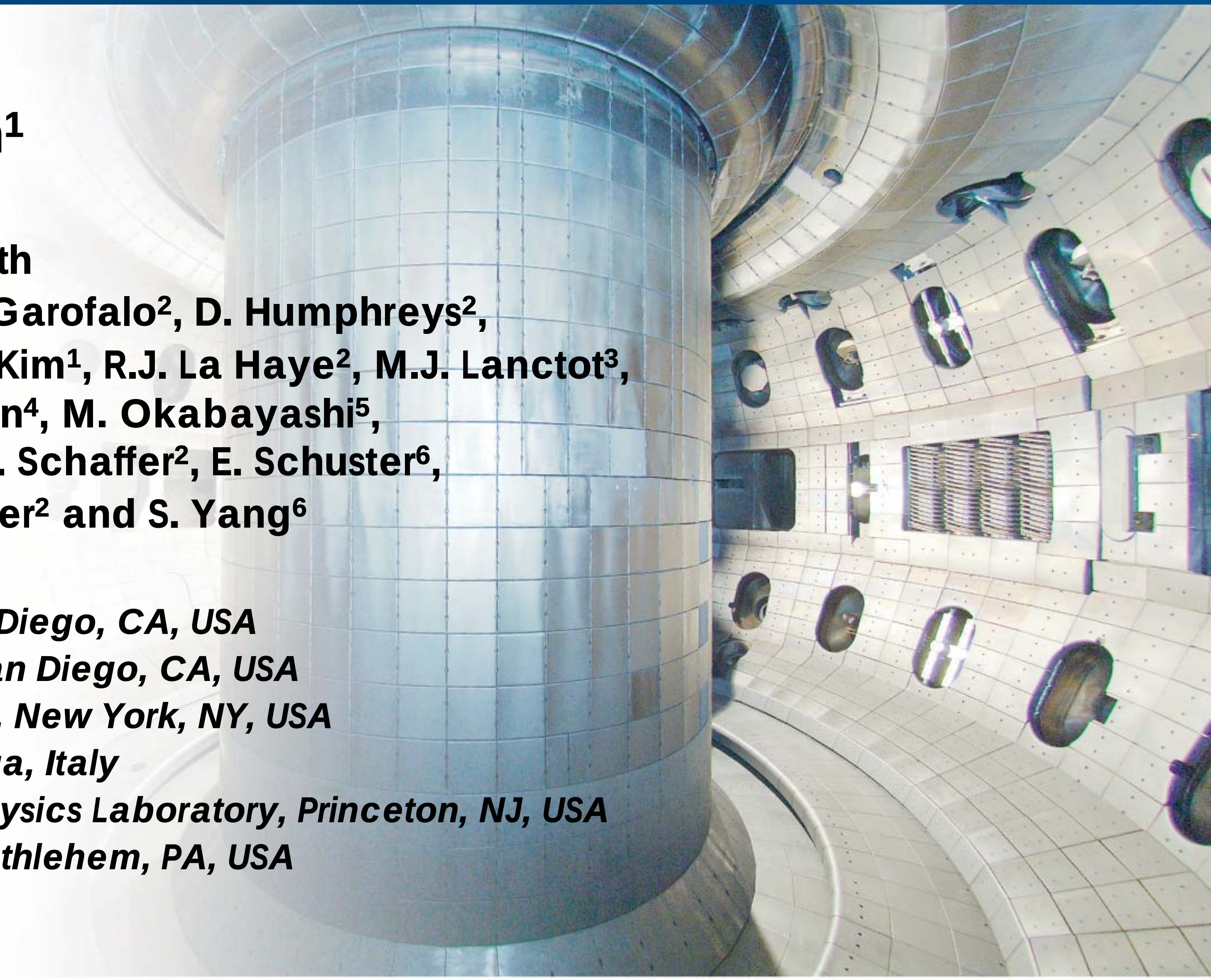
Efficacy of current-driven resistive-wall-mode feedback control



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The efficacy of feedback stabilization can be well addressed in terms of minimal plasma disturbances

- Highly reproducible current-driven RWM enables us to explore the RWM feedback control in detail
  - Due to the irreproducibility of pressure-driven RWMs, the RWM feedback process has not been evaluated thoroughly.
  - The RWM feedback control can be assessed using a reproducible RWM target at $q_{95} \sim 4$.

- The feedback stabilization efficacy needs to be assessed based on both internal and external plasma responses

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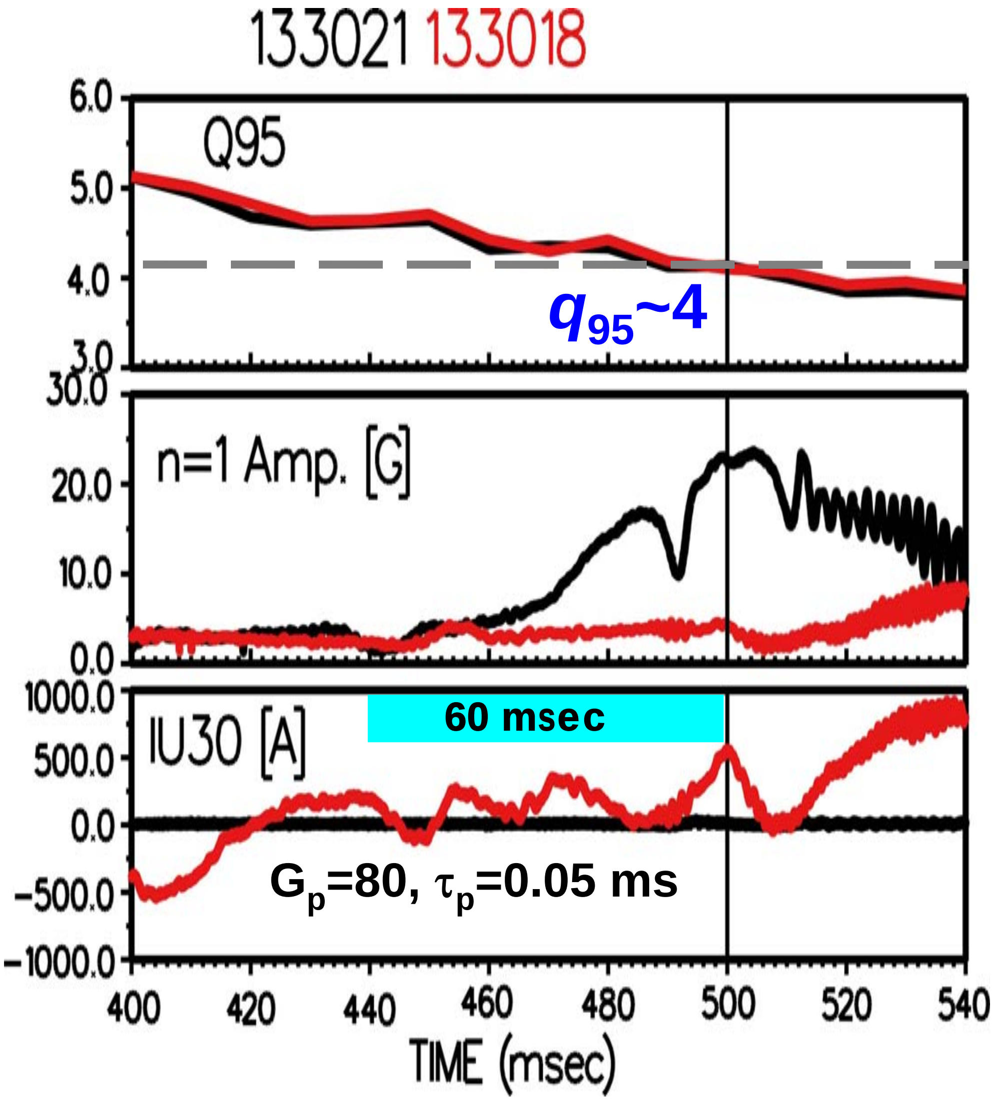
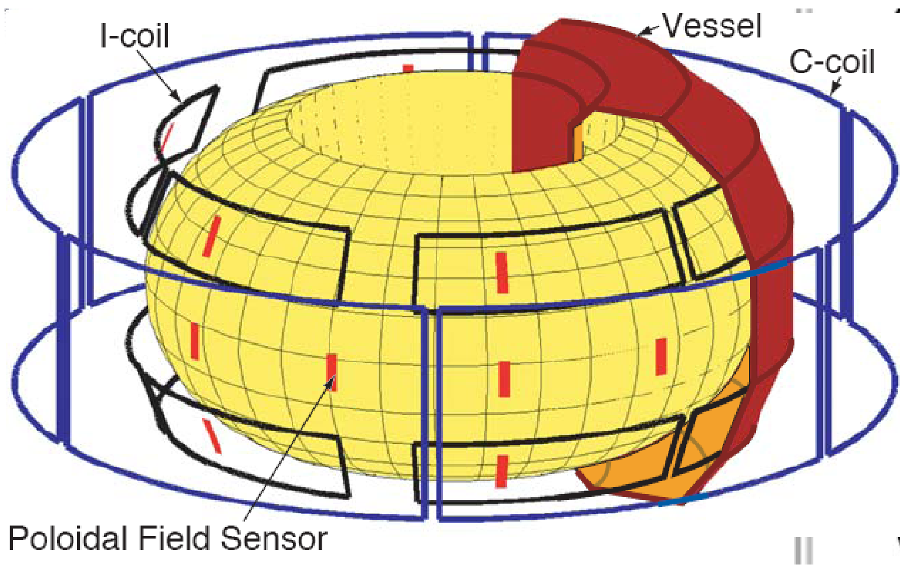
Complete feedback stabilization of current-driven RWM at q_{95}~4 has been achieved in DIII-D



- **Ohmic discharge with high current ramp-up rate**
- **Tools**
  - **Internal coils ("I-coils"): Direct Feedback + Dynamic error field correction (EFC)**
  - **External coils ("C-coils"): Static EFC**



The RWM feedback control loop is fully equipped with slow and fast time scale actuators

- **Feedback loop ($\tau_p << \tau_w$)**

$V_{FB}^{n=1}$

Power Supply → **Plant (DIII-D/RWM)**

$(\tau_w, \tau_{L/R}, \delta I_{FB}^{n=1})$

$\delta B^{n=1}$ + ?

PD Controller

$$K(s) = \frac{1}{1 + s\tau_p}\left[G_p + \frac{G_d s \tau_d}{1 + s\tau_d}\right]$$

$G_{p,d}$: Gain $\tau_{p,d}$: time constant
where p - proportional, and
d - derivative

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Key results

- **Current-driven RWM at q_{95} ~ 4 was completely stabilized by the RWM feedback control with G_p only.**

- The use of derivative gains (G_d=10G_p) expanded the stable range of proportional gains.
  - Reducing a phase lag in time avoids any mismatch between RWM and applied field.
  - High gain scan results suggest the contributions of the I-coils necessary for DEFC

- A phase-shifted *n*=1 field in the direction of co-I_p rotation is more effective than in the opposite direction.

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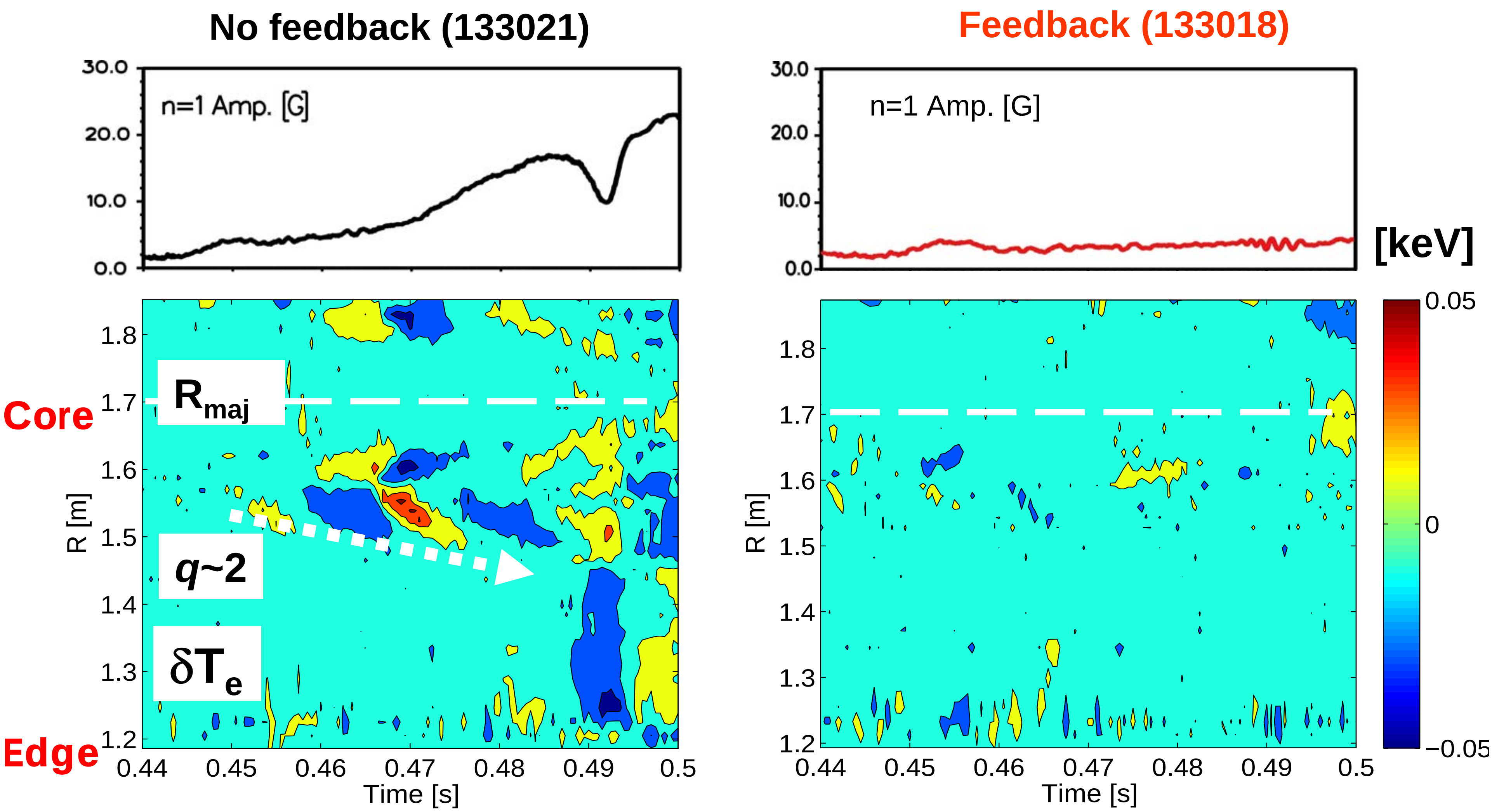
The RWM-associated internal structures are eliminated by RWM feedback control



- **RWM-induced edge disturbance is also suppressed.**

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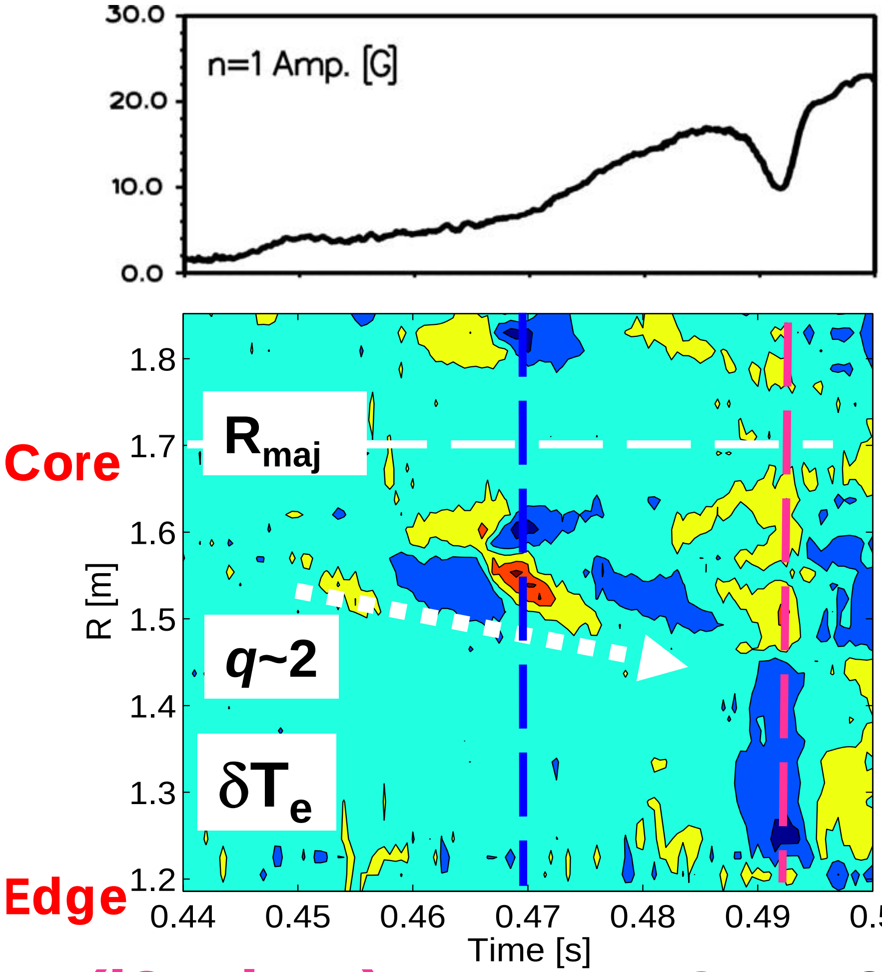
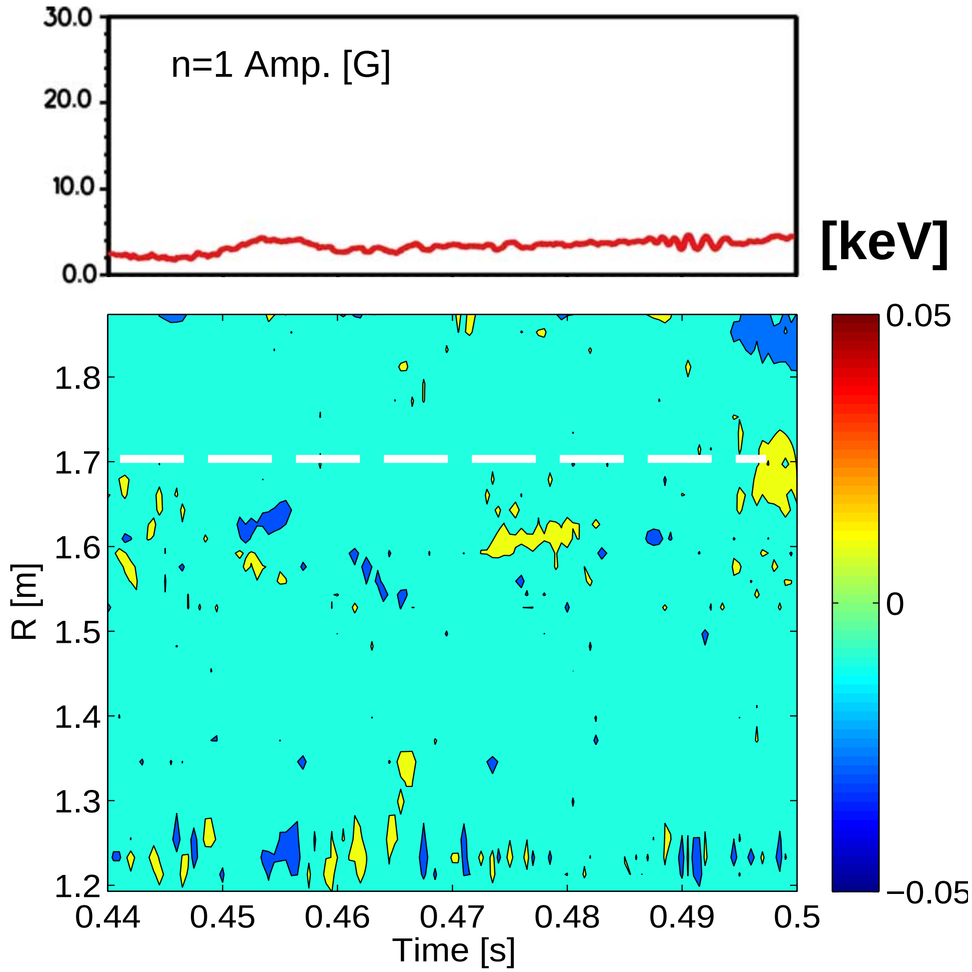
The $|\delta T_e|_{max}$ is reduced by more than a factor of 2 with optimized feedback

No feedback (133021)



$(|\delta T_e|_{max})_{No\ FBK}$: 40 ~ 50 eV

Feedback (133018)



$(|\delta T_e|_{max})_{optimized}$ < 20 eV)

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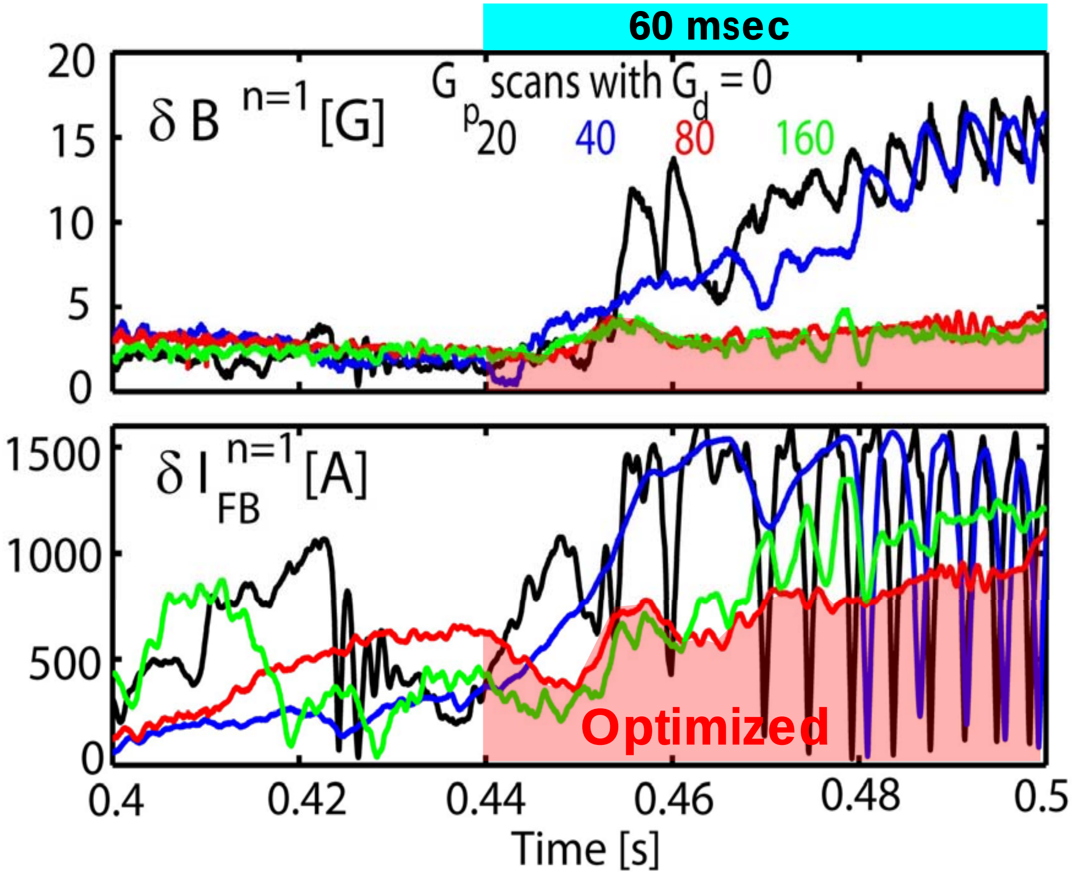
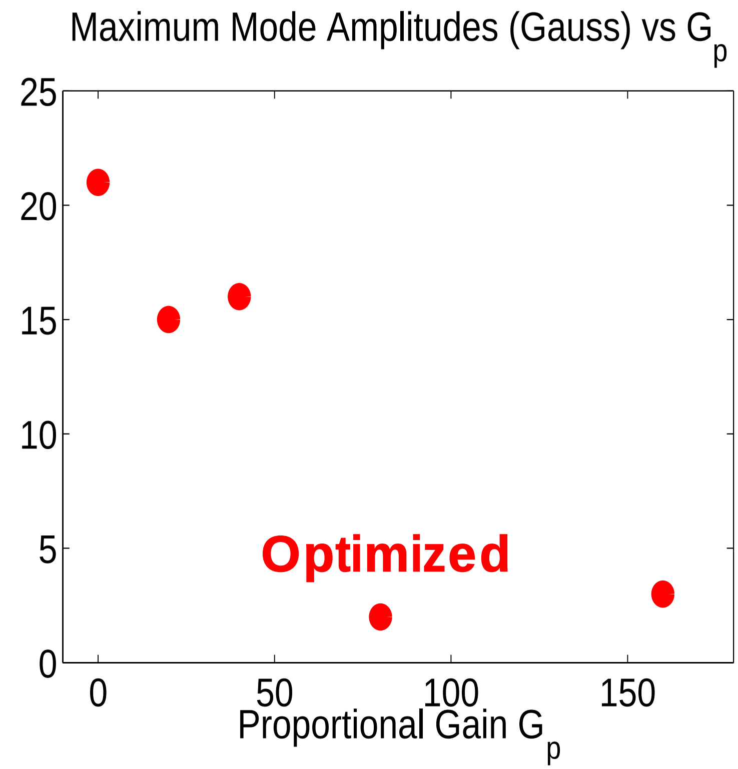
The optimized gain (G_p=80) has been found with G_p only





- **As the gain approaches the optimal level, the mode growth rate decreases as expected.**

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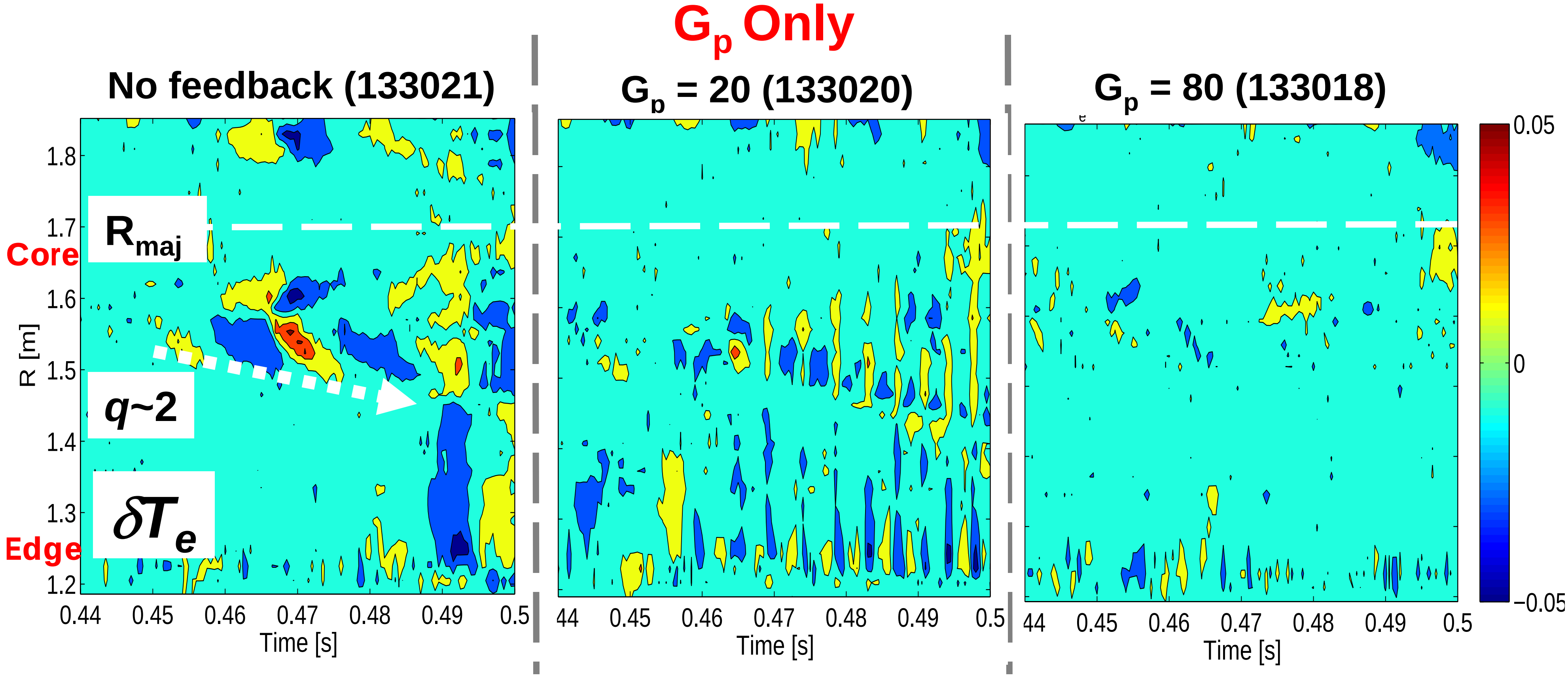
Sub-optimal gain is not only less effective in suppressing the RWM but also disturbs the plasma edge



- **Meanwhile, the edge disturbances are not observed at the over-optimal gain (e.g. G_p = 160).**

Key results

✓ Current-driven RWM at q_{95} ~ 4 was completely stabilized by the RWM feedback control with G_p only.

- The use of derivative gains (G_d=10G_p) expanded the stable range of proportional gains.
  - Reducing a phase lag in time avoids any mismatch between RWM and applied field.
  - High gain scan results suggest the contributions of the I-coils necessary for DEFC

- A phase-shifted n=1 field in the direction of co-I_p rotation is more effective than in the opposite direction.

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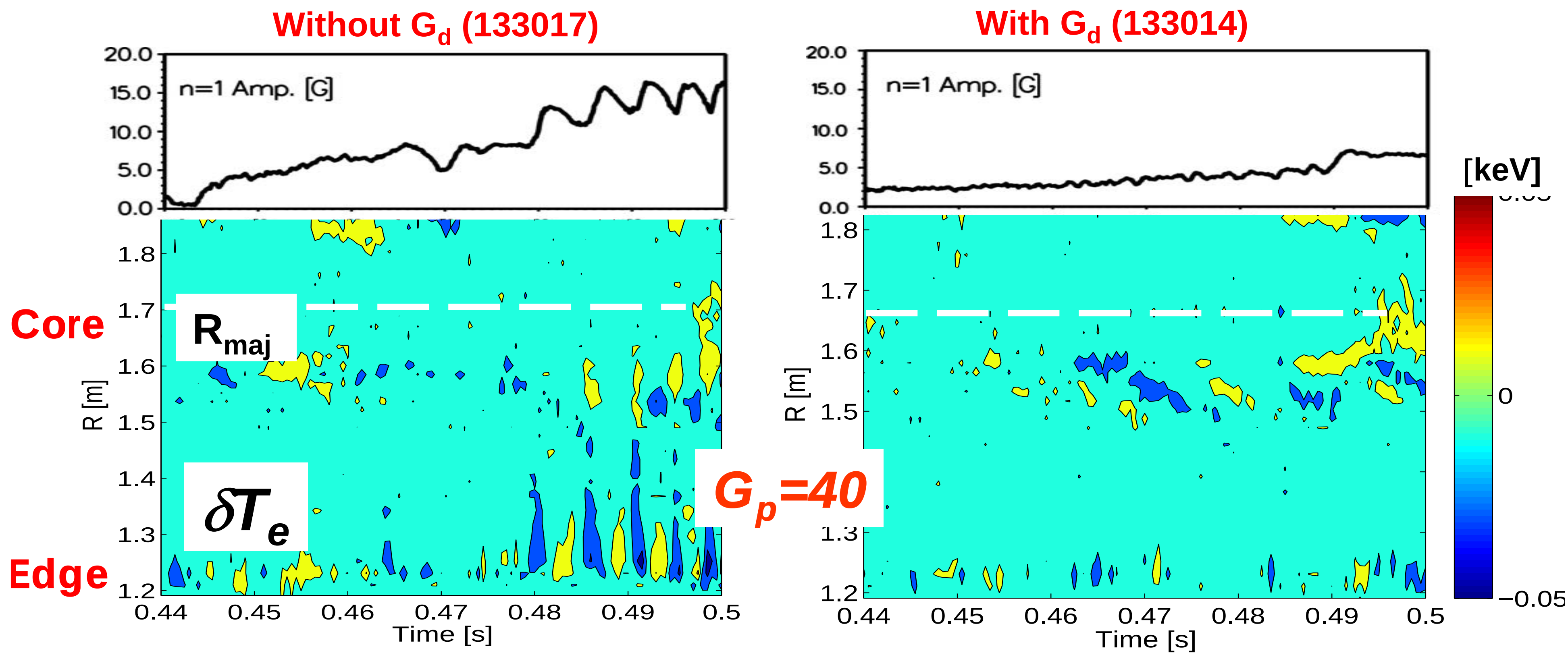
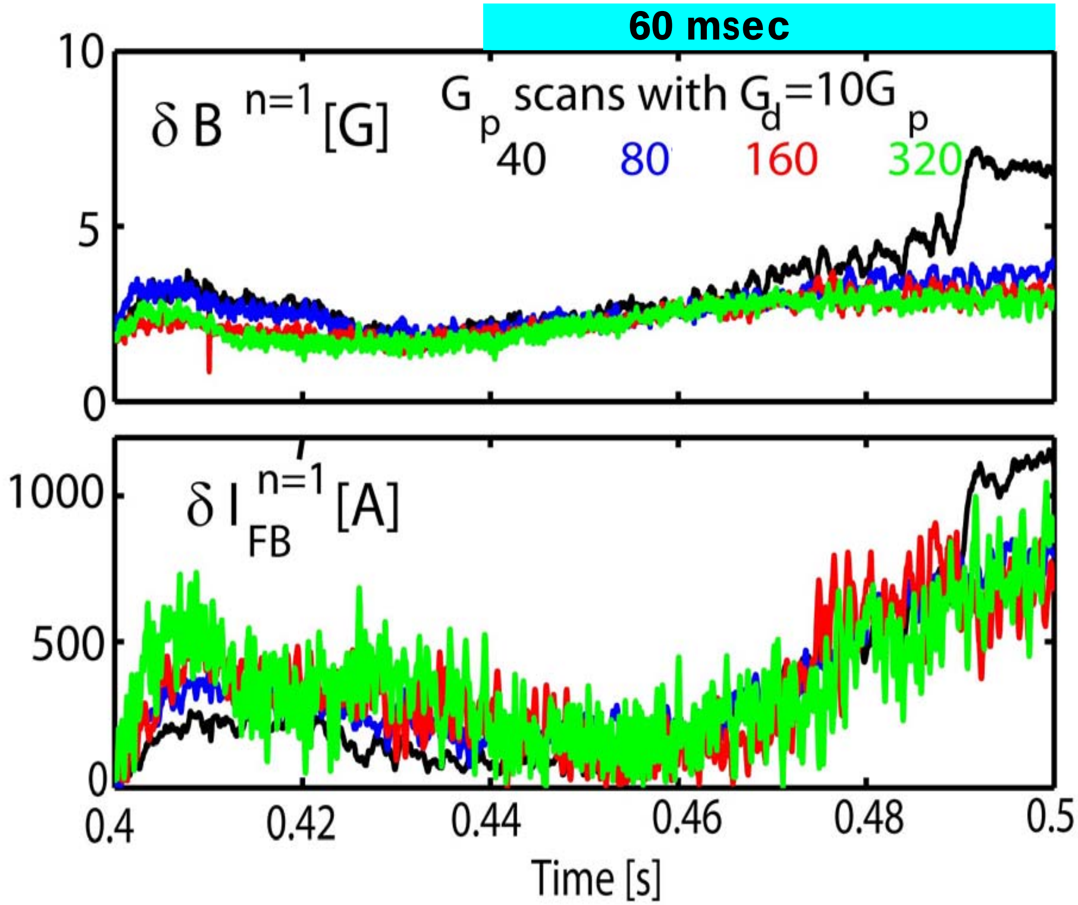
The use of derivative gain broadened the effective gain range for RWM feedback stabilization at q_{95}~4

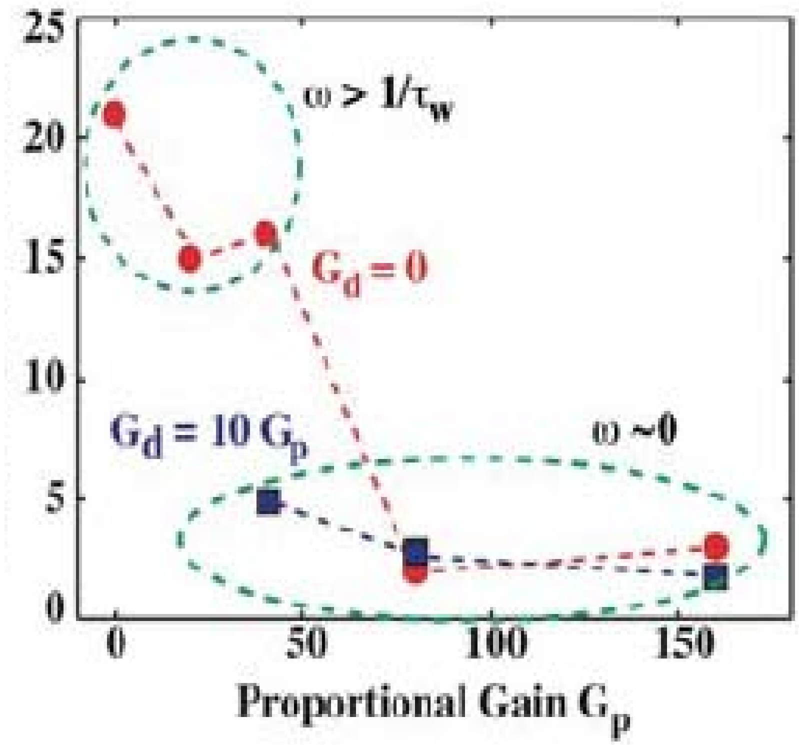


- **The addition of G_d minimizes the phase lag in time between RWM and the applied field.**
- **A value of G_d =10G_p is chosen to use voltage controller 'effectively' as current controller, based on τ_d and $\tau_{L/R}$ of the feedback system.**

Direct RWM control is the dominant stabilization process, while good error field correction is prerequisite



Maximum Mode Amplitudes [G] vs G_p



- Similarly finite amplitude of the coil currents at various G_p values indicate the EFC portion necessary for effective stabilization.

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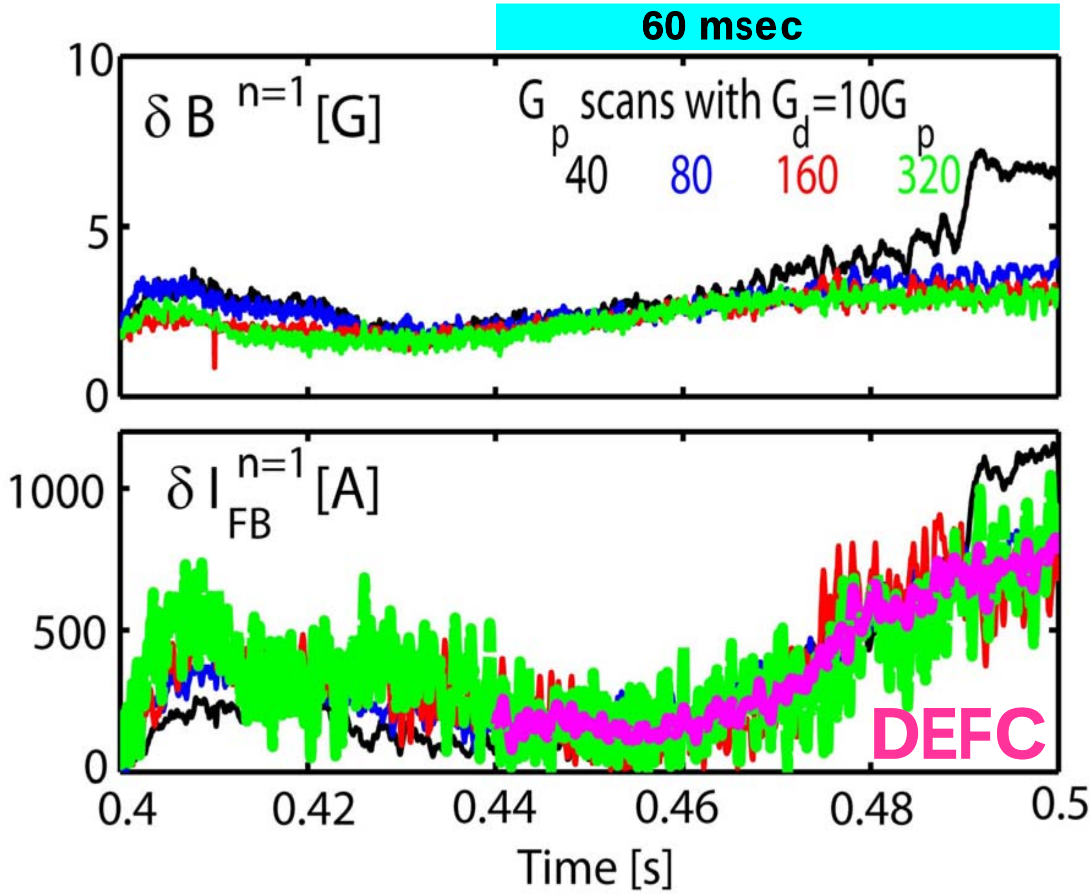
Direct RWM control is the dominant stabilization process, while good error field correction is prerequisite



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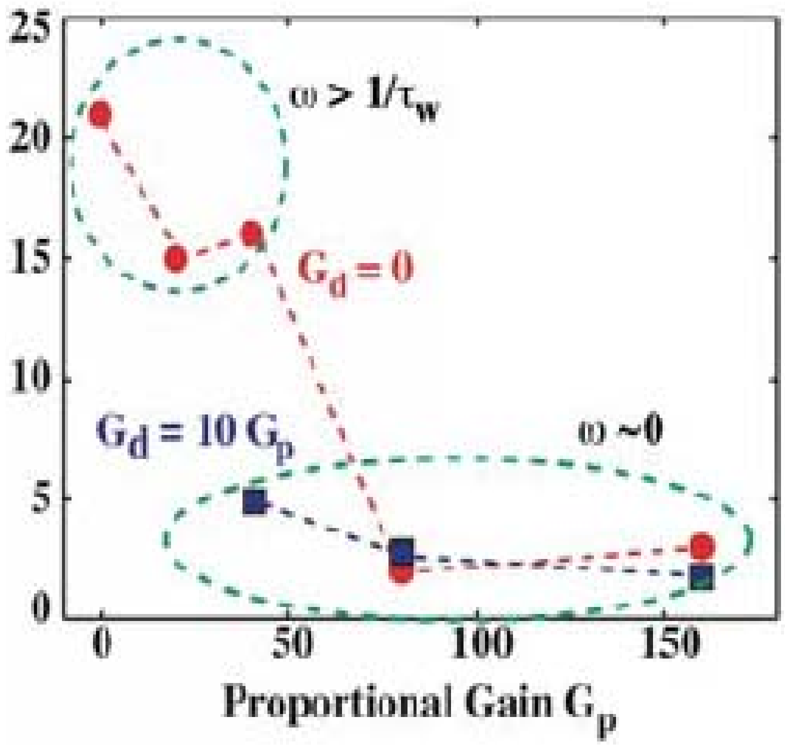

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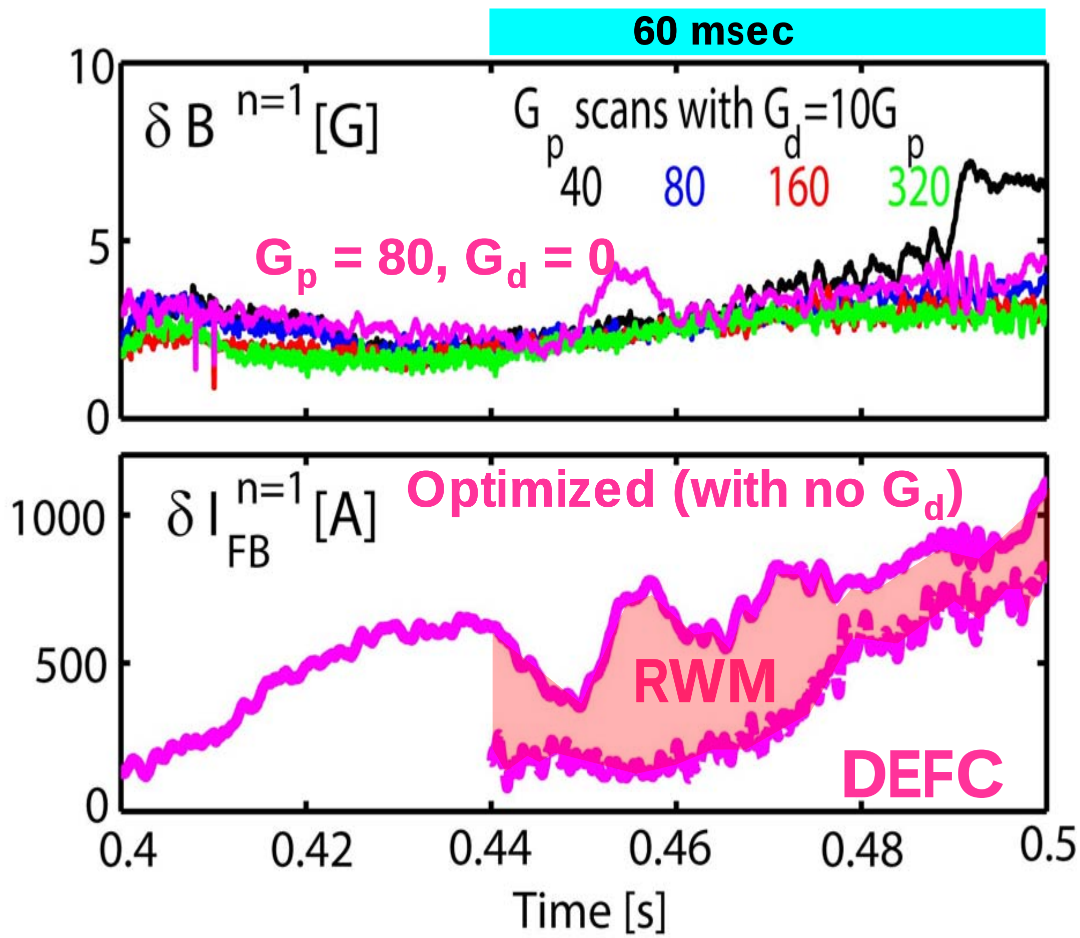

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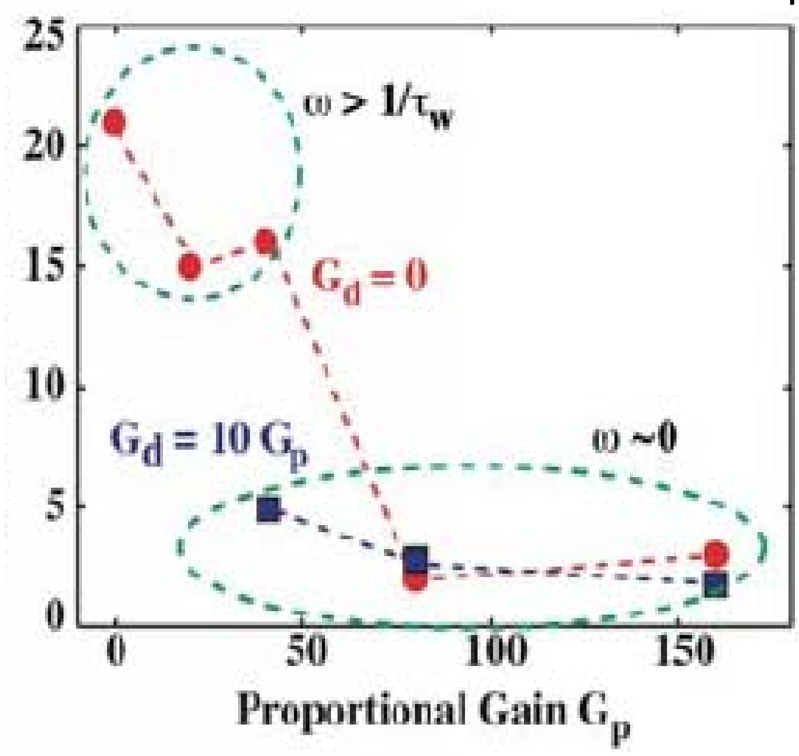

Complete stabilization
= RWM + DEFC

- From the known DEFC, the portion of the coil current necessary for the direct RWM control can be extracted.

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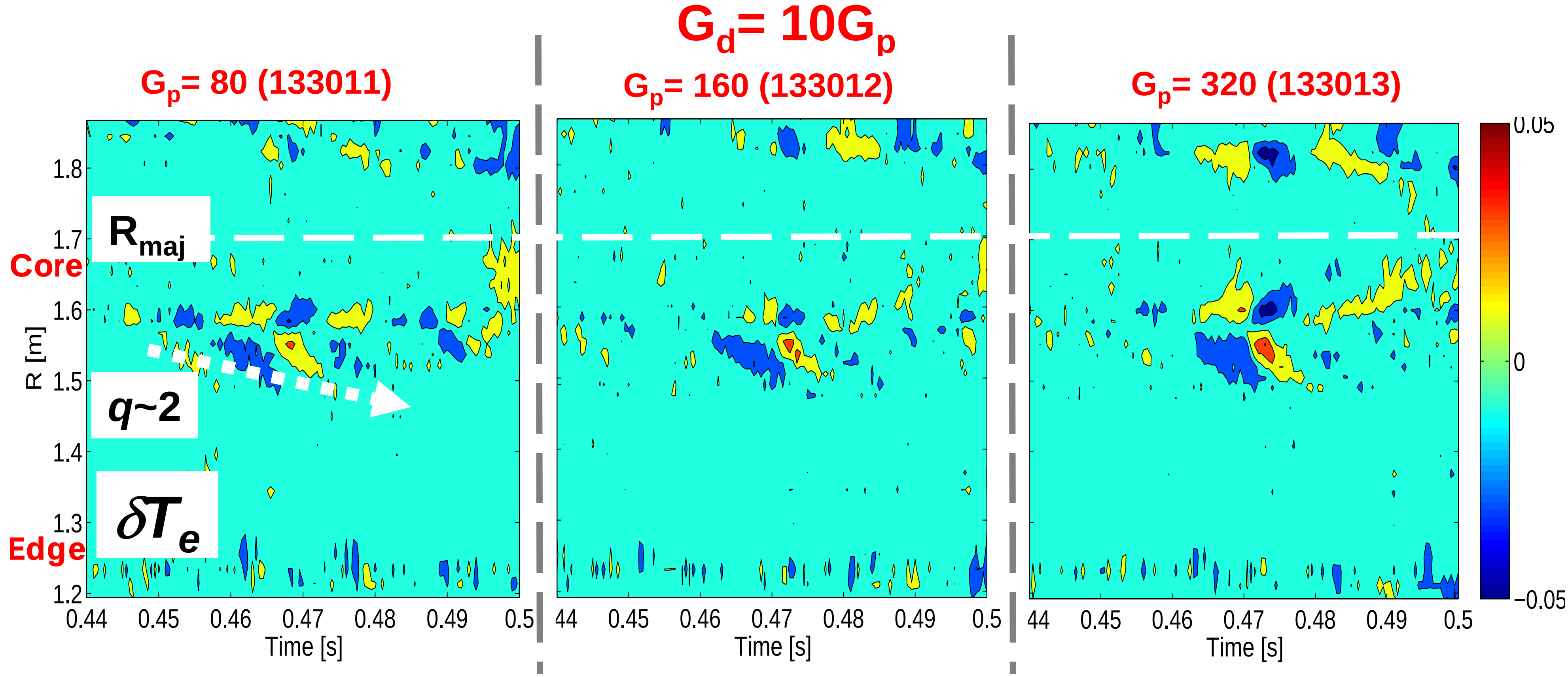
The efficacy of the feedback stabilization needs to be cautiously assessed based on magnetics alone



- Similar plasma responses based on magnetics may not reflect the detailed evolution of the RWM-associated internal structures.
- The choice of G_d may not be optimal yet (likely due to mode coupling to coil currents, $(\tau_{L/R})_{eff} \neq \tau_{L/R}$)

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Key results

- ✓ Current-driven RWM at q_{95} ~ 4 was completely stabilized by the RWM feedback control with G_p only.
- ✓ The use of derivative gains (G_d=10G_p) expanded the stable range of proportional gains.
  - — Reducing a phase lag in time avoids any mismatch between RWM and applied field.
  - — Similarly finite amplitudes at various gains suggest the DEFC portion necessary for effective stabilization.
- **A phase-shifted *n*=1 field in the direction of co-I_p rotation is more effective than in the opposite direction.**

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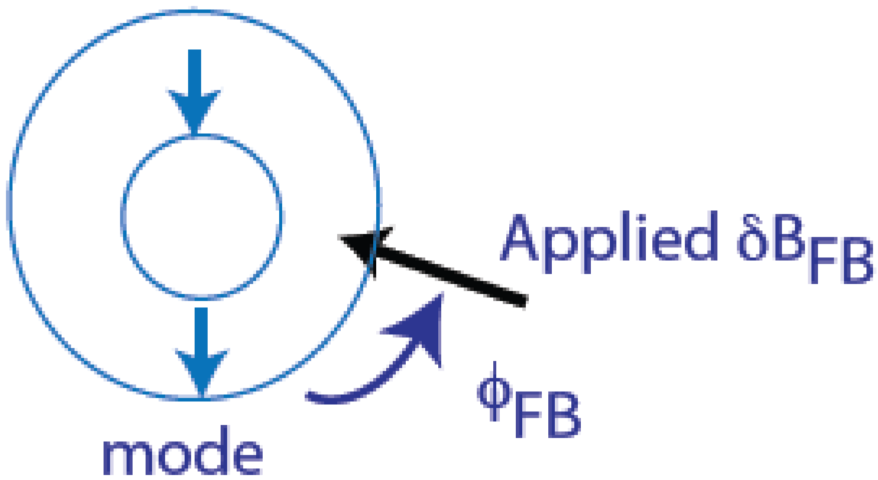
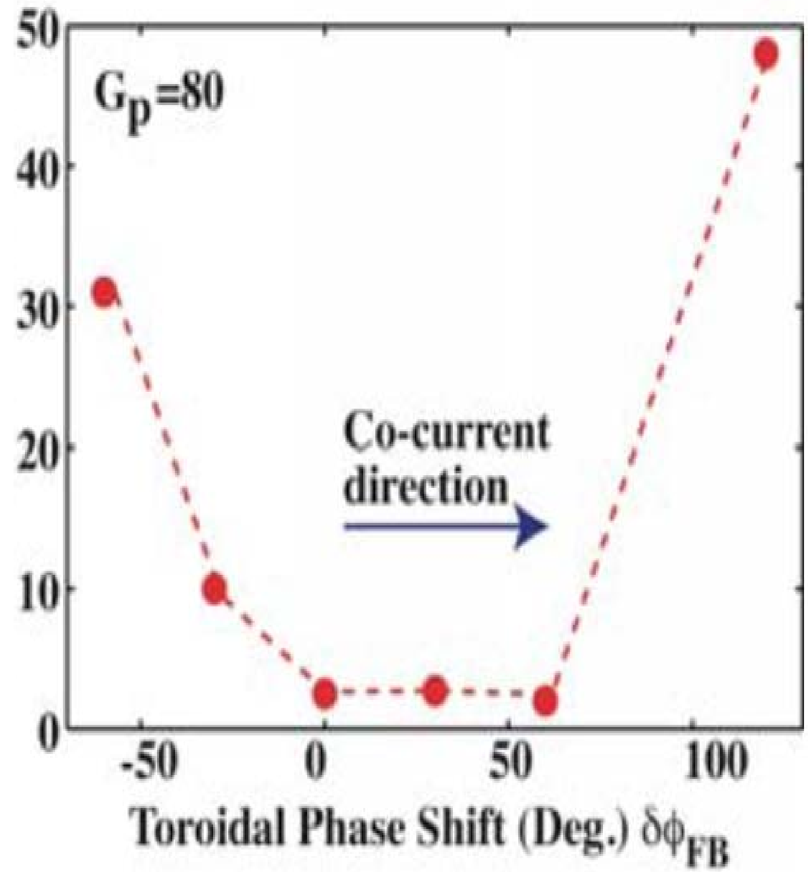
A phase-shifted n=1 field in the direction of co-I_p rotation is more effective than in the opposite direction.



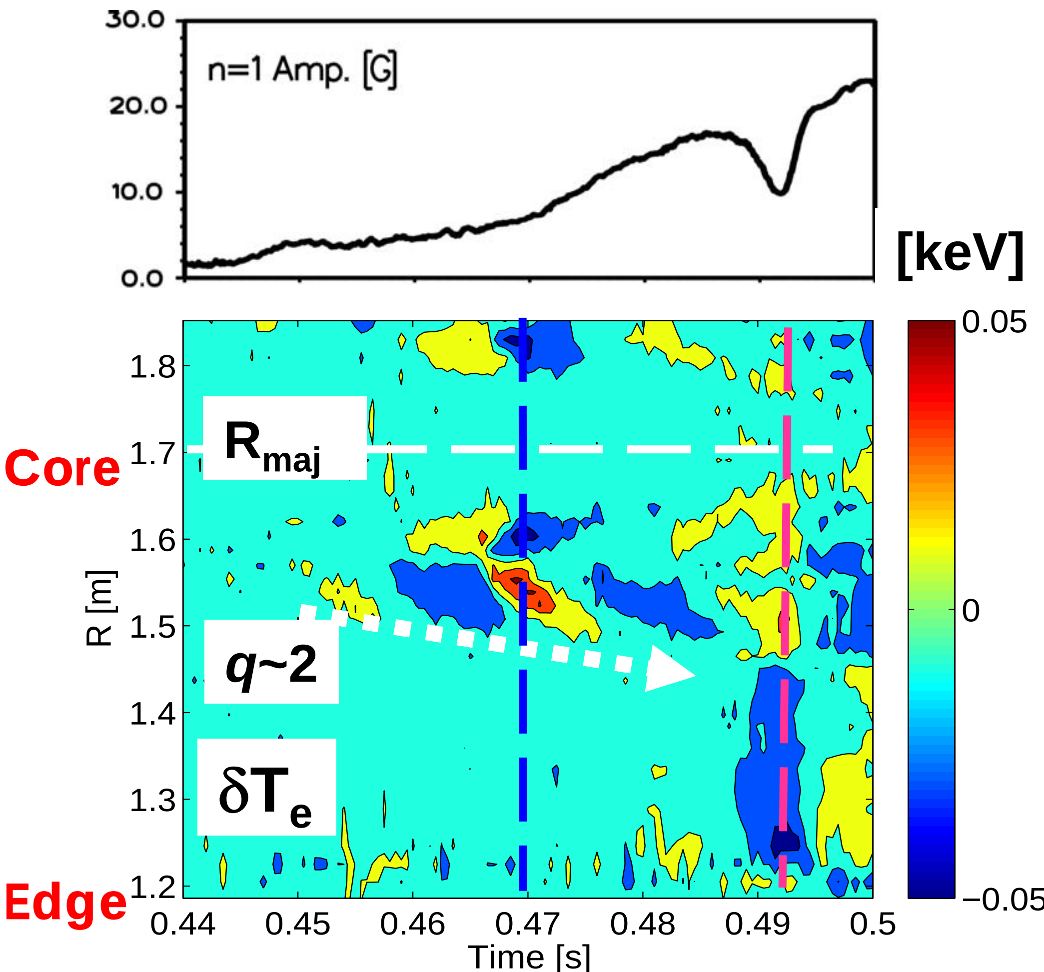
Maximum Mode Amplitudes [G] vs $\delta\phi_{FB}$



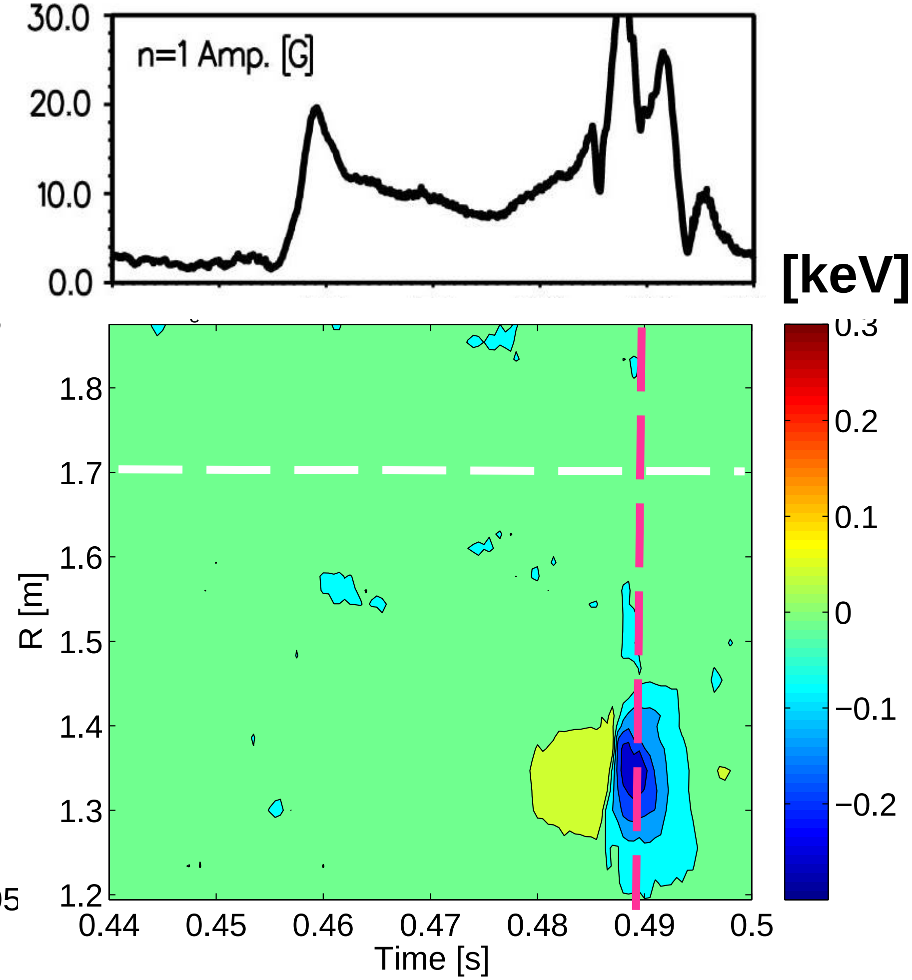
- **A range of preferred toroidal phase shifts ahead of the RWM exists for effective feedback**

An unfavorably phase-shifted δB_{FB} may form edge disturbance near a pitch-resonant surface

No feedback (133021)



$\delta\phi_{FB}$ = -60º (133025)



$(|\delta T_e|_{max})_{No\ FBK}$: 40 ~ 50 eV

$|\delta T_e|_{max}$ ~ 250 eV

= 6 x $(|\delta T_e|_{max})_{No\ FBK}$

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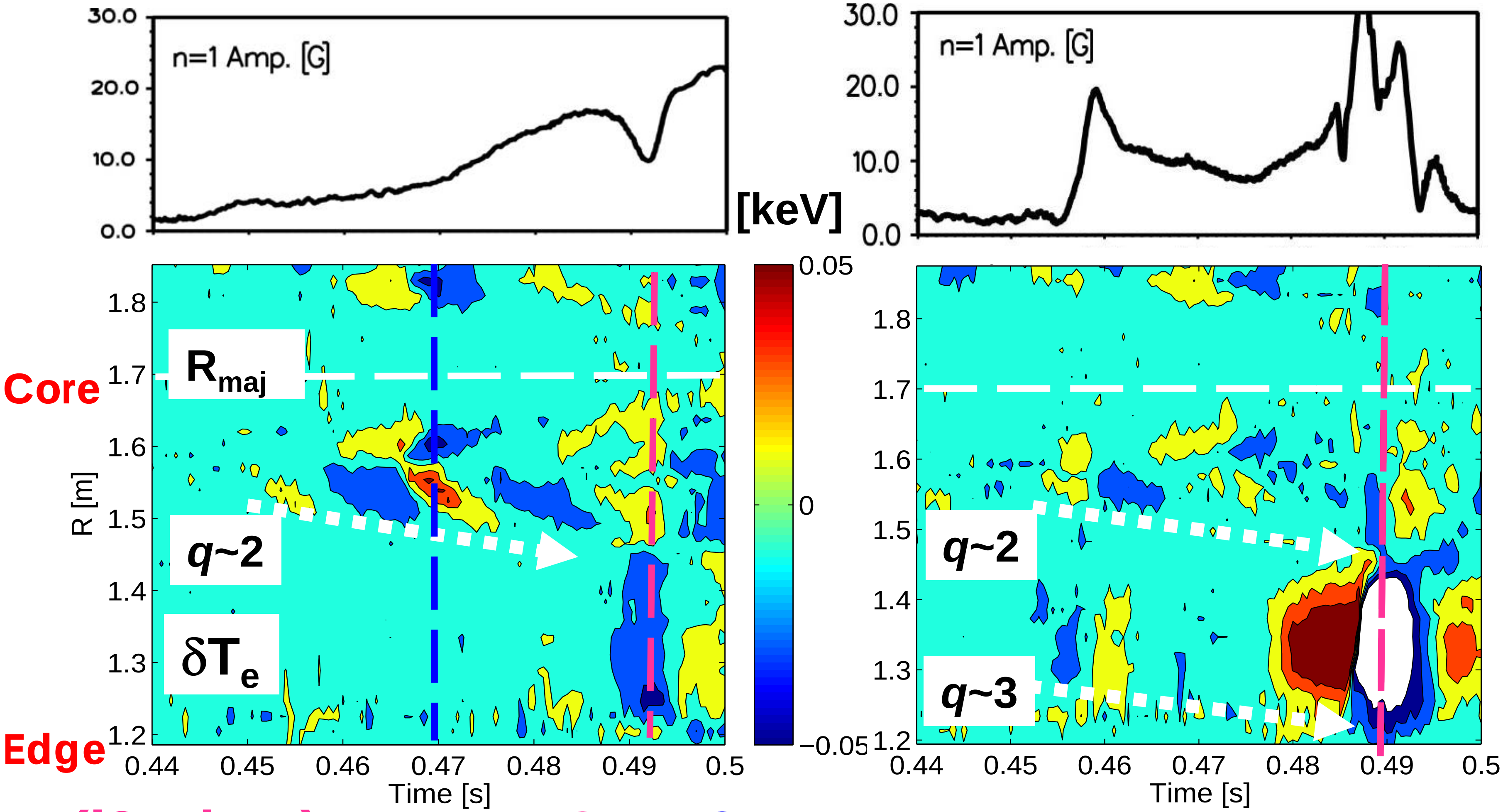
An unfavorably phase-shifted δB_{FB} may form edge disturbance near a pitch-resonant surface

No feedback (133021) $\delta\phi_{FB}$ = -60^{o} (133025)



$(|\delta T_e|_{max})_{No\ FBK}$: 40 ~ 50 eV

$|\delta T_e|_{max}$ ~ 250 eV

= 6 x $(|\delta T_e|_{max})_{No\ FBK}$

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Caveats to note

- Slowly growing RWM may play a role of ‘error’ field.
  - Once a certain level is reached, the RWM-induced magnetic islands are widespread in the outer region of the plasma.
  - Such RWM-induced magnetic islands consist of a mixture of poloidal modes (e.g. multiple resonant surfaces).
- In comparison, the EF-driven edge structure may be relevant to a pitch-resonant surface inside the plasma (e.g. m/n= 3 (or 2)/1 ?).
- Meanwhile, the edge disturbances during the sub-optimal gains might not have been from the same mechanism, in that
  - The edge disturbances are formed in the outermost region first, and then propagate inward, as a residual stray field increases without having a pitch resonant surface. -> kink?
  - BUT, the addition of G_d appears to prevent RWM+EF from making edge disturbances.

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Conclusions

- Current-driven RWM at q_{95} ~ 4 was completely stabilized by the RWM feedback control.
  - An optimized proportional gain (G_p=80) has been found without using derivative gain.
  - The use of derivative gains (G_d=10G_p) expanded the stable range of proportional gains.
    - Reducing a phase lag in time avoids any mismatch between RWM and applied field.
    - Similarly finite amplitudes at various gains suggest the DEFC portion necessary for effective stabilization.
- A phase-shifted n=1 field in the direction of co-I_p rotation is more effective than in the opposite direction.

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Conclusions (cont'd)

- The efficacy of the feedback stabilization needs to be cautiously assessed based on magnetics alone

- The success of stabilization of the current-driven RWM at $q_{95} \sim 4$ is primarily due to the direct RWM control, while a good error field correction is overlaid.

- Similar feedback performance is expected even for the pressure-driven RWM in high-β plasmas, as long as the difference of the plasma responses between low and high-β plasmas is properly addressed.

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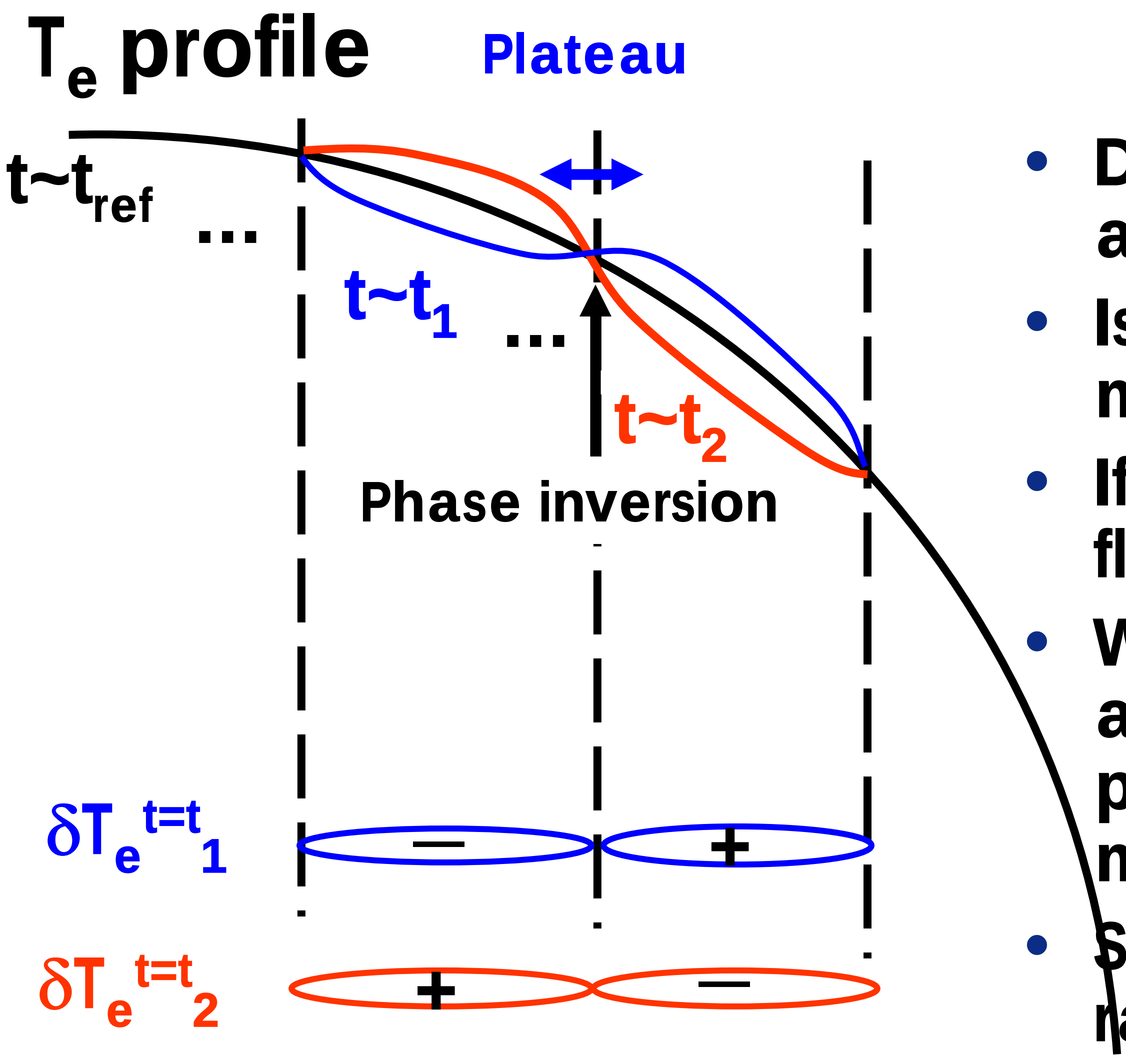
Open question about magnetic islands



- **Does a kink mode form a magnetic island?**
- **Is plateau essential for magnetic island?**
- **If so, what degree of flatness is necessary ?**
- **When the δTe becomes a tiny 'wiggle' without plateau, is it still magnetic island?**
- **Should the inversion radius be located at a rational surface?**

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