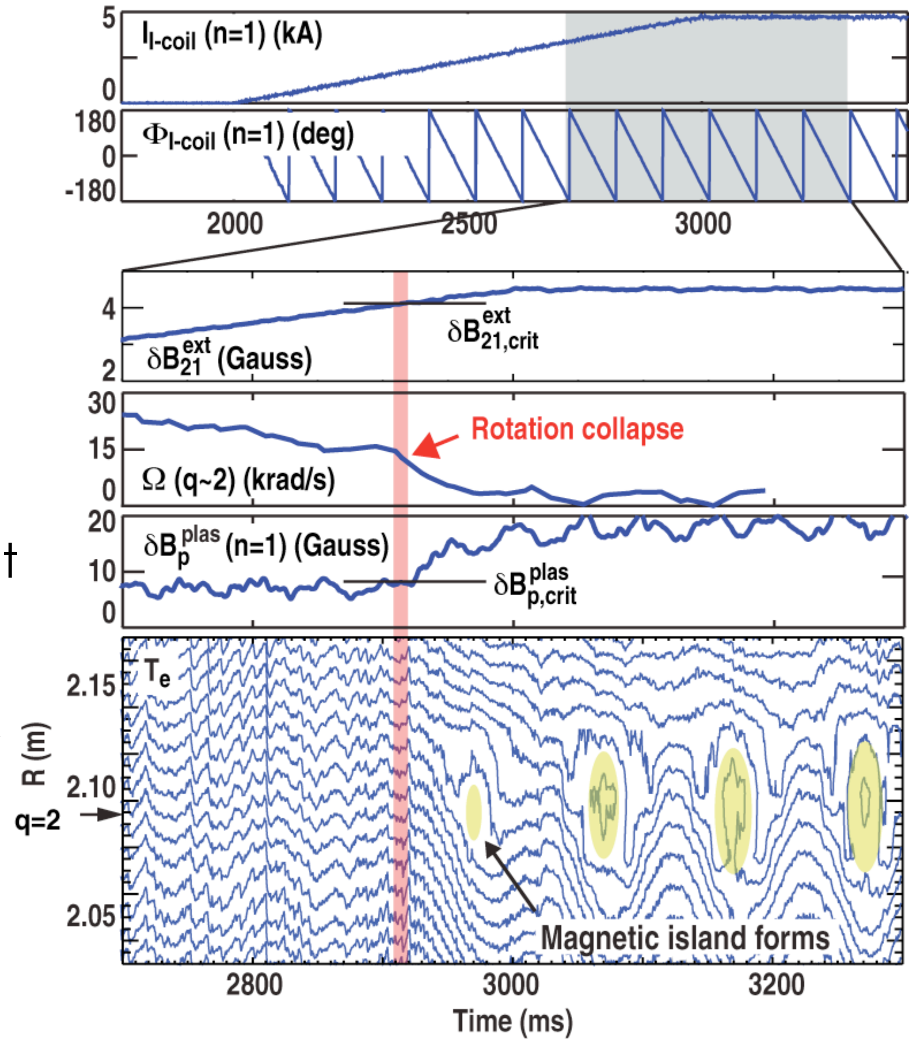
- **Torque balance $d\Omega/dt = 0$ when** $\Omega = \frac{T_{tot}\tau_{L,0}}{2I} \pm \sqrt{\left(\frac{T_{tot}\tau_{L,0}}{2I}\right)^2 - \frac{K_R\tau_{L,0}}{I}\delta B_R^2}$
  - Bifurcation at $\Omega = \frac{\Omega_0}{2}$ (with $\Omega_0 = \frac{T_{tot}\tau_{L,0}}{I}$ being the unperturbed rotation), when resonant perturbation exceeds $\delta B_{R,crit} = T_{tot}\sqrt{\frac{\tau_{L,0}}{4IK_R}}$

Error field tolerance in NBI heated H-modes is determined by resonant braking leading to a loss of torque balance

- **Increase the amplitude of an external $n = 1$ "*error*" field $\delta B^{ext} \propto I_{I\text{-coil}}$**

↓

- **Rotation evolution is described by resonant braking** [A.M. Garofalo, et al., *Nucl. Fusion* (2007)]
  – At high rotation external resonant field is shielded, but exerts a torque
  – Rotation decrease is followed by a loss of torque balance
  – Magnetic island opens after rotation collapses



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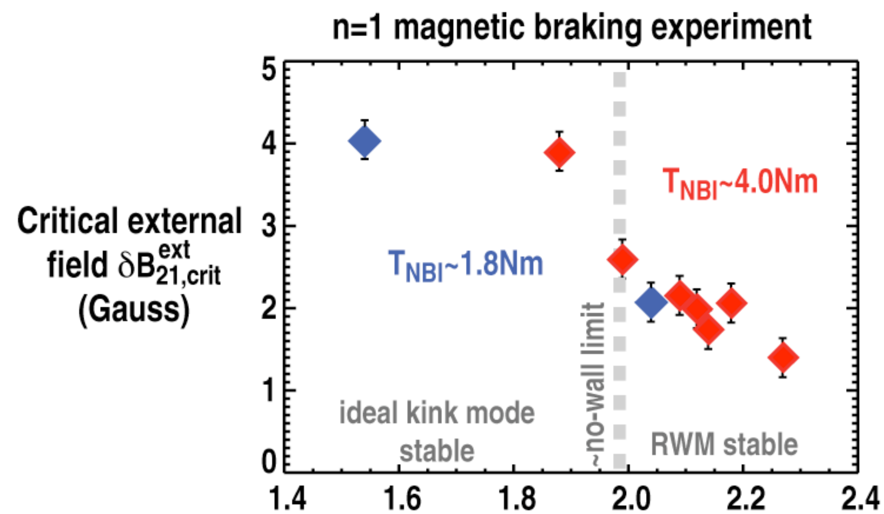
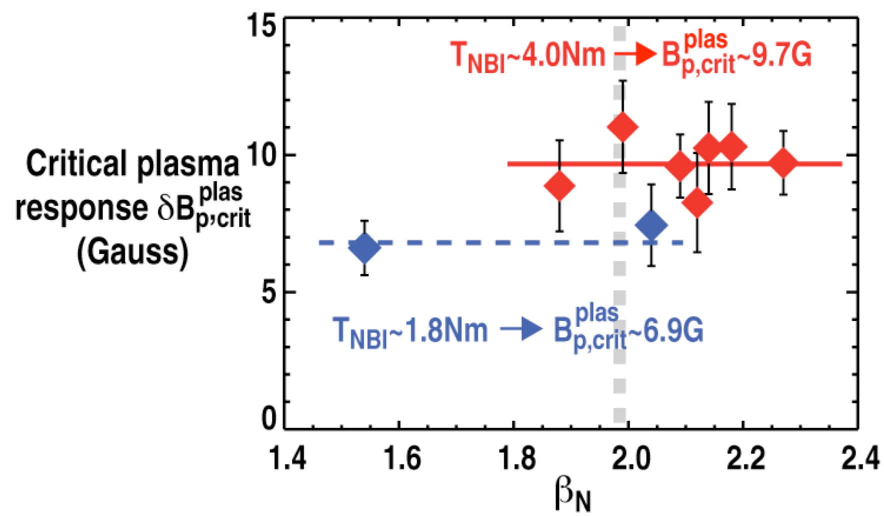
Tolerance to external n=1 perturbations decreases with increasing β_N due to plasma amplification

- **Decrease of critical external field $\delta B_{21,crit}^{ext}$ is particularly strong above the no-wall limit**
  - External field is also increasingly amplified

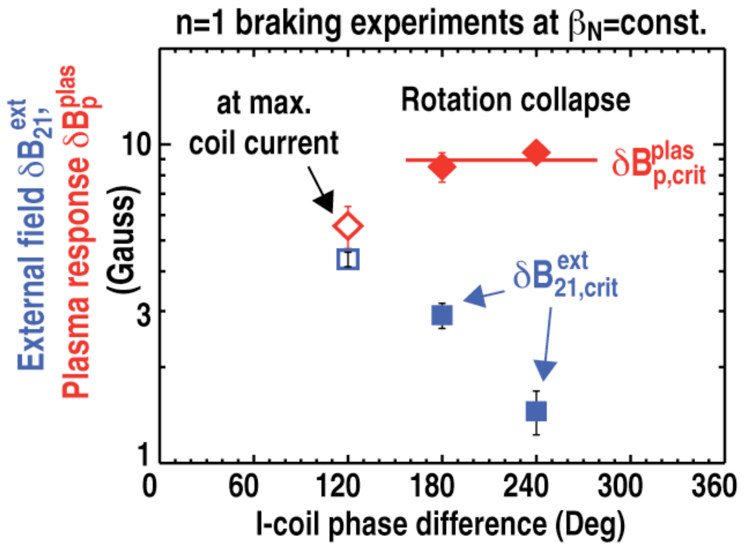


- **Rotation collapse occurs at a fixed plasma response $\delta B_{p,crit}^{plas}$**
- **Critical plasma response $\delta B_{p,crit}^{plas}$ increases with NBI torque T_{NBI}**

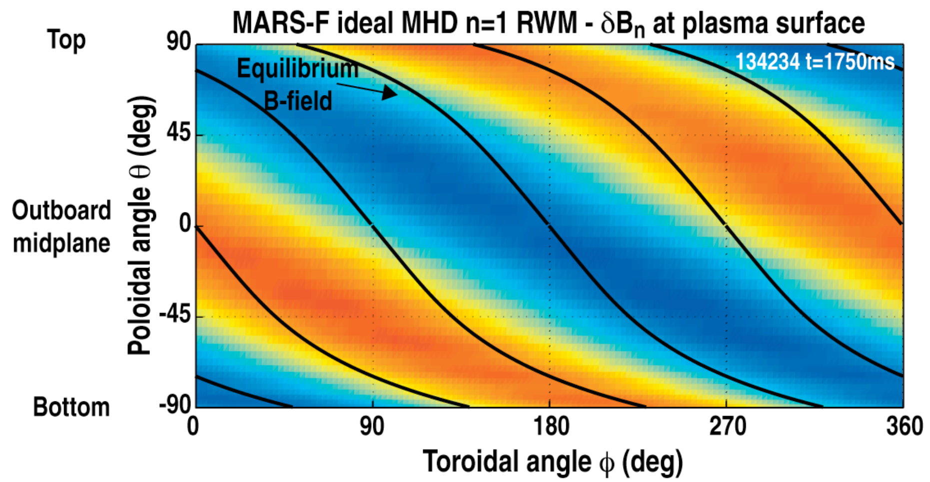


Resonant braking is determined by external field that is kink-mode resonant (and not necessarily pitch resonant)

- **I-coil phasing scan also results in a critical plasma response $\delta B_{p,crit}^{plas}$**
  - Tolerable external resonant field $\delta B_{21,crit}^{ext}$ varies by more than a factor of 3

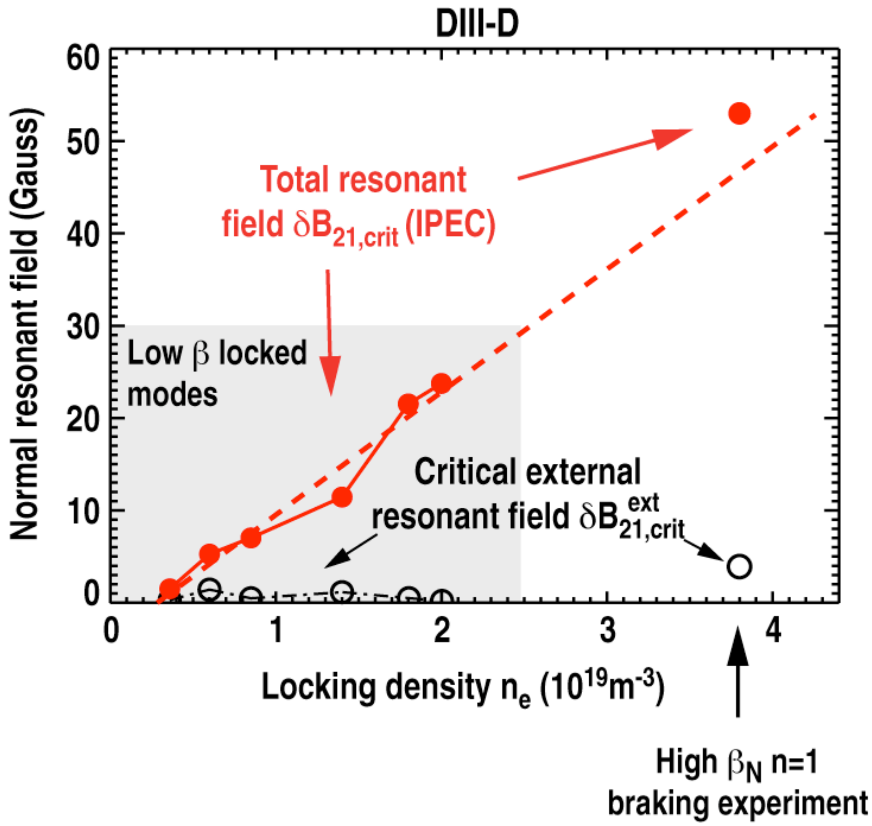


- **Pitch angle of kink mode at outboard midplane (and high β_N) differs from equilibrium field**
  - Pitch of equilibrium field at outboard midplane changes only weakly with radius, i.e. q



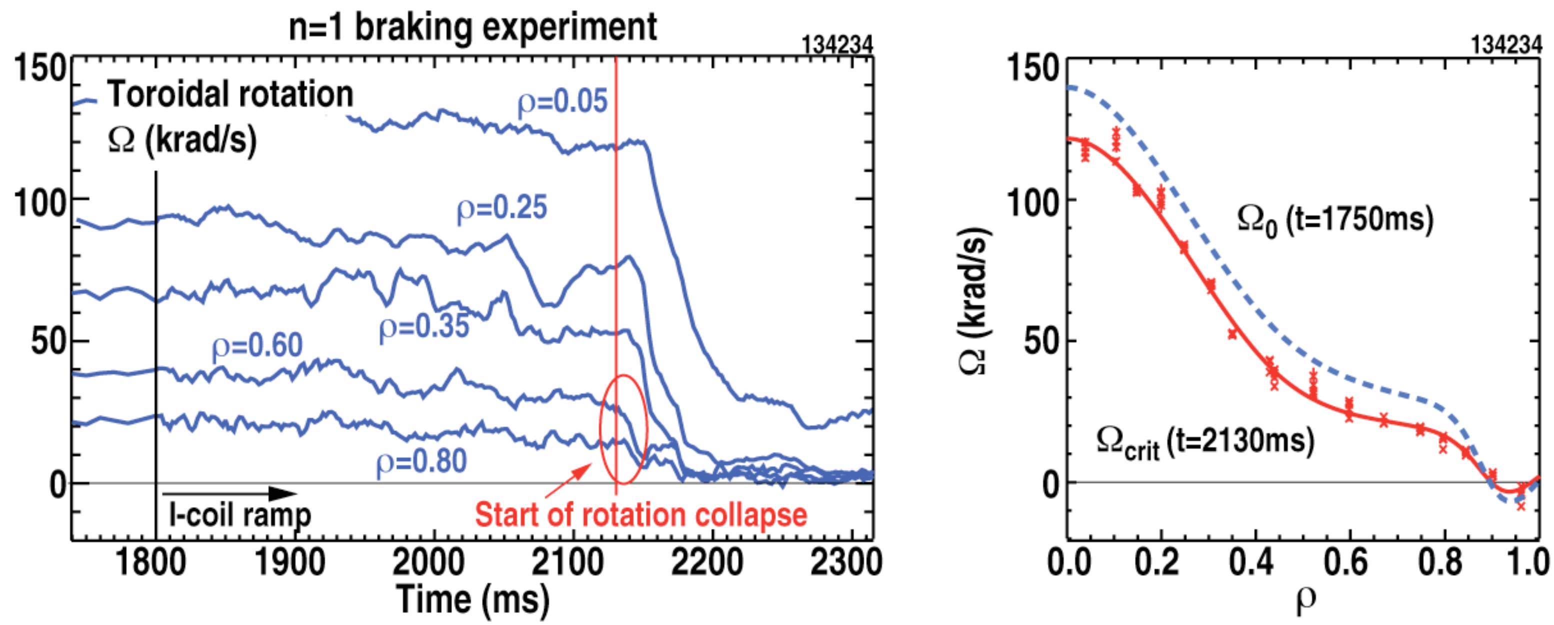
Plasma response (IPEC) connects error field tolerance at high β with Ohmic plasmas via the linear density scaling

- **Plasma response is key to restore linear density scaling of the error field threshold in low β locked mode experiments** [J.-K. Park, et al., *Phys. Rev. Lett.* (2007)]
  - Perturbation modeled with ideal perturbed equilibrium code (IPEC) [J.-K. Park, et al., *Phys. Plasmas* (2007)]



- **Total resonant field (IPEC) at rotation collapse $\delta B_{21,crit}$ in low T_{NBI} H-mode discharge with β_N=1.5 is in good agreement with the low β density scaling**

n=1 magnetic braking leads to rotation decrease across the entire profile until a sudden rotation collapse occurs



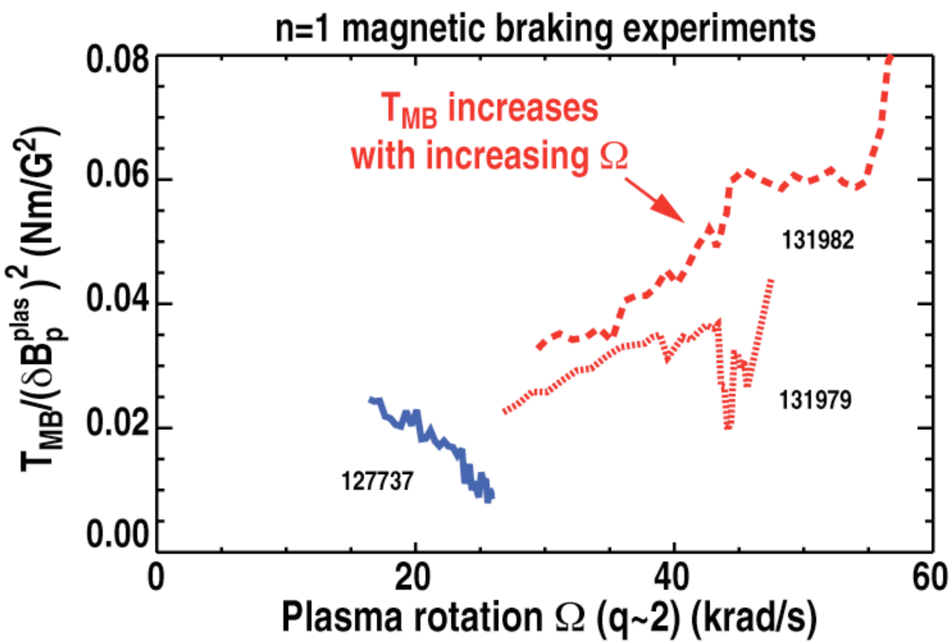
- Rotation measurements up to the rotation collapse show no evidence of localized braking (limited by uncertainty of Ω' and Ω")
- Rotation collapse starts at the outer half of the profile

Measured n=1 braking torque reveals importance of a non-resonant magnetic braking component

- **Measured angular momentum evolution yields magnetic braking torque** T_{MB}

$$T_{MB} = T_{NBI} - \frac{L}{\tau_{L,0}} - \frac{dL}{dt}$$

  - Assume $T_{MB} \propto (\delta B^{plas})^2$ to reveal rotation dependence



- **At low rotation T_{MB} increases with decreasing Ω consistent with a resonant torque** [R. Fitzpatrick, *Nucl. Fusion* (1993)]
- **At high rotation T_{MB} increases with Ω → typical for a non-resonant torque** [K.C. Shaing, *Phys. Plasmas* (2003)]

Effect of simultaneous resonant and non-resonant braking

- **Adding a non-resonant component to the magnetic braking torque in the torque balance***

$$I\frac{d\Omega}{dt} = T_{tot} - \frac{I\Omega}{\tau_{L,0}} - K_R \delta B_R^2 \Omega^{-1} - K_{NR} \delta B_{NR}^2 \Omega$$

leads to a reduction of the tolerable resonant field :

$$\delta B_{R,crit} = T_{tot} \left(\tau_{L*}/(4IK_R)\right)^{1/2}$$

where $\tau_{L*} = \left(\tau_{L,0}^{-1} + I^{-1} K_{NR} \delta B_{NR}^2\right)^{-1}$ is a reduced momentum confinement time

- **Non-resonant braking changes the dependence of $\delta B_{R,crit}$ on torque input**
  - Resonant magnetic braking only :

$$\delta B_{R,crit} \propto T_{tot}$$

  - Adding a strong non-resonant torque :

$$\delta B_{R,crit} \propto T_{tot}^{\,0.5}$$

***Neglect offset rotation in counter-Ip direction** [A. Cole, et al., *Phys. Rev. Lett.* (2007), A.M. Garofalo, et al., *Phys. Rev. Lett.* (accepted)]

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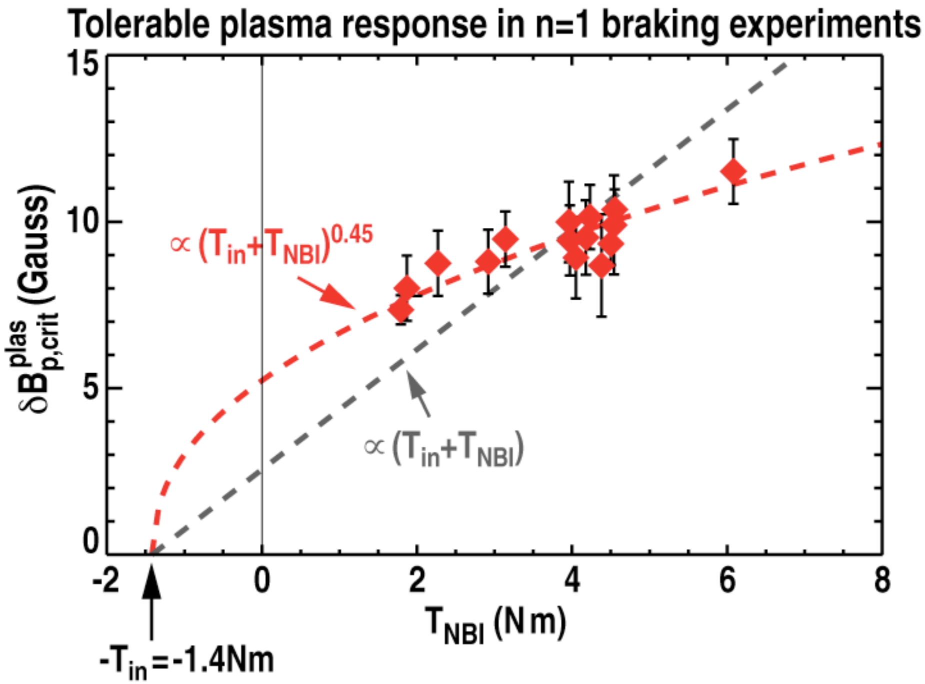
NBI torque dependence of error field tolerance consistent with a significant contribution of non-resonant braking

- **Fit T_{NBI} dependence of the measured error field tolerance**
  - Amplification is linear → $\delta B_R, \delta B_{NR} \propto \delta B_p^{plas}$
  - Total torque includes an intrinsic torque T_{in} (estimated from experiment)



➢ **Observed dependence of the n=1 error field tolerance on NBI torque is consistent with a significant contribution of non-resonant braking**

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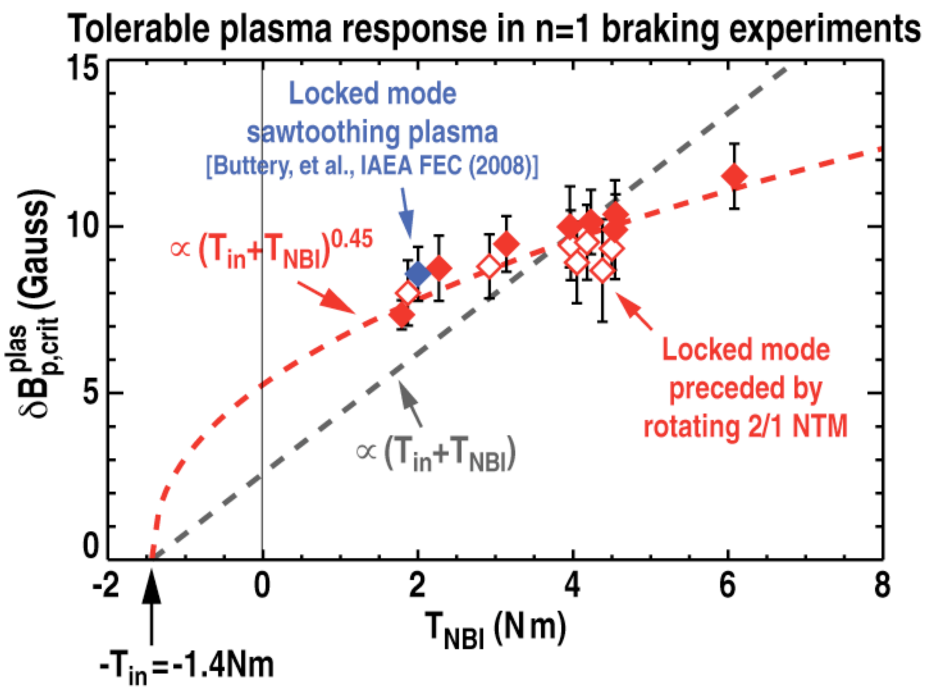
NBI torque dependence of error field tolerance consistent with a significant contribution of non-resonant braking

- **Fit T_{NBI} dependence of the measured error field tolerance**
  - Amplification is linear → $\delta B_R, \delta B_{NR} \propto \delta B_p^{plas}$
  - Total torque includes an intrinsic torque T_{in} (estimated from experiment)



➢ **Observed dependence of the n=1 error field tolerance on NBI torque is consistent with a significant contribution of non-resonant braking**

Summary/Conclusions

- **RWM in DIII-D can remain stable over a wide range of rotation profiles**
  - Suppressing 2/1 NTM extends operating regime below the previously reported rotation threshold
- **Wall-stabilized plasmas test linear models of kinetic RWM stabilization**
  - MARS-K calculations using a non-perturbative approach result in weaker damping than observed in DIII-D
    - RWM mode structure is not modified by kinetic effects
    - Reduced stability is probably due to a new RWM branch
  - MISK calculations indicate the importance of hot ions (NBI), which have not yet been included in the MARS-K calculations
- **RWM can be triggered by other localized instabilities such as ELMs and *q*=2 fishbones suggesting the possibility of non-linear RWM destabilization mechanisms**

Summary/Conclusions (cont.)

- **Stable kink mode can amplify external non-axisymmetric fields**
  - Plasma sensitive to fields that are resonant with the kink mode
  - RFA (amplitude and phase) depends on kink mode stability
    - RFA measurement has potential for real-time stability measurement
- **Tolerable external non-axisymmetric field (*resonant* with the kink mode) is determined by resonant braking (*resonant* with equilibrium field)**
  - Error field tolerance determined by plasma response to external field
    - Increase of RFA with β_N explains decrease off error field tolerance
    - Plasma is most sensitive to an external kink-type perturbation
  - Plasma response connects error field tolerance in high β H-modes with the locking threshold in Ohmic plasmas via the linear density scaling
  - Magnetic braking occurs through resonant and non-resonant effects
    - Non-resonant braking reduces the benefit of additional torque input

Backup slides

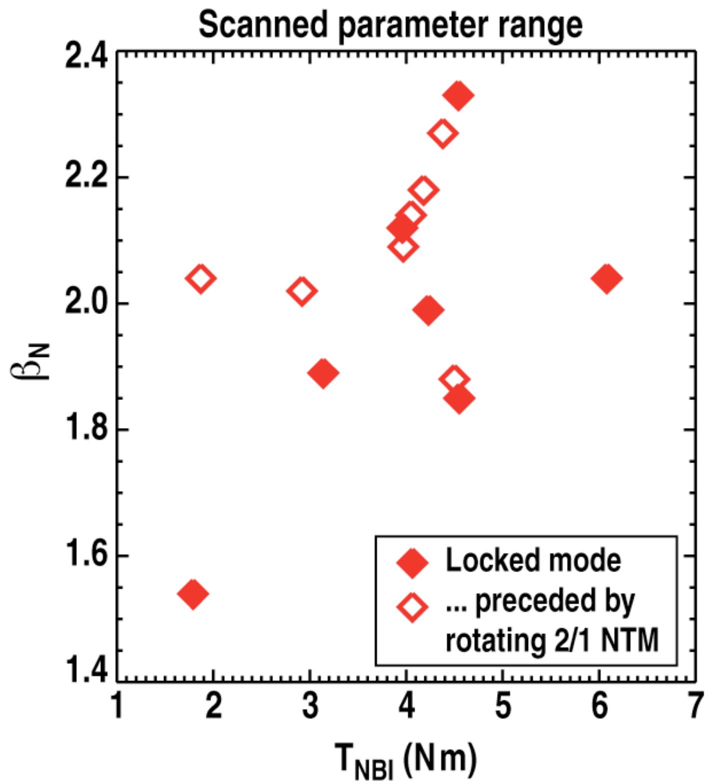
Plasma rotation through the perturbed field of an RWM can lead to damping

- **In ideal MHD β_N is usually limited by a long-wavelength (*n*=1) kink mode**
  - Growth rate without a conducting wall : $(\gamma\tau_A)^2 = \delta W_\infty$
  - Growth rate with an ideal conducting wall : $(\gamma\tau_A)^2 = \delta W_b$
    - Marginal value of β_N increases when an ideal conducting wall imposes a constant flux boundary condition : $\beta_{N,\text{ideal-wall}} > \beta_{N,\text{no-wall}}$

- **Finite wall resistivity allows RWM to grow when $\beta_N > \beta_{N,\text{no-wall}}$**
  - RWM growth rate [S.W. Haney, J.P. Freidberg, *Phys. Fluids B* (1989)] : $\gamma\tau_W = -\frac{\delta W_\infty}{\delta W_b}$
    - Characteristic wall time scales $\tau_W >> \tau_A$
  - Plasma flow/particle resonances can modify RWM stability [A. Bondeson, D. Ward, *Phys. Rev. Lett.* (1994), A. Bondeson, M.S. Chu, *Phys. Plasmas.* (1996)]
    - Include kinetic effects in the δW formulation and add precession frequency [B. Hu, R. Betti, *Phys. Rev. Lett.* (2004)]

$$\gamma\tau_W = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

Analyze *n*=1 error field tolerance in magnetic braking experiments at various values of β_N and NBI torque



- **At low T_{NBI} (i.e. low rotation) and/or high β_N the rotation collapse is frequently preceded by the onset of rotating 2/1 NTMs**
  - Consistent with a reduction of the critical β_N for the onset of the 2/1 NTM with decreasing rotation [R.J. Buttery, et al., Phys. Plasmas (2008)]

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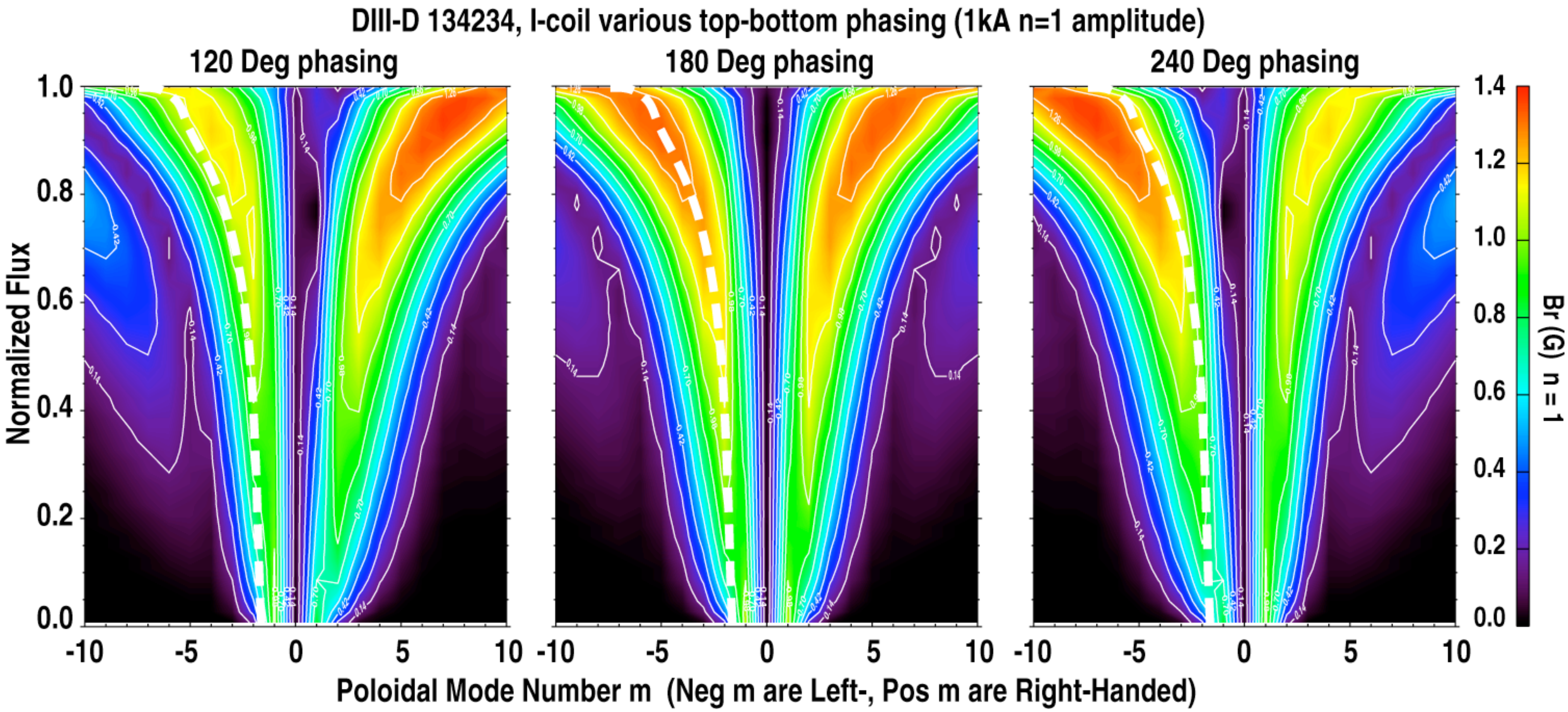
Vary poloidal spectrum (pitch angle) of the external *n*=1 perturbation using the I-coil



- **180 Deg phasing maximizes the resonant component of the external perturbation**

Frequency response well described by a single weakly damped mode

- **Frequency response of stable high β plasma is well described by a single mode model**

$$\tau_w \frac{dB_s}{dt} - \tau_w \gamma_0 B_s = M^*_{sc} I_c$$

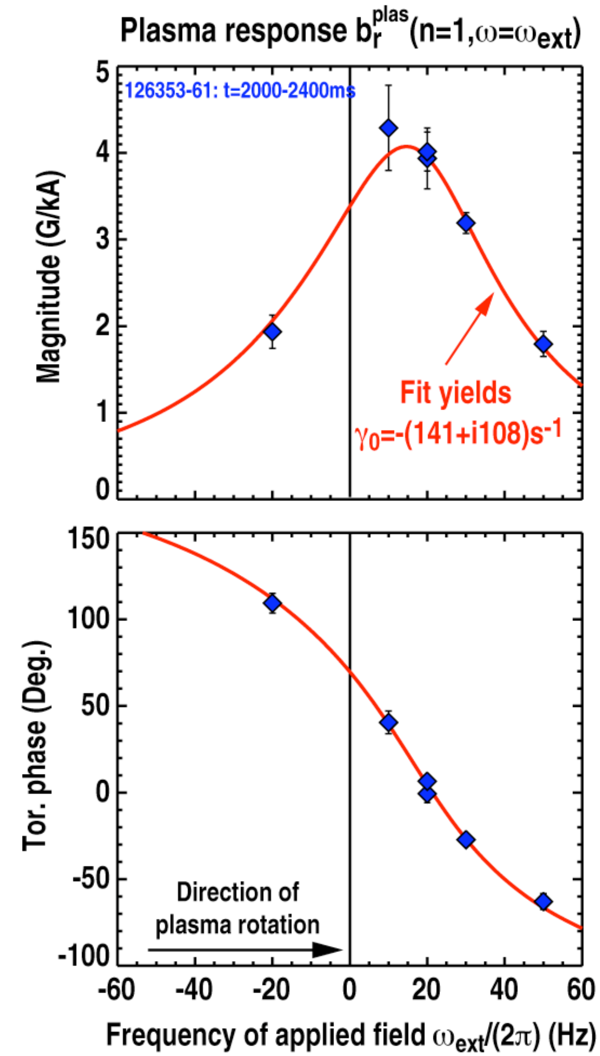
with $\gamma_0 = \gamma_{RWM} + i\omega_{RWM}$

  – Fit of measured spectrum yields

Damping rate	$-\gamma_{RWM}$
Mode rotation frequency	ω_{RWM}
Effective mutual inductance	M_s^*

  – RFA spectrum has also been observed in NSTX [Sontag et al, *NF* (2007)] and JET [Gryaznevich et al, EPS (2007)]

- **Consistent with MARS-F calculations showing that a rotationally stabilized plasma is well described by a single pole** [Liu et al, *PoP* (2006)]



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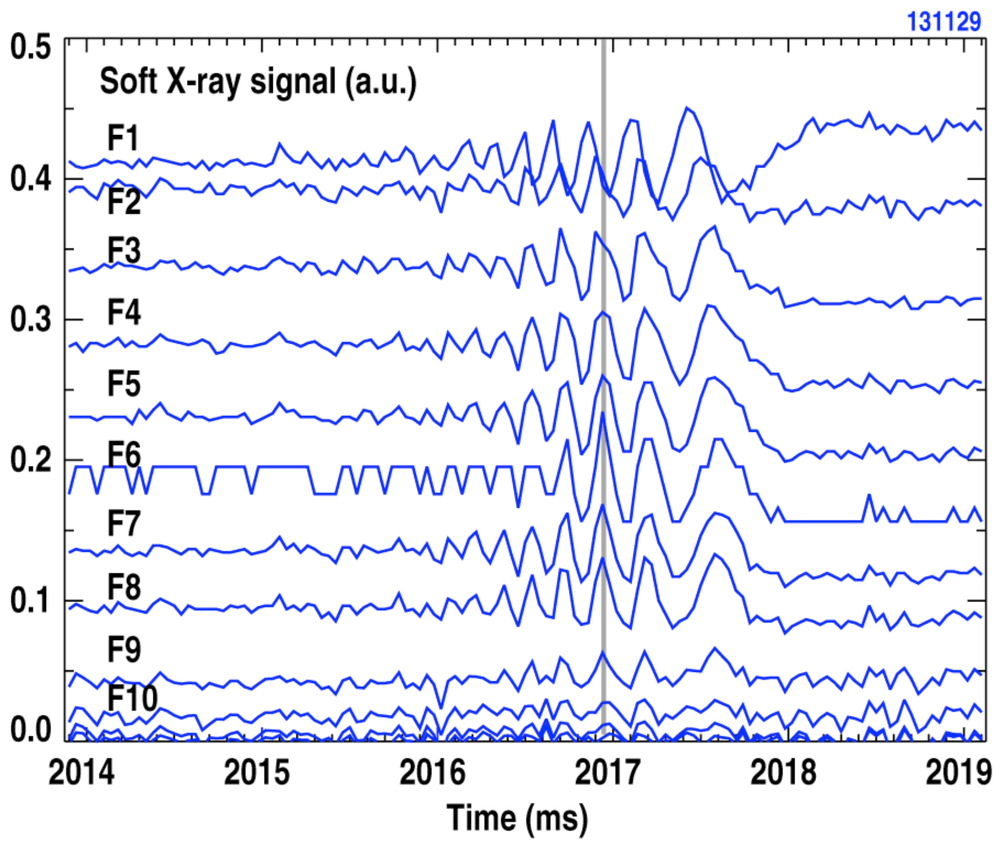
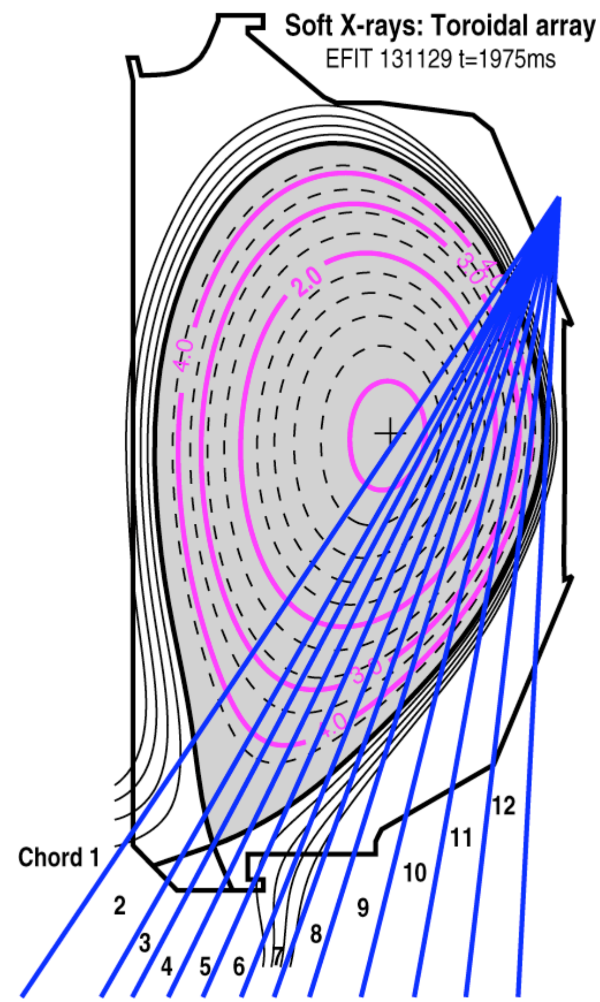
Internal structure of "q=2 fishbone" is consistent with a kink mode





- **Soft X-ray measurements do not show any island structure**