Tailoring 3D fields across confinement modes to optimize plasma instability control

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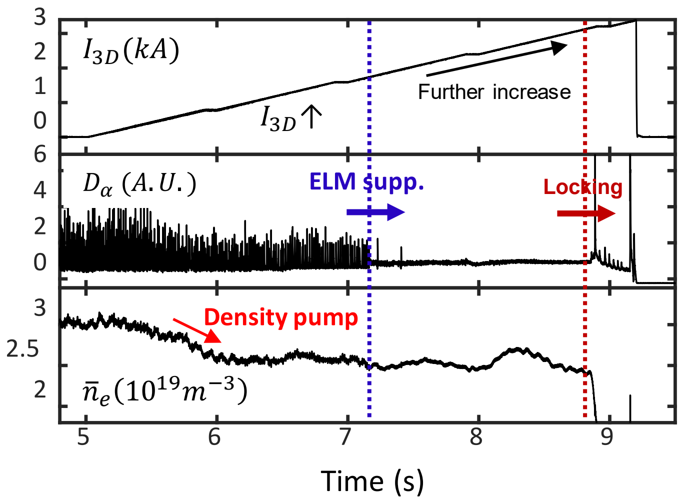
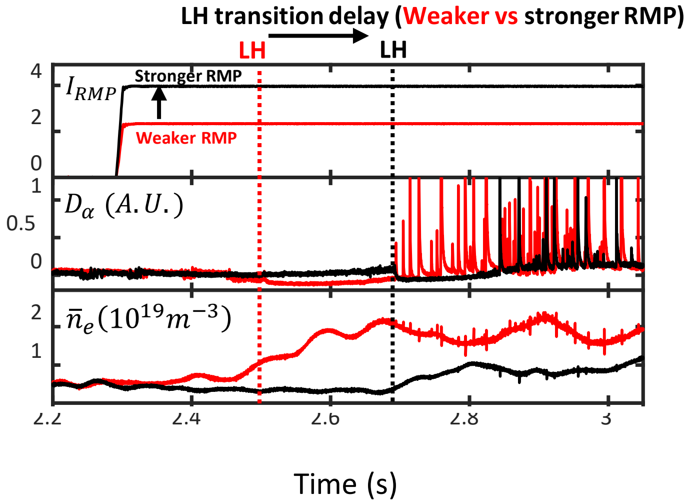
Outline

- Issues in optimizing 3D fields
- Tailoring 3D field
  - Method
  - ELM suppression for the entire period of discharge with n=1 field
  - Additional benefits of the ERMP scheme
    - ELM suppression with reduced confinement degradation
    - Control of RMP induced fast ion orbit loss to reduce wall heating
- Other approaches to improve 3D field-induced degradation
  - Preventing core RMP penetration
  - NTV control (electron NTV and torque matrix)
  - Understanding 3D field-induced L-H transition delay
- Future work

Introducing 3D field effect: ELM suppression and other effects

- 3D field can **suppress edge localized modes** (ELMs), which can cause intolerable damage to plasma-facing components in a future reactor.
- 3D field application for ELM suppression can lead to other effects.
  - **Mode locking** that eventually terminates plasmas.
  - **Density pump**, angular momentum degradation, and fast ion orbit loss.
  - **Delay or prevention of L-H transition** (if applied before L-H transition)



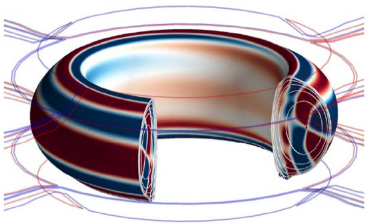


Need to isolate edge RMP to optimize ELM control

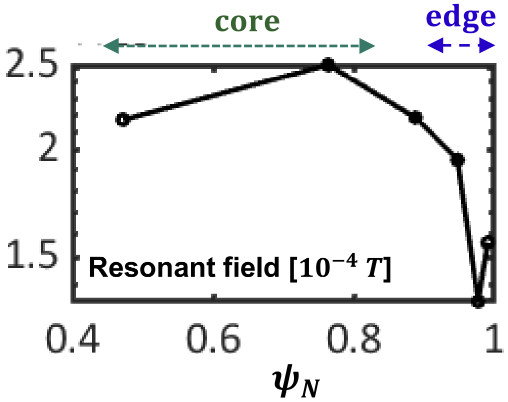
- Resonant Magnetic Perturbation (RMP, $\delta\vec{B}_{\rm res}$) is known to be important for ELM suppression.
  - The edge RMP penetration can suppress ELM [1,2] $\delta\vec{B}_{\rm res} \gg \vec{B}_{{\rm pen},th}({\rm n_e}, \omega_\phi, \ldots)$.
  - However, core RMP can drive disruptive Locked Modes (LMs).
  ➔ Edge RMP needs to be maximized but core RMP should be minimized to optimize ELM control
- However, external 3D coils **typically apply both edge and core RMP.**

[3D coils for RMP ELM control]

[Park et al., Nature Physics (2018)]



[RMP profile used for ELM control]



[1] R. Nazikian et al., PRL, (2015)]
[2] Q. M. Hu et al., PRL, (2020)]

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New scheme developed : Systematic RMP localization

- A systematic approach can minimize core response and maximize edge response by introducing core-null space projection, $\overleftrightarrow{P}_{c,null}$ [S.M. Yang et al., NF, 2020].
- This edge localized RMP eliminates core resonant response (core δB=0) while it maintains sizable edge response with good efficiency (only ~30 % penalty in edge δB).

[Systematic RMP localization]

[S.M. Yang et al., NF, 2020]

[edge dominant optimization]

$$\delta\vec{B}_{edge} = \overleftrightarrow{C}_{edge} \cdot \vec{V}_b^x$$ (Considers edge RMP only)

⇓

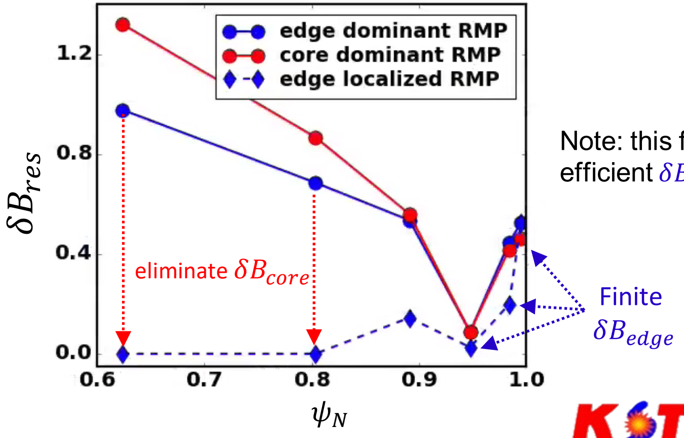
[Edge localized optimization]

$$\delta\vec{B}_{edge} = \overleftrightarrow{C}_{edge} \cdot \overleftrightarrow{\boldsymbol{P}}_{\boldsymbol{c,null}} \cdot \vec{V}_b^x$$ (Considers both edge and core)

Removal of core coupling

[Example of edge-localized RMP]

- zero core δB vs finite edge δB

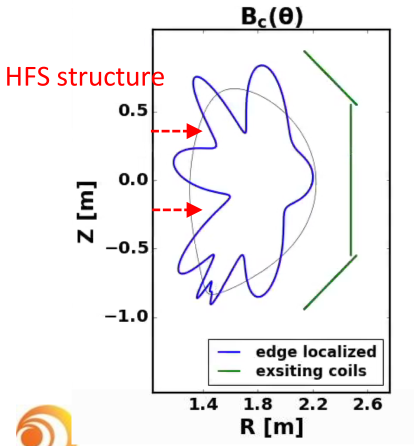


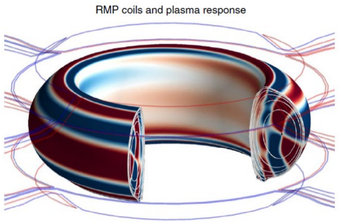
Note: this finds the most efficient δB_{edge} drive!

Difficulties in validating edge localized RMP

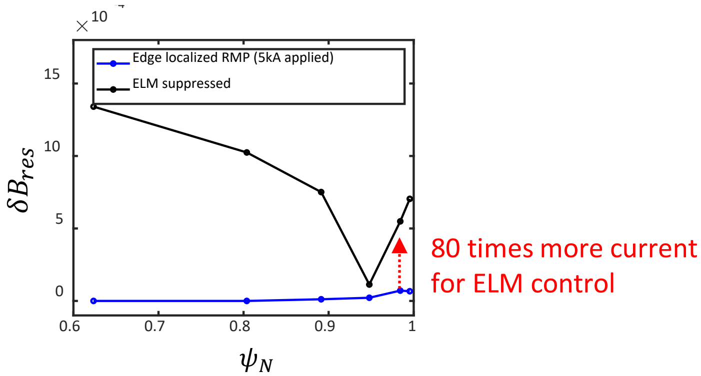
- However, the geometry and location of RMP coils limit the realization of the most efficient edge localized RMP for safe ELM control.
- For example, it is impossible to follow the variation of edge localized RMP at HFS using existing coils.
- The edge localized RMP is predicted to be inefficient for ELM suppression, despite of flexible KSTAR 3D coils.

[Existing coils cannot produce HFS structure]





[Edge localized RMP with the existing coil is inefficient]



➔ Impossible to test ERMP with existing system (power supply is not enough)

Penalizing core RMP for experimental application

- We introduced penalizing factor, c_{opt}, that can strike a balance between coupling efficiency and safety of RMP for ELM suppression. [S.M. Yang, J.-K. Park et al., PRL submitted]
  - $c_{opt}=0$ is edge efficient RMP that neglects core RMP response.
  - $c_{opt}=1$ is edge localized RMP without penalization (δB_{edge} is not sufficient for ELM suppression)
  - Increase of c_{opt} localizes RMP, by removing core RMP, $\delta B_{core}/\delta B_{edge}$.

[edge efficient optimization]

$$\delta\vec{B}_{edge} = \overleftrightarrow{C}_{edge}\cdot\vec{V}_b^x$$

+

[edge localized optimization]

$$\delta\vec{B}_{edge} = \overleftrightarrow{C}_{edge}\cdot\overleftrightarrow{P}_{c,null}\cdot\vec{V}_b^x$$

Removal of core coupling

→ [Combined for practical application]

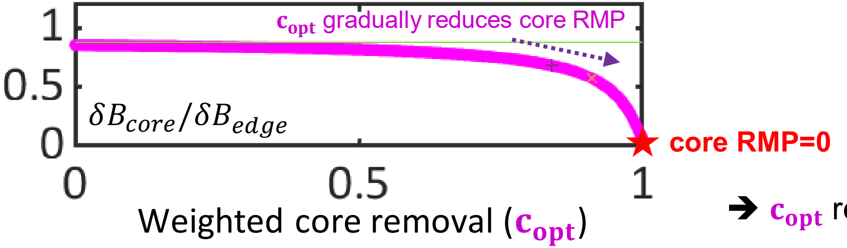
$$\delta\vec{B}_{edge} = \overleftrightarrow{C}_{edge}\cdot(\overleftrightarrow{I} - c_{opt}\overleftrightarrow{U}_c)\cdot\vec{V}_b^x$$

weight removal of core coupling

At $c_{opt}=1$

✓ **core RMP=0 (edge localized RMP)**

[Weight core removal (c_{opt}) VS core RMP]



→ c_{opt} removes core RMP

Penalizing core RMP for experimental validation

- We introduced penalizing factor, c_{opt}, that can strike a balance between coupling efficiency and safety of RMP for ELM suppression. [S.M. Yang, J.-K. Park et al., PRL submitted]

  - c_{opt} =0 is edge efficient RMP that neglects core RMP response.
  - c_{opt} =1 is edge localized RMP without penalization (δB_{edge} is not sufficient for ELM suppression)
  - Increase of c_{opt} leads unnecessary reduction of edge RMP, δB_{edge}, due to overlap between core and edge.

[edge efficient optimization]

$$\delta \vec{B}_{edge} = \overleftrightarrow{C}_{edge} \cdot \vec{V}_b^x$$

+

[edge localized optimization]

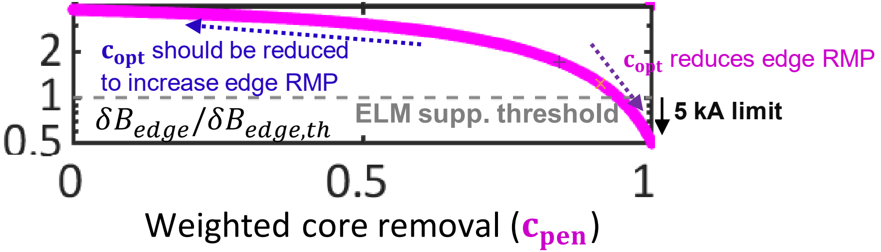
$$\delta \vec{B}_{edge} = \overleftrightarrow{C}_{edge} \cdot \overleftrightarrow{P}_{c,null} \cdot \vec{V}_b^x$$

Removal of core coupling

At $c_{opt} = 0$

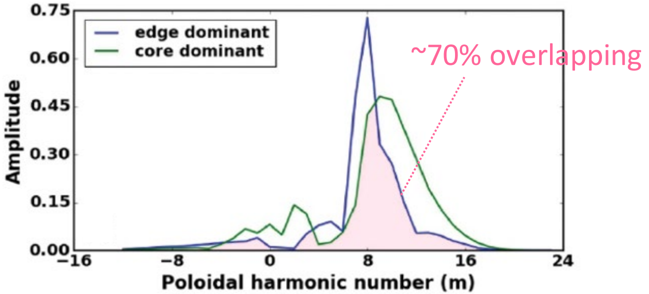
✓ **edge RMP maximized**

[Weight core removal (c_{opt}) VS edge RMP]



[Why δB_{edge} reduces?]

- Due to extensive overlap between core and edge



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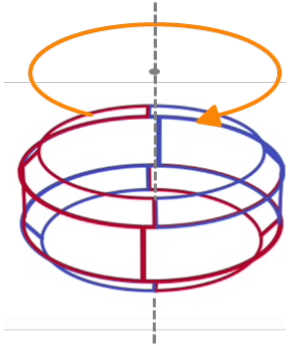
n=1 RMP optimization using KSTAR 3D coils

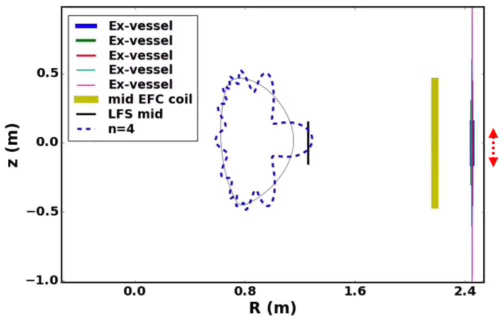
- KSTAR has three rows of flexible 3D coil arrays for the n=1 RMP optimization.
- The n=1 (low-n) RMP is attractive for future reactors needing ex-vessel 3D coils to avoid nuclear contamination.
  - COMPASS-U ex-vessel coil examples shows the efficiency of low-n RMP (logarithmic decay with n)
- However, the n=1 RMP is tricky to use as its core RMP penetration is disruptive. (ITPA MDC-19 is about low-n core error field correction)

[KSTAR 3D coil]



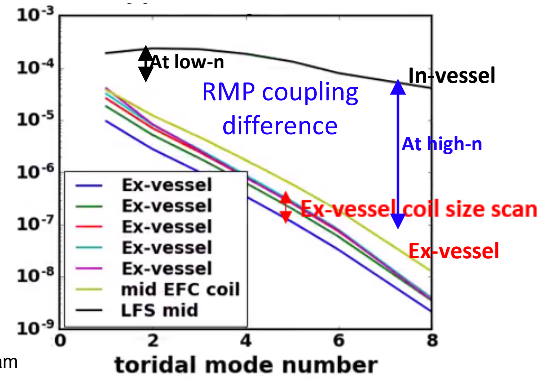
A flexible n=1 field is possible

[COMPASS-U ex-vessel coil size scan]



*collaboration with T. Markovic and COMPASS-U team

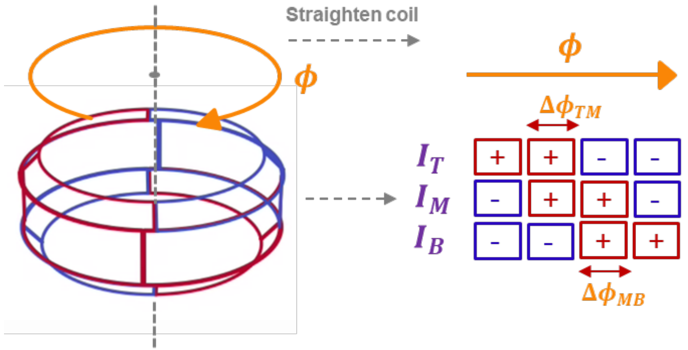
[RMP coupling of In-vessel vs Ex-vessel]



n=1 RMP optimization using KSTAR 3D coils

- For the safe use of n=1 RMP, we designed edge localized RMP (ERMP) with KSTAR 3D coils.
- Three rows of RMP coils in KSTAR (as in ITER) allows 5D freedom (Amplitude: I_T, I_M, I_B, phasing: $\Delta\phi_{TM}$, $\Delta\phi_{MB}$) to improve ELM suppression.
- The ERMP optimization using multiple rows of coils can benefit DIIID & ITER as well.

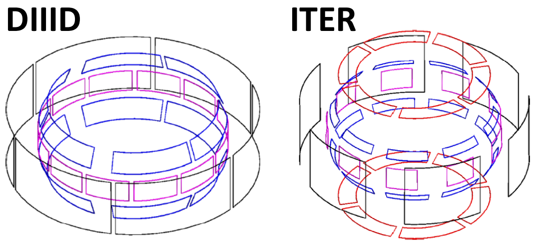
[KSTAR 3D coil] **[2D view of KSTAR 3D coil]**



KSTAR: 3 rows, 5 dimensions (I_T, I_M, I_B, $\Delta\phi_{TM}$, $\Delta\phi_{MB}$)

[Planned for DIIID and ITER]

[Weisberg et al., NF 2019]



DIIID: 4 rows (7 dimension)
ITER: 3+3 rows (5+6 dimensions)
➔ 3D optimization will be useful for future

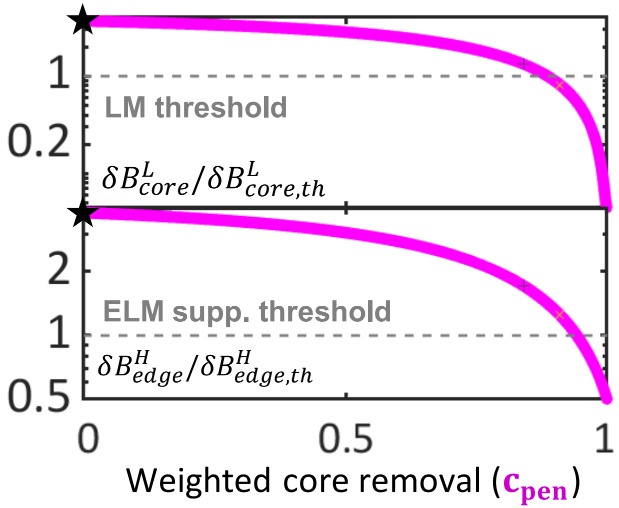
ELM suppression for the entire period of discharge

- In future reactors, ELMs should be suppressed for the entire period of discharge.
  - Single ELM burst is dangerous. This needs ELM suppression at transient entries and exits of H-mode.
- RMP before the L-H transition is the easiest approach.
  - This requires multi-target optimization (from L-mode to H-mode)
- L-mode plasma is vulnerable to core LMs due to low density and rotation, especially for n=1 field.
  - Core RMP in L-mode (δB^L_{core}) turns out to be the most disruptive and limiting force.

★ ERMP optimization for the entire discharge

1. Localize RMP to avoid core LMs
   - Edge RMP gets weaker due to core/edge coupling
2. Penalize localization to suppress ELMs
   - Penalty of core RMP increase

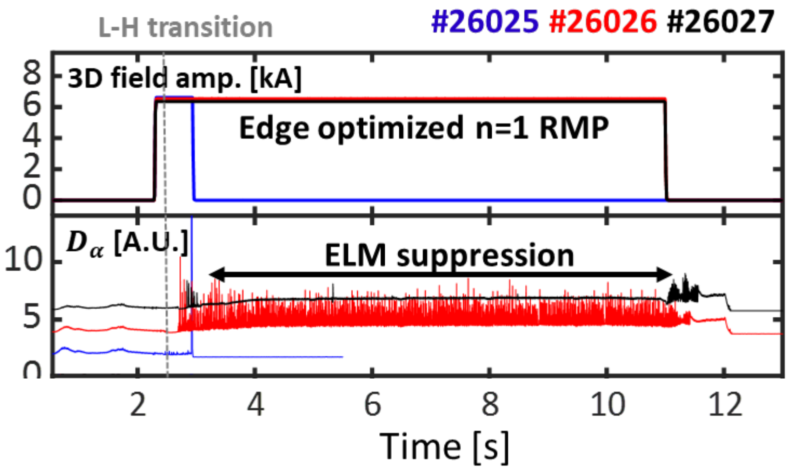
=> Edge localized RMP (ERMP) for experimental application.
GPEC [1] response used for optimization

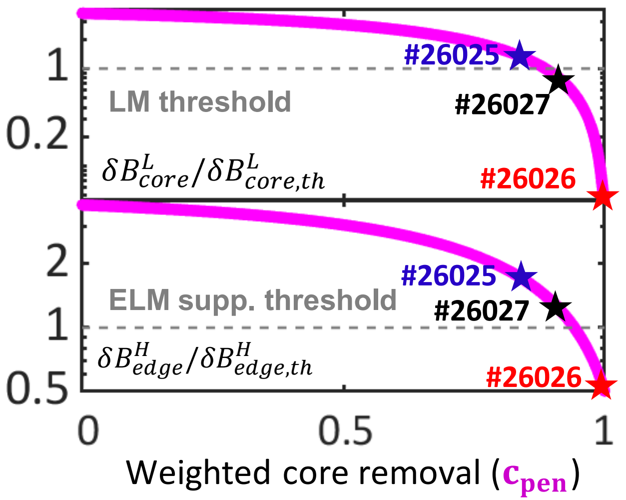


[1] J.-K Park et al., POP (2007)

ELM suppression for the entire period of discharge

- The ERMP optimization allowed the application of n=1 RMP before the L-H transition for ELM suppression for the first time. (n=1, strong enough for ELM control, not disruptive in L-mode)
- Other RMPs with different core removal executed as expected [S.M. Yang, J.-K. Park et al., PRL submitted]
  - **#26027 (ELM controlled from the beginning, mitigated at early phase due to q95 evolution)**
  - **#26025 (Disrupted early by LMs)**
  - **#26026 (weak edge RMP, ELM not mitigated)**





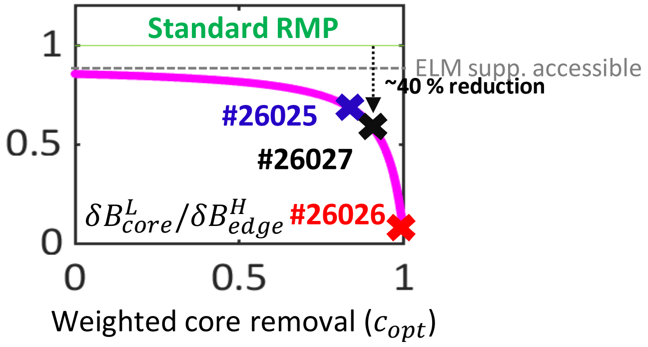
ELM suppression for the entire period of discharge

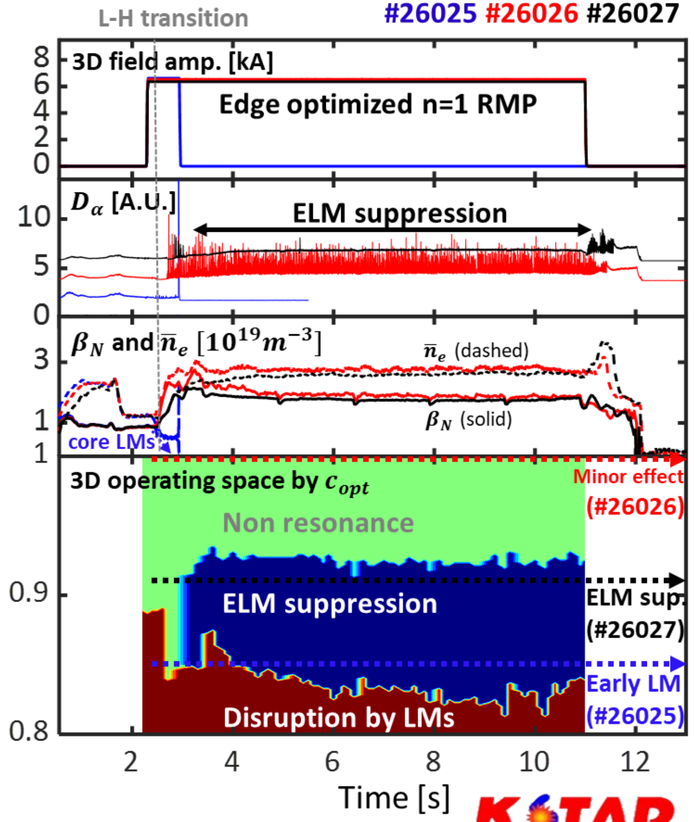
- ERMPs has a unique operating point in the coil space
  - Amplitude, phasing that has never been used.

  $I_T : I_M : I_B = 1 : 0.11 : 0.85$ (Standard [1] : $I_T = I_M = I_B$)

  $\phi_{TM} : \phi_{MB} = 170^{\circ} : 196^{\circ}$ (Standard [1] : $\phi_{TM} = \phi_{MB} = 90^{\circ}$)

- ERMP significantly improve safety of n=1 RMP
  - Core LM in L-mode (**Standard RMP does not work**)





=> Validated ERMP significantly improve safety of n=1 RMP

[1] Y.M. Jeon et al., PRL, (2012)

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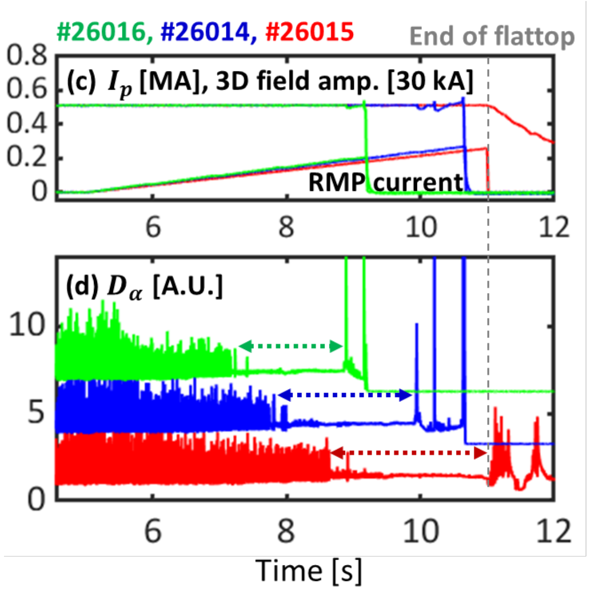
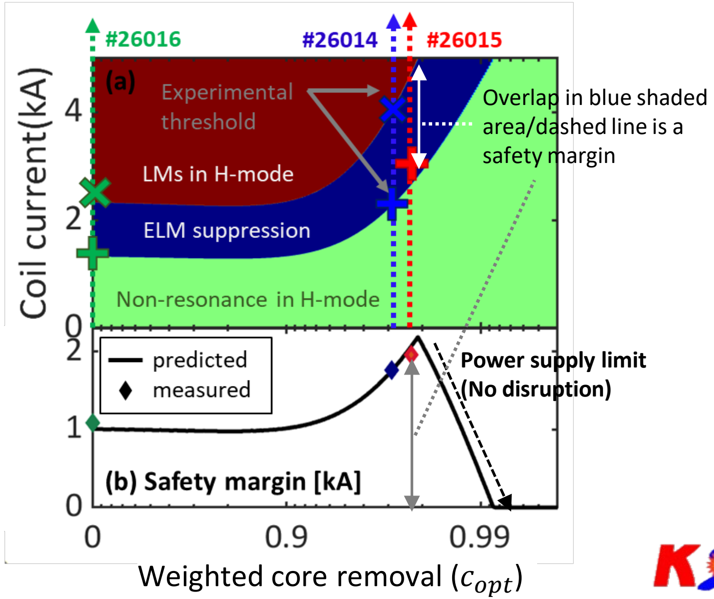
Effect of core-removal at ELM suppressed state

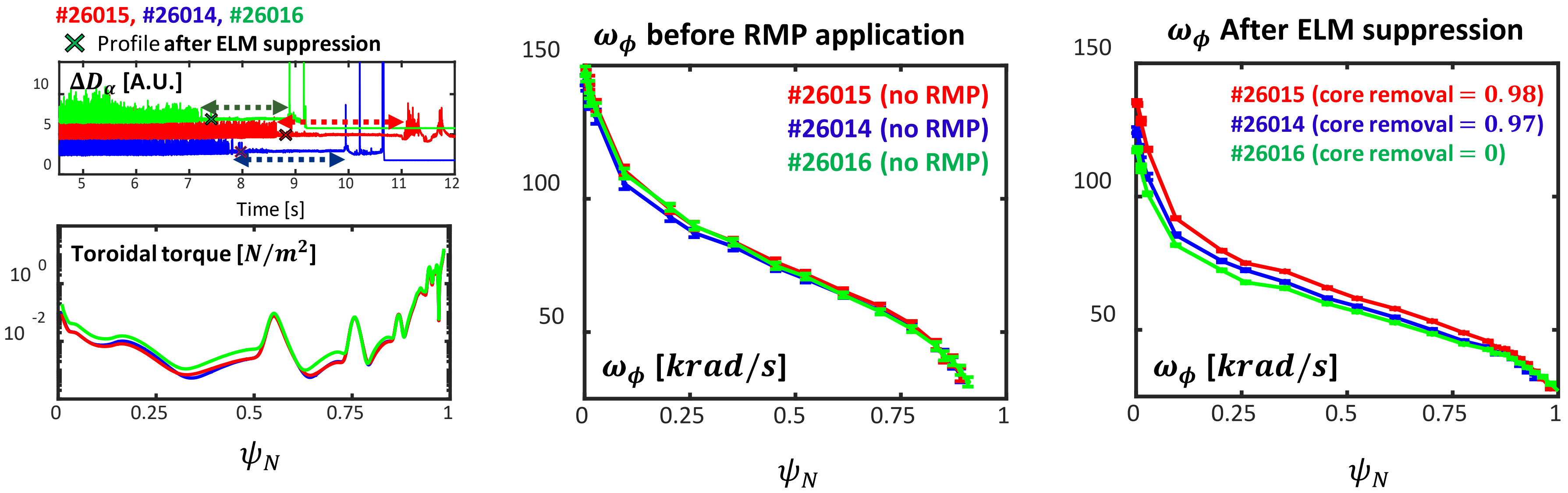
- We ramped up optimized RMP with different core-removal (δB^{H}_{core}) to get ELM suppressed state.
  - To see effect of edge localization at the ELM suppressed state.
- We predicted ELM suppression time and safety windows, using **two most important optimized RMP.**
  - #26016 (core removal $= \mathbf{0}$): Requires least RMP current for ELM suppression (useful if core RMP is not critical).
  - #26015 (core removal $= \mathbf{0.98}$): Safety is maximized (More robust with change/uncertainties of plasma condition)





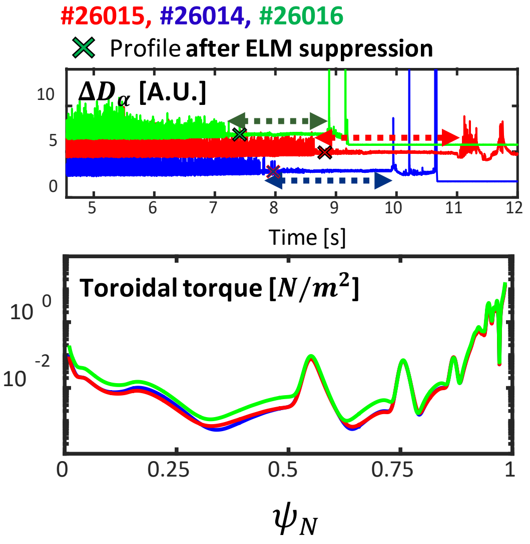
Benefit of core-removal: Reduced rotation degradation

- At the initial ELM suppressed phase, a reduction of overall perturbations (with core removal) is expected as indicated by NTV response. (#26016 has the largest torque)
- Reduction of NTV (due to core removal) reduces rotation degradation at ELM suppressed state.

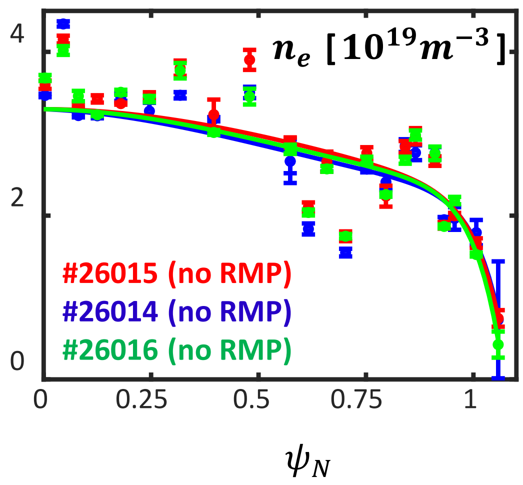


Benefit of core-removal: Reduced density degradation

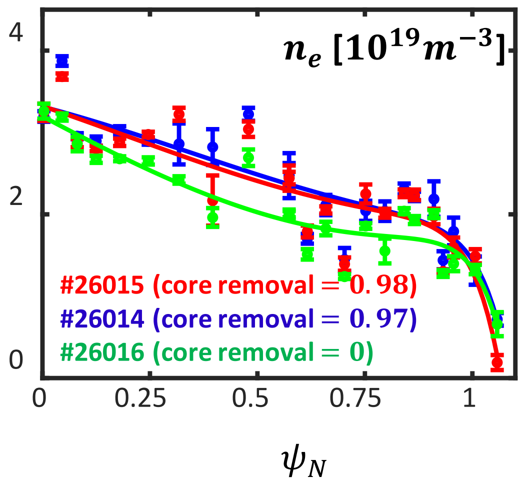
- Reducing the core resonant field results in the NTV reduction in ELM suppressed phase.
- Core removal reduces density degradation at ELM suppressed state (e.g., **core removal = 0.98** vs **0**)
  - Physics of different density degradation is not clear (under investigation, turbulent transport?)



n_e before RMP application

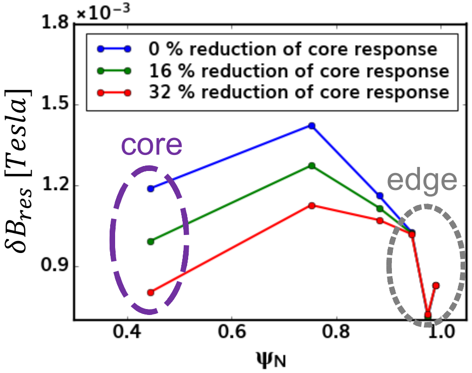


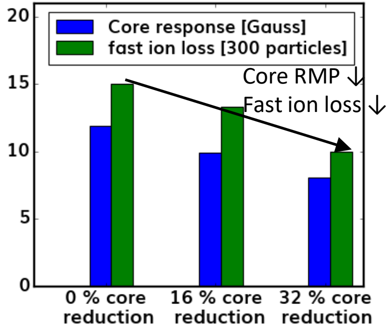
n_e after ELM suppression

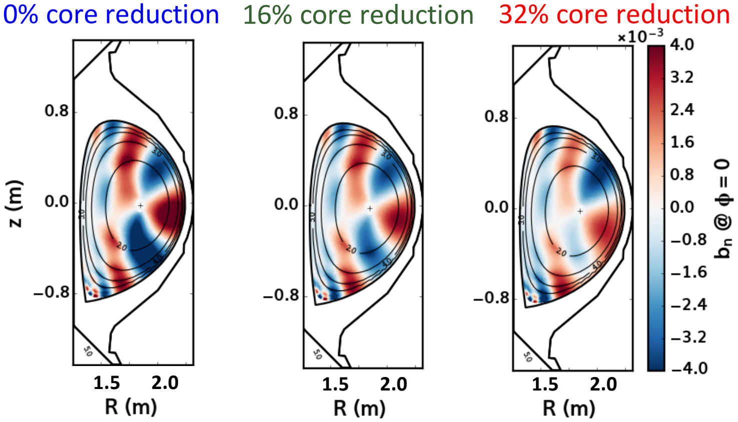


Benefit of core-removal: reduced fast ion loss (simulation)

- Under different core removal, we simulated fast ion orbit loss using NuBDeC [1] and GPEC simulations.
  - δB_{edge} maintained but δB_{core} reduced
- With a reduced core RMP response, simulation shows a reduction of fast ion loss.
- Simulation implies that ELM suppression can be maintained with improved fast ion confinement by core removal





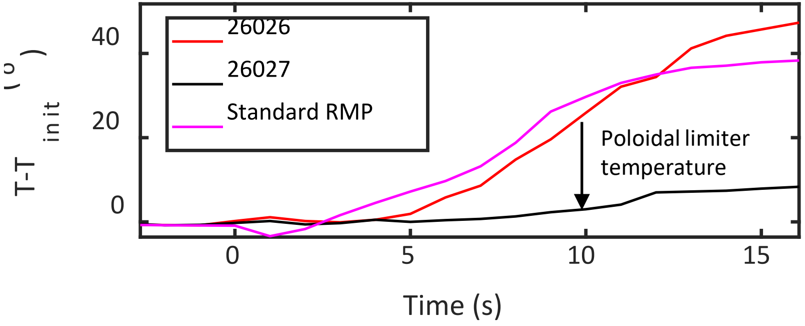


[1] T. Rhee et al., POP (2019)

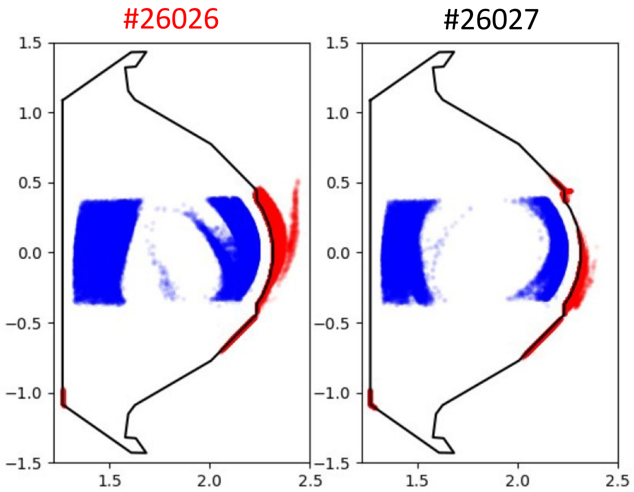
Benefit of core-removal: reduced loss to poloidal limiter

- We investigated increase of poloidal limiter temperature to validate fast ion orbit loss. (diverted plasma)
- Poloidal limiter temperature increases shows good agreement with simulation.
- RMP with core-removal reduced temperature increase of poloidal limiter temperature compared to standard RMP.

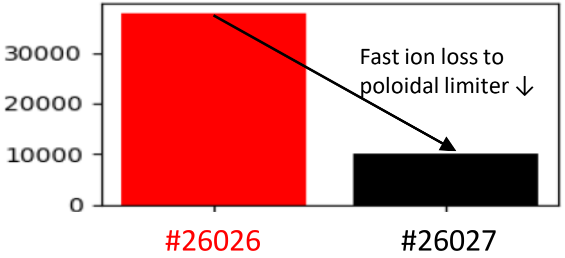
[Experimental result]



[Simulated fast ion loss]



[Simulated fast ion loss]

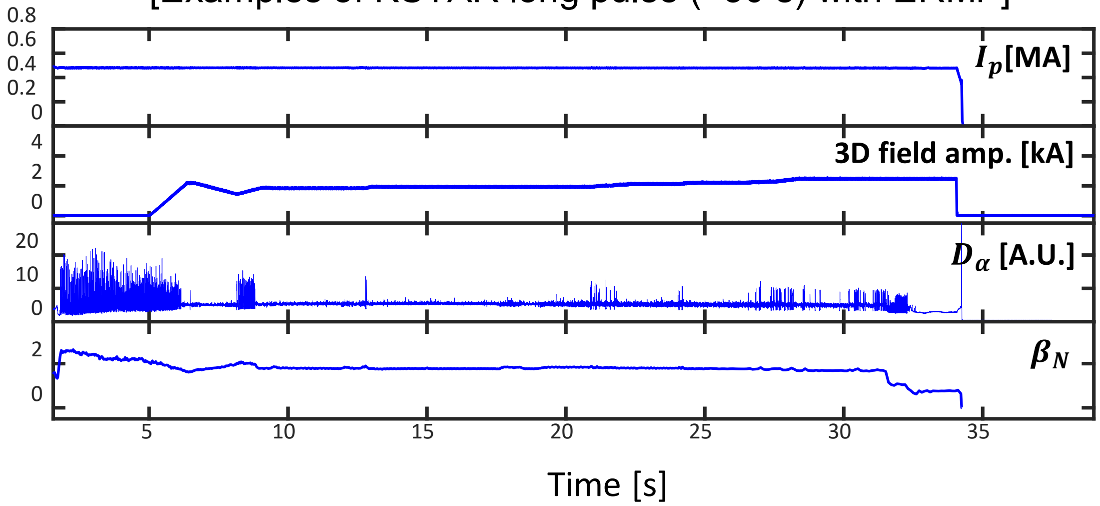


Summary: Tailoring RMP

- Edge localized RMP is proposed to optimize ELM suppression.
- Validated benefits of core removal in KSTAR are as follows
  - Improved safety in RMP-ELM suppression (ex. Robust during performance degradation in long pulse operation)
  - Lessened confinement degradation (rotation and density)
  - Lessened poloidal limiter temperature increase (This was a critical issue in KSTAR long pulse)

➢ ERMP becomes reference 3D configuration for US-KSTAR long pulse operation considering the benefits

[Examples of KSTAR long pulse (~30 s) with ERMP]



+ Poloidal limiter temperature < $600°C$ limit

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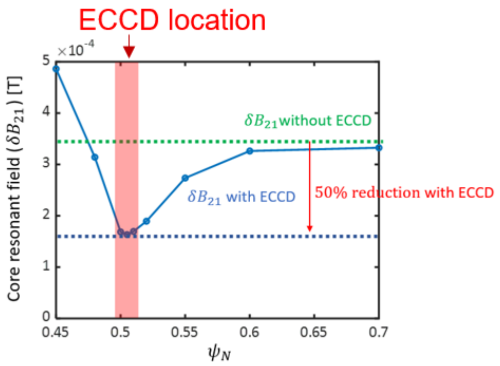
- **Other approaches to improve 3D field-induced degradation**
  - **Preventing core RMP penetration**
  - **NTV control (electron NTV and torque matrix)**
  - Understanding 3D field-induced L-H transition delay
- Future work

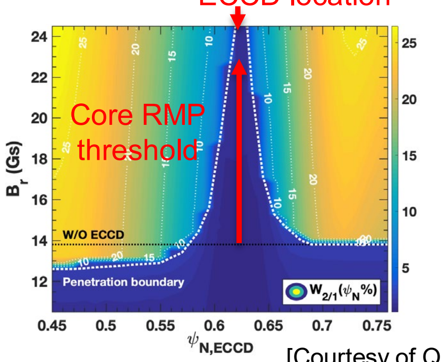
Localized ECCD to prevent core RMP penetration

- Preventing core RMP penetration was a key to improve the safety (degradation as well) of ELM suppression.
- Simulation result shows that localized ECCD prevents core RMP penetration.
  - GPEC has shown that local current profile can reduce external drive for tearing (Δ'_{ext}, It is different from replacing bootstrap current).
  - TM1 has shown that ECCD can increase the core RMP threshold
- This can significantly improve low-n RMP ELM suppression in any scenario by reducing core LM potential while maintaining strong edge RMP. ($I_{RMP,crit}$ is required RMP for penetration)

[Reduction of external δB_{21}, GPEC simulation]

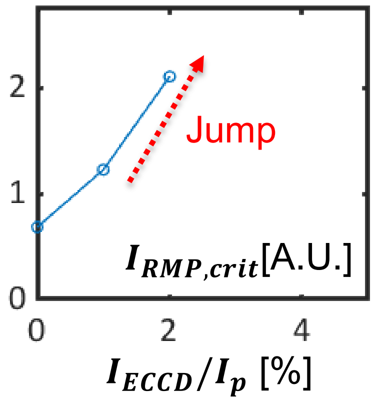


[Increase of EF threshold, TM1 simulation]



[Courtesy of Q. Hu]

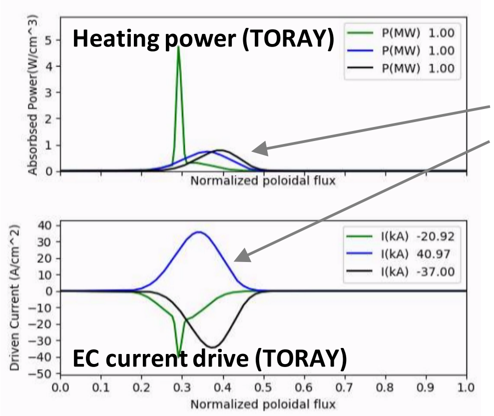
[More ECCD, higher EF allowed]



Localized ECCD to prevent core RMP penetration

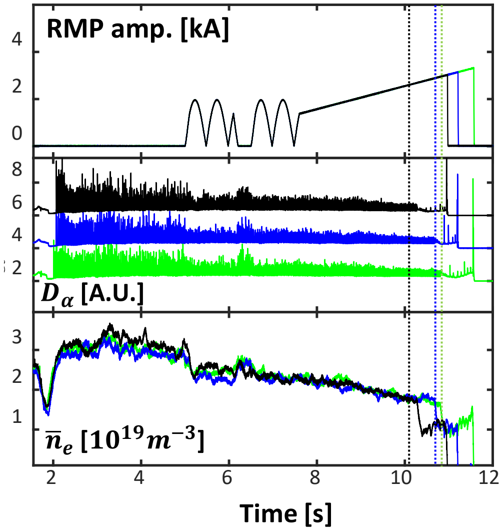
- ECCD is applied with a different toroidal angles to see the change of the LM threshold in KSTAR.
  - To modify localized current drive while maintaining same heating power
- Only injection angle of 15° shows different LM threshold compared with 20° and -20°, possibly due to its injection near the q=2 surface. (No RMP ELM suppression at $q_{95}\sim 6.2$.)
- More experiments are required for validation (more promising in DIII-D)

Toray calculation:
ECCD toroidal angle: 20°, -20°, 15°



-20° vs 15° injection
- Similar heating power
- Different localized current drive

ECCD toroidal angle: 20°, -20°, 15°



Understanding core RMP threshold

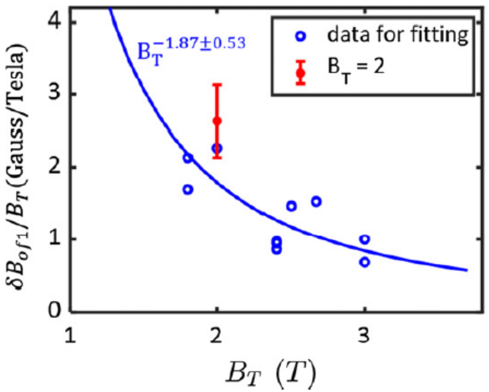
- We also tried to find robust regime in core RMP penetration .

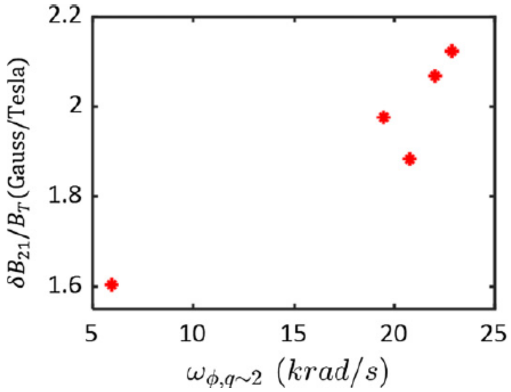
  [1] S.M. Yang et al., Nuclear Fusion (2021)

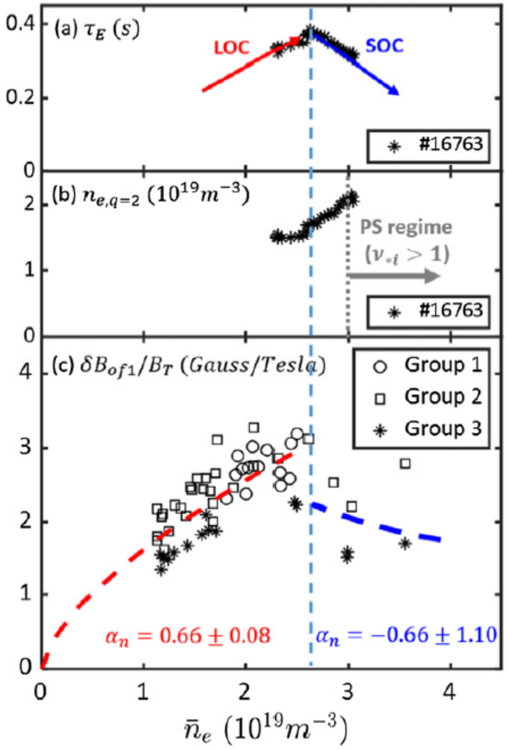
  - Core RMP becomes more dangerous at high Bt
  - Toroidal rotation can stabilize core RMP penetration
  - Density dependence shows non-monotonic dependence.
- A role over of density dependence can be explained with modified theoretical error field (EF) scaling with LOC-SOC transition.

EF scaling in LOC [2]: $\delta B_r/B_T \propto n_e^1\, B_T^{-9/5} R_0^{-1/4}$ → **EF scaling in SOC [1]:** $\frac{\delta B_r}{B_T} \propto n_e^{4/70}\, B_T^{-87/70} R_0^{11/70}$

[2] R. Fitzptrick et al., PPCF (2012)]

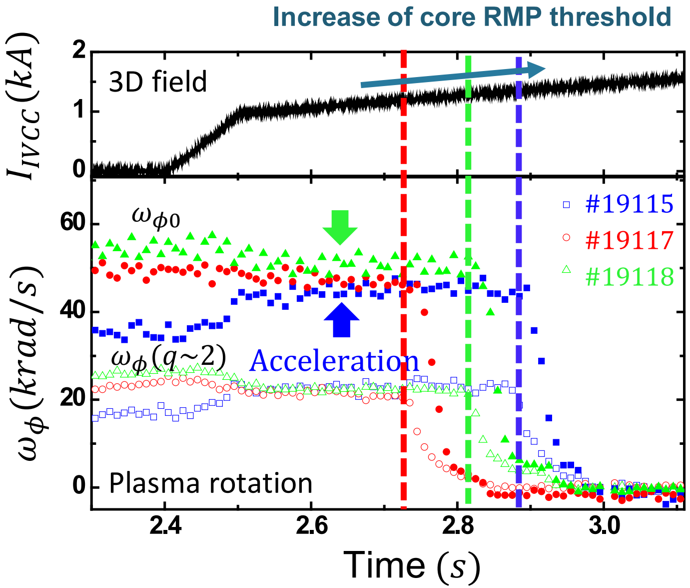






Rotation control to improve core RMP threshold

- If 3D field can accelerate plasma rotation, this can also improve core RMP threshold.
- Experiment show that plasma rotation can be accelerated by 3D field
  - # 19115 shows acceleration of plasma rotation. (unlike other discharges)
  - This result to the increase of core RMP threshold.

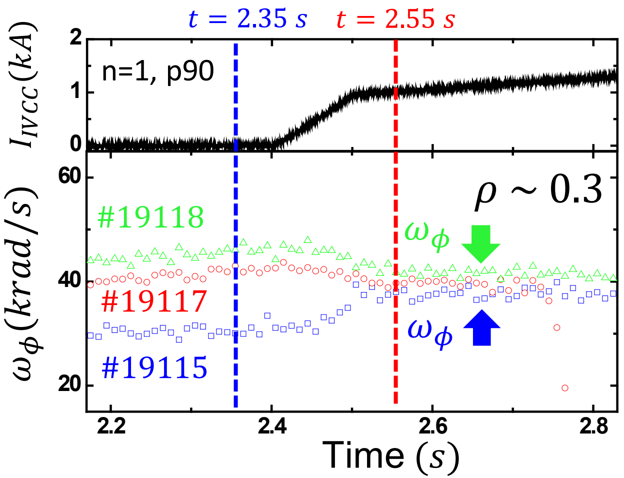


Rotation control to improve core RMP threshold

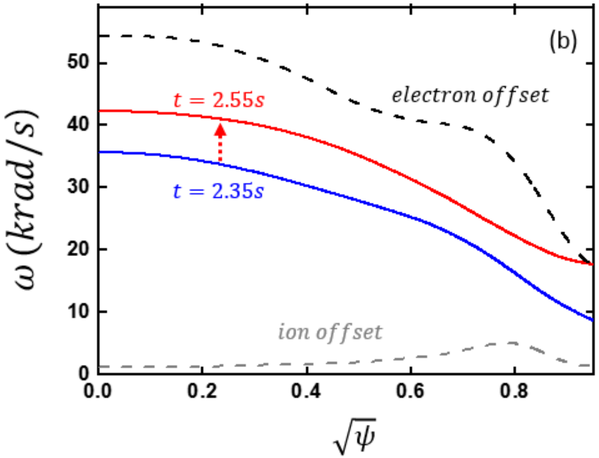
- We validated that electron NTV accelerates plasma rotation.
  - Rotation acceleration toward NTV offset is observed
  - Simulation quantitatively agrees with measured response torque.

[S. M. Yang, J.-K. Park et al., PRL (2019)]

[Rotation acceleration with applied 3D field]



[Estimated NTV offset]



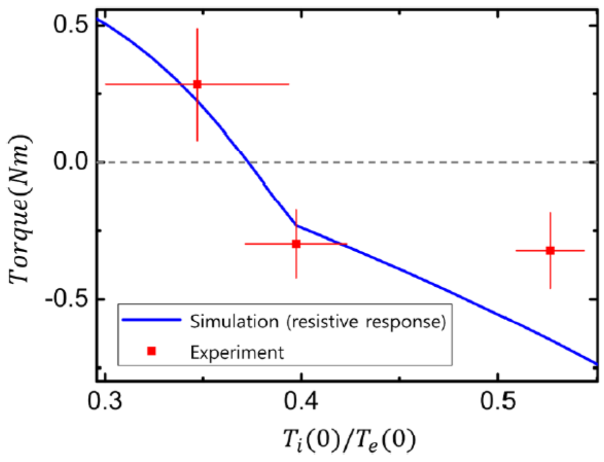
Rotation control to improve core RMP threshold

- We validated that electron NTV accelerates plasma rotation.
  - Rotation acceleration toward NTV offset is observed
  - Simulation quantitatively agrees with measured response torque.

[S. M. Yang, J.-K. Park et al., PRL (2019)]

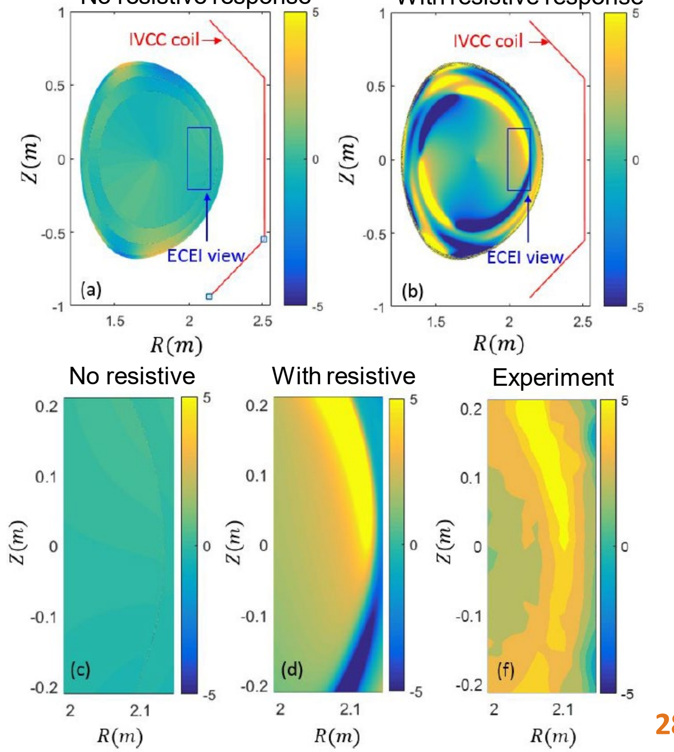
=> Rotation acceleration (electron NTV) improved core RMP threshold.

[Measured torque]



[Measured response]

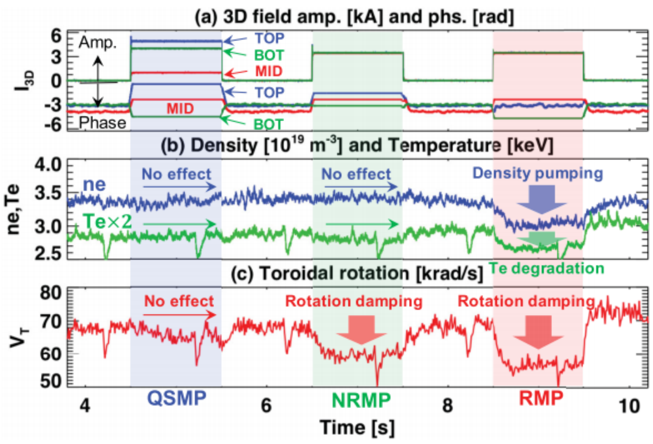
2D displacement contour

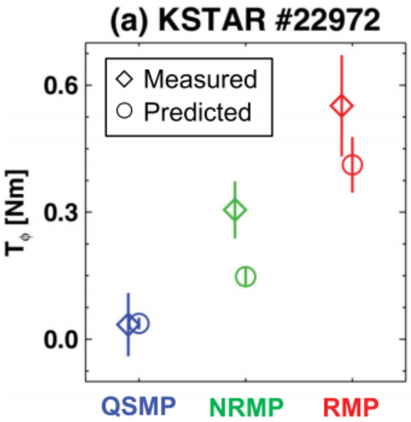


Optimizing NTV using torque response matrix

- A further optimization of NTV is possible using torque response matrix. [J.-K. Park et al., POP (2017)]
- The eigenvector of torque response matrix with minimum eigenvalue, QSMP is validated in KSTAR.
  - RMP caused density pump, T_e degradation, and rotation damping. [J.-K. Park, S.M. Yang et al., PRL (2021)]
  - NRMP drives rotation damping without density&T_e degradation.
  - QSMP did not show any degradation.

=> NTV optimization is validated in KSTAR. It can be used to improve core RMP threshold



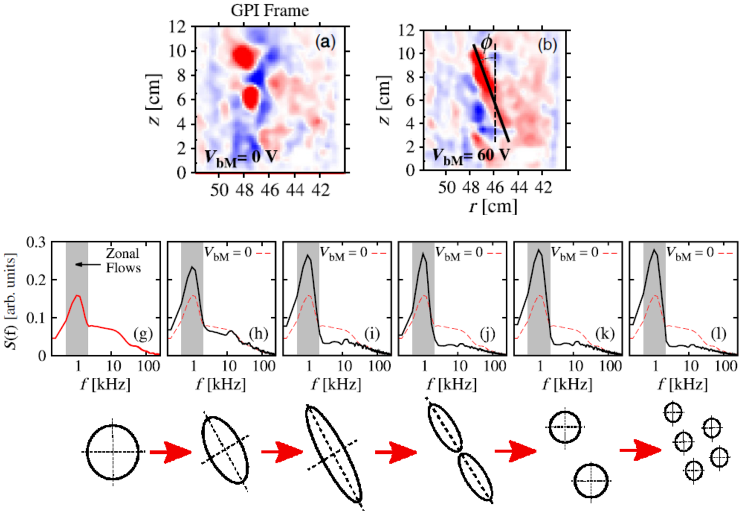


Outline

- Introduction
- Tailoring 3D field
  - Method
  - ELM suppression for the entire period of discharge with n=1 field
  - Additional benefits of the ERMP scheme
    - ELM suppression with reduced confinement degradation
    - Control of RMP induced fast ion orbit loss to reduce wall heating
- **Other approaches to improve 3D field-induced degradation**
  - Preventing core RMP penetration
  - NTV control (electron NTV and torque matrix)
  - **Understanding 3D field-induced L-H transition delay**
- Future work

Introduction: Zonal flow and 3D field in L-H transition

- A fluctuating small scale $E \times B$ shear such as zonal flow is understood as a triggering mechanism of L-H transition in tokamak.
- Recent study showed that 3D field can increase effect on turbulence transport, particularly in L-H transition power threshold.

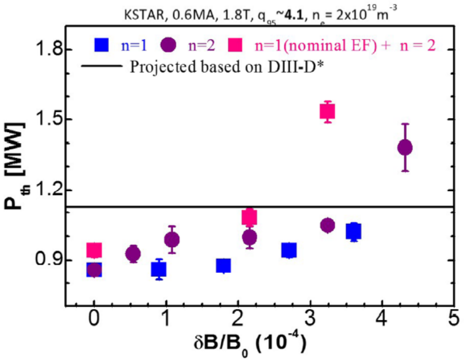


[I. Shesteikov et al., PRL, 2013].

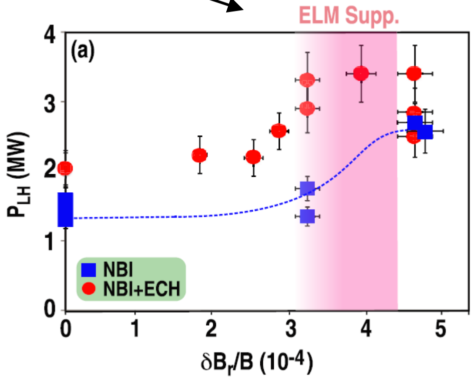
[3D field VS L-H power threshold]

KSTAR

DIII-D



[Y. In et al., NF, 2017]

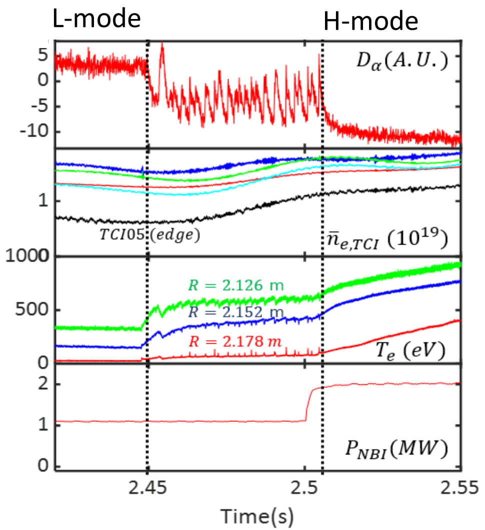


[L. Schmitz et al., NF, 2019]

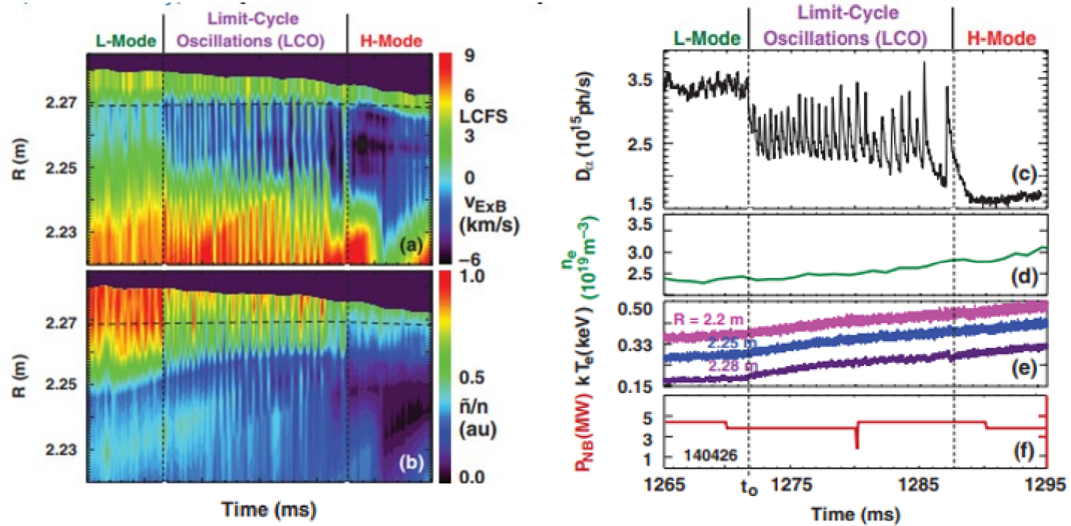
Observation of limit-cycle oscillation before L-H transition

- We found oscillation of D_α, increase of $\bar{n}_e, T_e$ that indicates confinement enhancement right between L-mode and H-mode phase in KSTAR.
- The observation in KSTAR before L-H transition resembles zonal flow oscillation in DIII-D, which shows edge density and temperature increase.

[Oscillation before L-H transition in KSTAR]



[Zonal flow oscillation in DIIID]

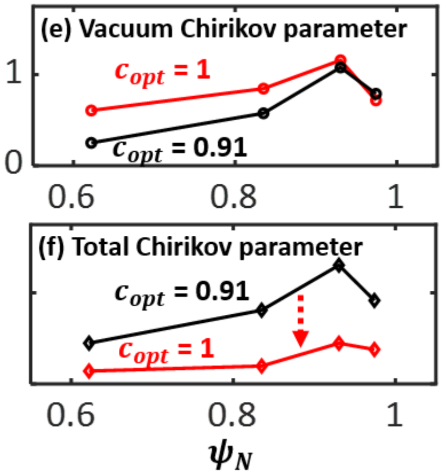


[L. Schmitz et al., PRL 2012]

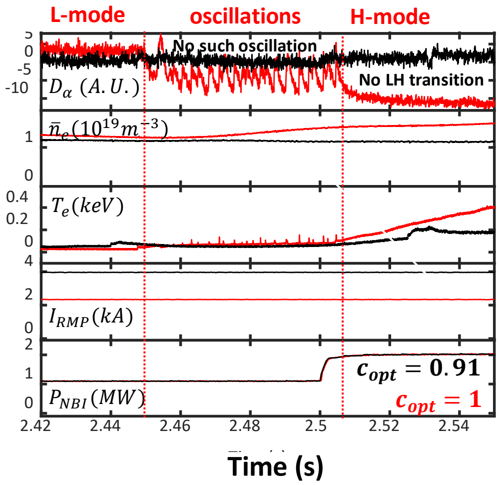
RMP optimization improves L-H transition delay

- RMP optimization improves L-H transition delay and turbulence (nonlinear interaction).
  - With less removal of RMP ($c_{opt} = 0.91$ vs $c_{opt} = 1$), nonlinear interaction is reduced even with increased turbulence.
- Reduction of the zonal flow could be the primary reason for the observed delay of L-H transition.
- Note that RMP optimization for L-H transition should include plasma response. (Vacuum vs total Chirikov)

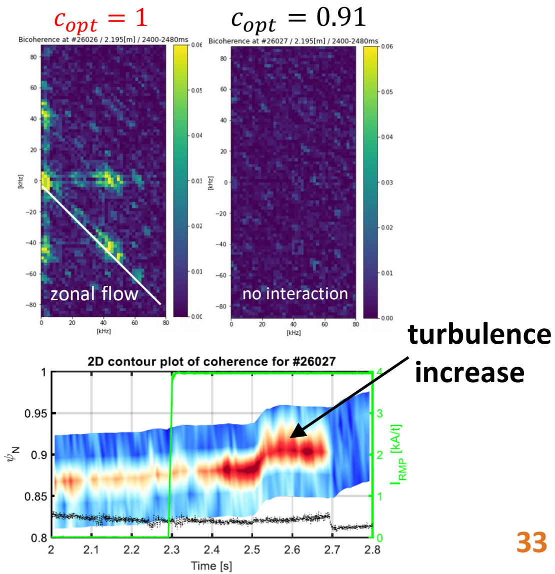
[RMP optimization result]



[Zonal flow oscillation affected by RMP optimization]



[RMP suppress non-linear interaction]



Future work

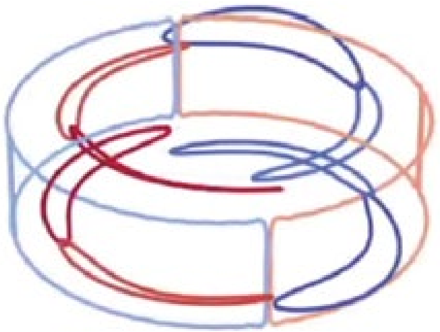
- ELM control coils for other devices (e.g., next phase of KSTAR including K-DEMO) will be studied
  - Based on the ERMP scheme, as already studied for KSTAR and COMPASS-U.

[Geometry optimized KSTAR coil]

- ERMP scheme applied to improve ELM suppression
- Stellarator tool applied to optimize geometry

=>141 % increase of safe ELM suppressed window

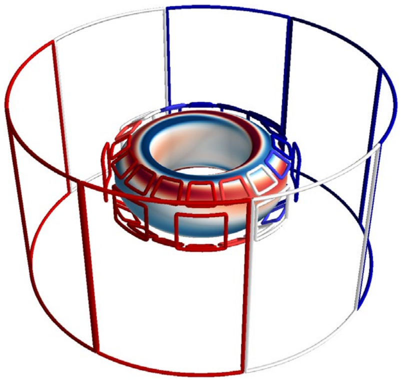
[S.M. Yang et al., NF, 2020]



[Ex-vessel and in-vessel COMPASS-U coil]

- Efficiency of ex-vessel coil tested (ERMP applied)
- Best option chosen with given realistic coil geometry

[J. K. Park et al., COMPASS Final Design review (2021)]



Future work

- Extension of validated ERMP optimization scheme for ITER application
  - High-n optimization will be done with better diagnostics (run-time (1.5 day) expected in DIII-D)
  - Physics of lessened confinement degradation will be investigated in both KSTAR and DIII-D.
- Validation of fast ion loss study under 3D field
  - More experimental (KSTAR + DIII-D) and simulation (NubDec + ORBIT) is planned.
- Validation of ECCD effect on core RMP threshold
  - Propose more experiments, analyze existing data in KSTAR (DIII-D, run-time requested but …)
- Turbulence study to understand RMP induced L-H transition delay
  - Analyze turbulence measurement (ECEI) to see nonlinear interaction change and its structure
  - Application to negative triangularity discharge to prevent L-H transition
- Heat flux under RMP
  - Continue collaboration with UW-Madison (supports EMC3-EIRNE simulation in KSTAR).

END

Back up : q95 window of ELM suppression in KSTAR

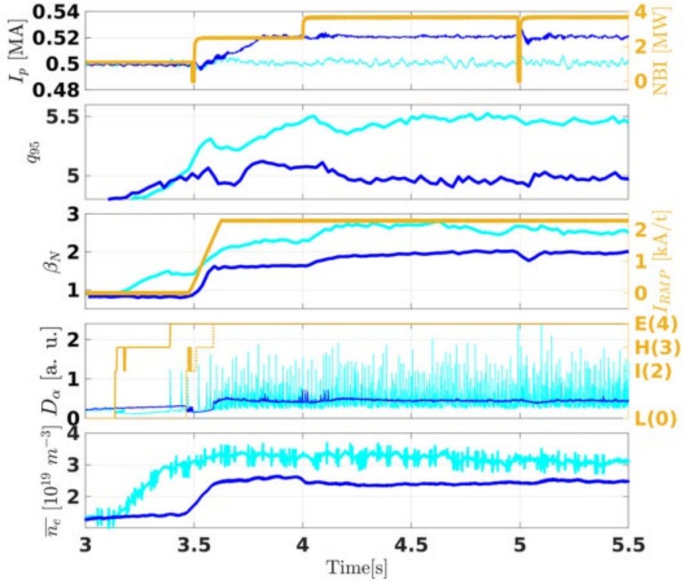
* Radial position control coil is not available with a flexible 3D setup
* So, shaping control is not good enough during the transient phase

- Why initial ELMs are not suppressed?

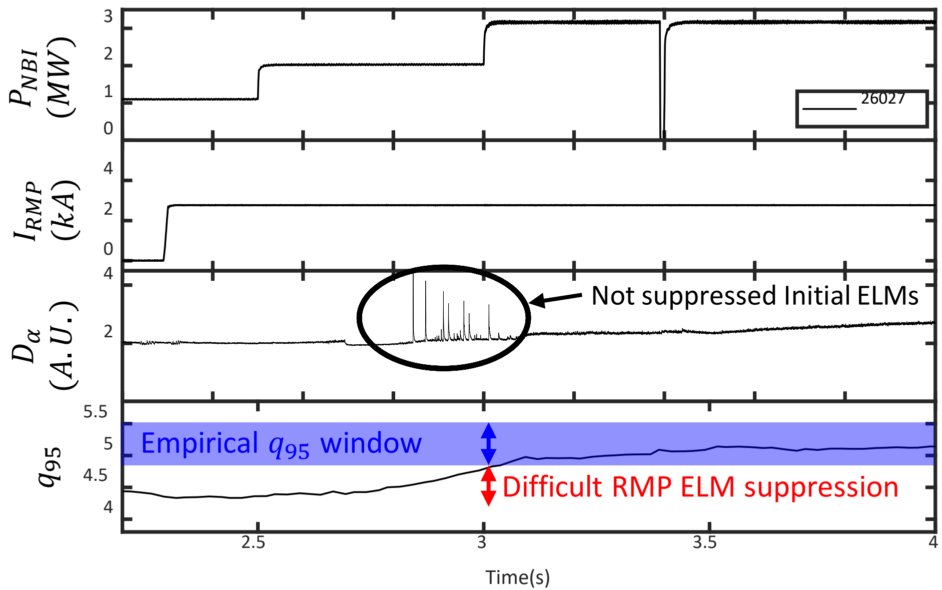
  -These initial ELMs can be related to q_{95} windows ($4.85 < q_{95} < 5.5$)

- When q_{95} is controlled initial ELM crashes are suppressed.

[Shin et al., Nuclear Fusion (2022)]



[ELM suppressed discharge]



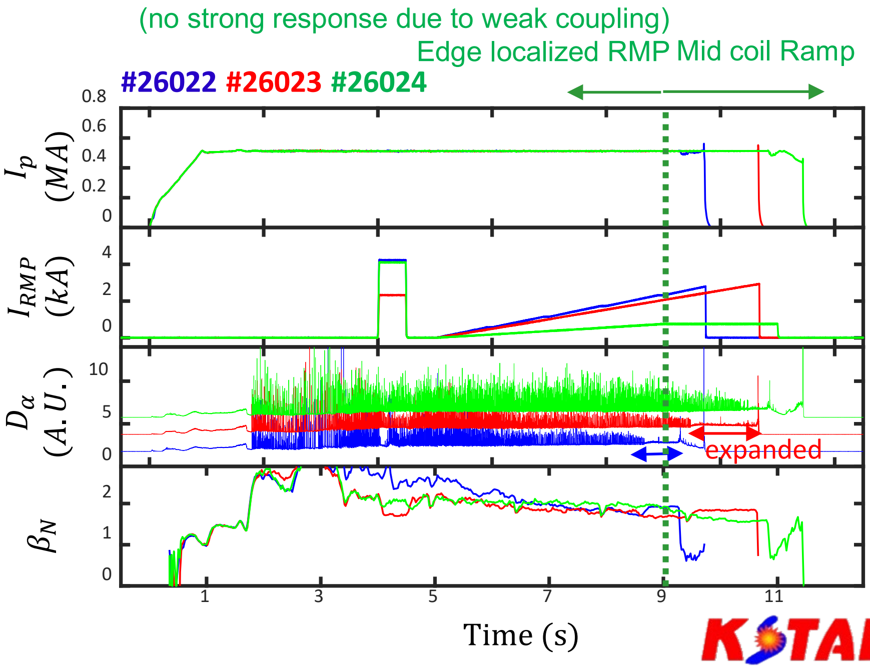
Back up : 3D optimization with existing coils: Validation in KSTAR

- Three different RMP spectrum is investigated at $P_{NB} = 3.9\ MW$ target discharge.
  - 90 degree phasing (26022)
  - Largest window (26023)
  - Ideal edge localized RMP until 9s (26024)

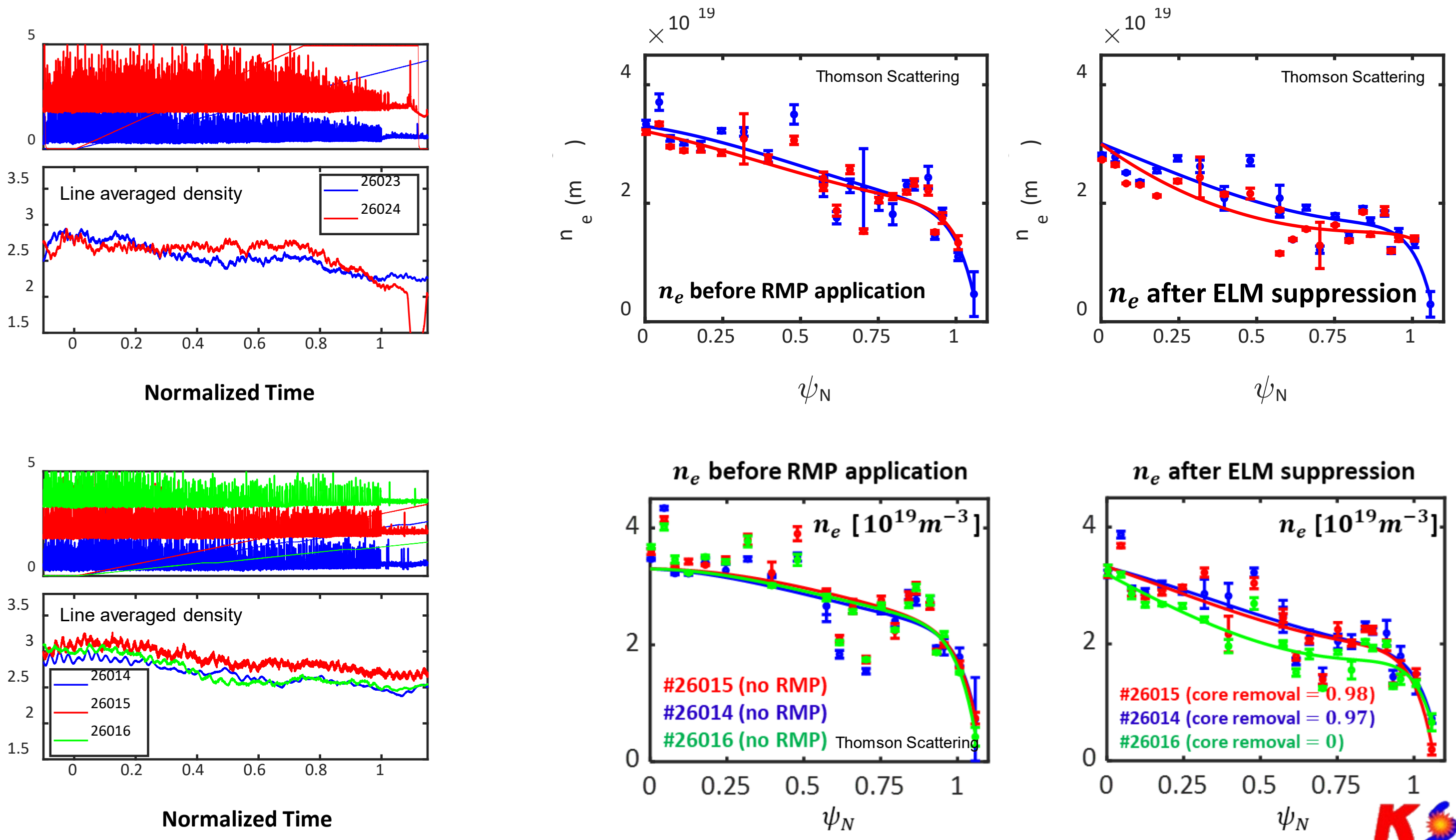
- The window was narrower at higher $\boldsymbol{P_{NB}}$ as empirical found in KSTAR.

- One can expand ELM suppression window for this target by 3D optimization.

- Ideal edge localized RMP is too weak as expected. It can lock the plasma by raising mid coil current after 9s.



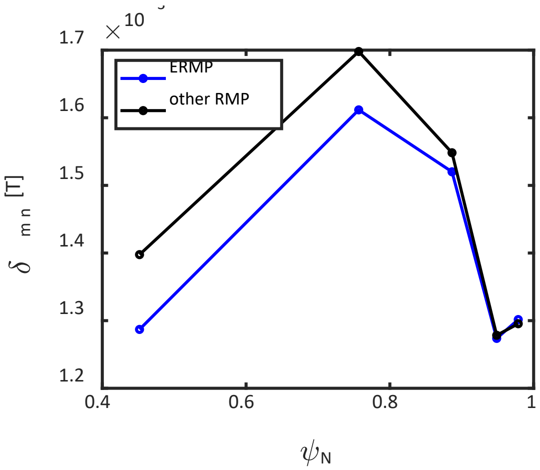
Back up : Density degradation cross calibration& across different target



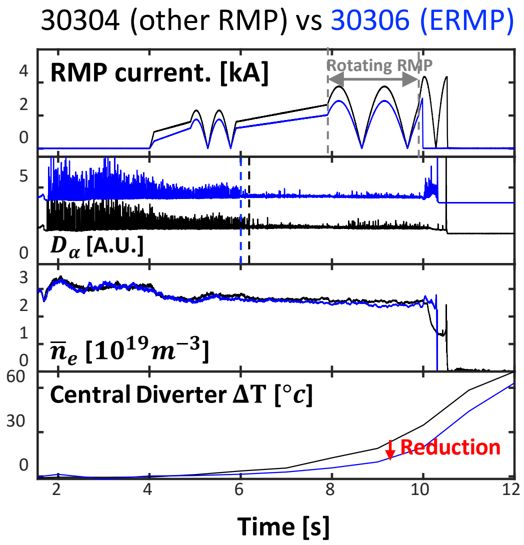
KSTAR

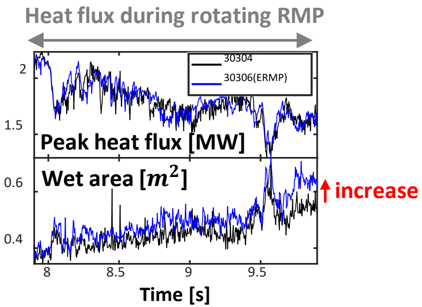
Back up : ERMP reduced diverter temperature increase

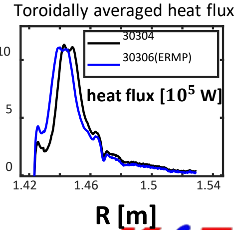
- ERMP shows less increase of central diverter temperature than **other RMP** with a similar plasma condition (even with a slightly higher edge RMP level).
- ERMP shows increased wet area with comparable peak heat flux for all toroidal angles.
- Rotating RMP will also be used to estimate the fast ion orbit loss.



Applied in KSTAR (30304 vs 30306)



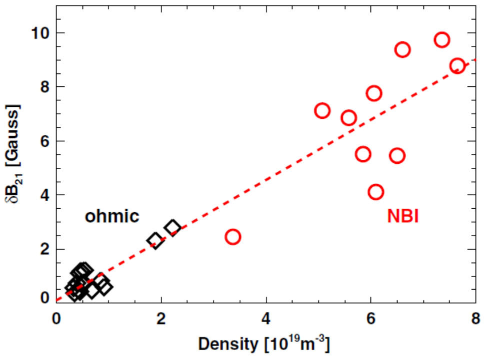




Back up : ELM suppression for the entire period of discharge

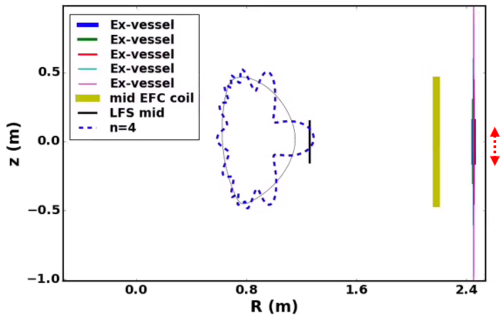
- In future reactors, ELMs should be suppressed for the entire period of discharge.
  - This needs ELM suppression at transient entries and exits of H-mode.
- Easiest approach is to apply RMP before the L-H transition
  - This requires multi-target optimization (from L-mode to H-mode)
- L-mode plasma has low density and rotation and is vulnerable to core LMs, especially for n=1 field.
- n=1 (low-n) RMP is attractive for future reactors needing ex-vessel 3D coils to avoid nuclear contamination. Great synergy with edge localized RMP.

[Density vs. n=1 core RMP threshold]



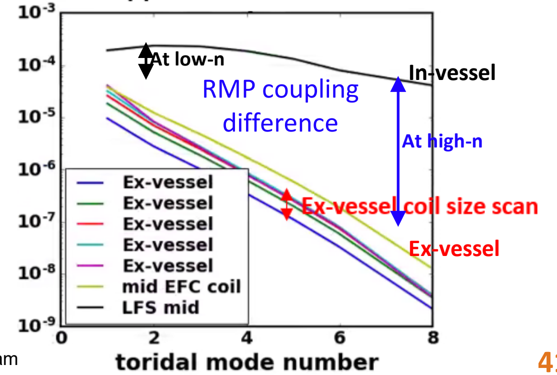
[J.-K. Park et al., NF, 2012]

[COMPASS-U ex-vessel coil size scan]



*collaboration with T. Markovic and COMPASS-U team

[RMP coupling of In-vessel vs Ex-vessel]



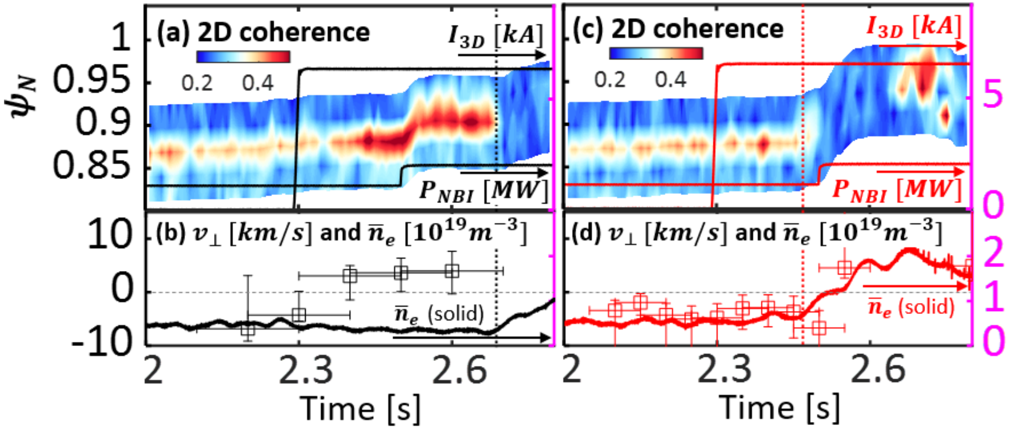
Back up : RMP optimization for efficient L-H transition

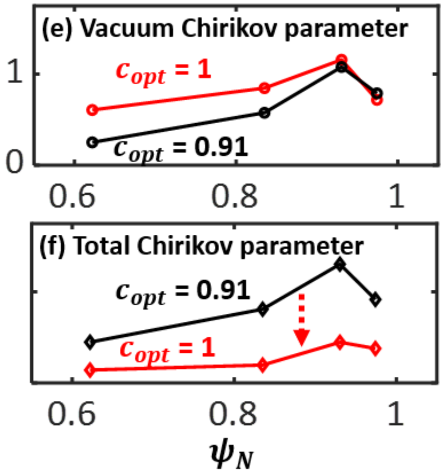
- Removal of RMP in L-mode with c_{opt} is validated with efficient L-H transition.
  - At $c_{opt} = 0.91$, edge turbulence increase, $\bar{n}_e$ and $v_\perp$ change is observed with $t_{LH} = 2.66\ s$
  - At $c_{opt} = 1$, no change in turbulence with $t_{LH} = 2.47\ s$ (even without additional heating)

  ➔ More efficient L-H transition with $c_{opt} = 1$
- Note that vacuum response is not decreased at $c_{opt} = 1$ unlike total response.

#26027 ($c_{opt} = 0.91$) #26026 ($c_{opt} = 1$)

$t_{LH} = 2.66\ s$ $t_{LH} = 2.47\ s$

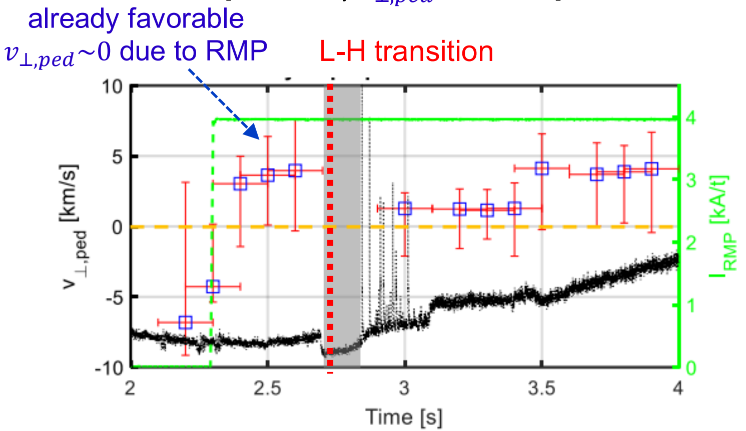




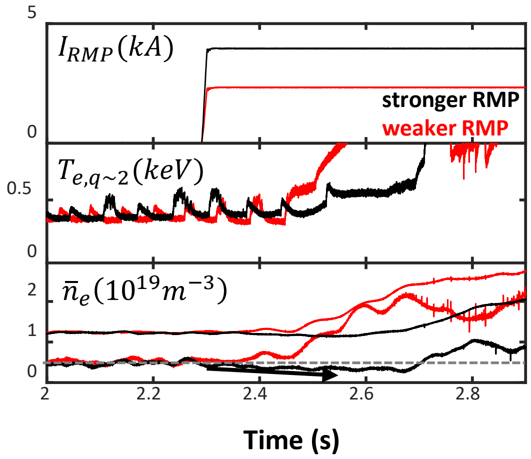
3D field induced L-H transition delay due to turbulence change

- A necessity of integrated optimization implies the importance of RMP control during the transient phase such as L-H transition.
- We found that zonal flow oscillation and non-linear interaction are affected by RMP optimization.
- Reduction of the zonal flow could be the primary reason for the observed delay of L-H transition.
- A physics behind this behavior is under investigation but the early opening of edge island is a candidate.

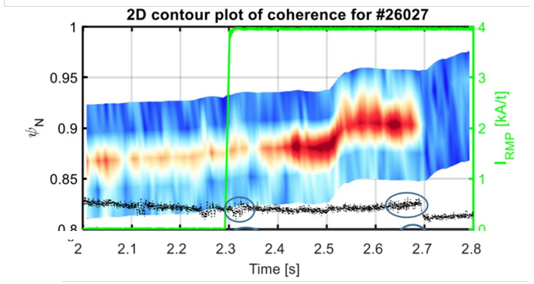
[stationary $v_{\perp,ped}$ evolution]



[edge density drop]



[edge turbulence increase]

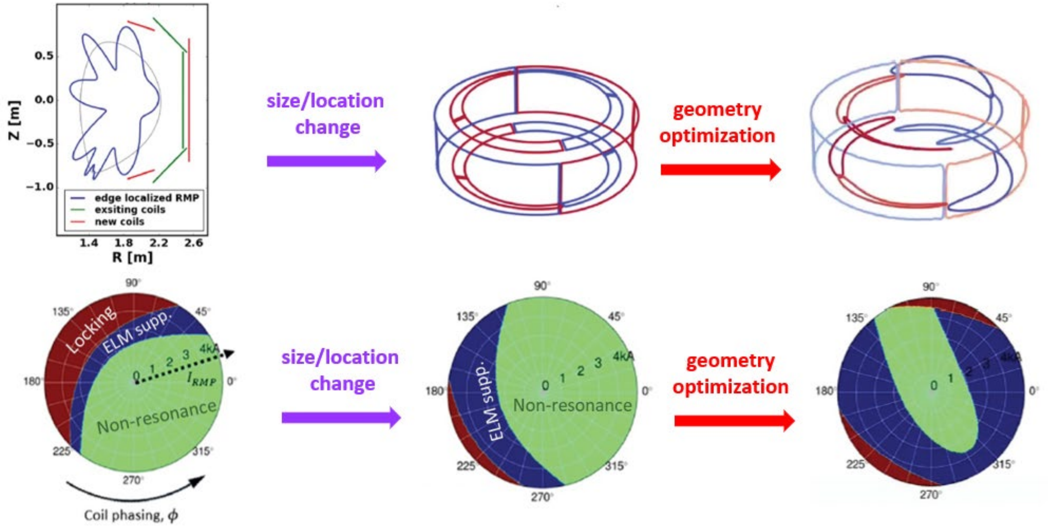


Back up : 3D coil design with edge localized RMP

- Edge localized RMP can significantly improve the design of ELM control coils.
- The modified coil size and location based on the edge-localized RMP shows that the ELM suppression window can be expanded. (41 % increase of safe ELM suppressed window)
- A geometry optimization with FOCUS can further improve the ELM suppression window.

(141 % increase of safe ELM suppressed window)

[S.M. Yang et al., NF, 2020]



3 important region with 3D coil

- Dominantly non-resonant δB **(No strong change)**
- **safe** ELM suppressed window (From **edge δB**)
- Plasma disrupted window (From **core δB**)

DIIID Breakout result (preliminary)

- Introduced ERMP optimization scheme will be applied to DIII-D tokamak at higher-n with better diagnostics

➢ Optimizing RMP across the L to H confinement modes to suppress ELMs

- **Tier 1 priority in ELM control ROF (1 day + 1 LRHO)**
  - "Entering H-mode without an ELM, then minimizing confinement degradation n =3 RMP ELM suppression" (1 day + 1 LRHO)
- **High chance to get shots in prepare for ITER ROF (0.5 day)**
  - "Entering H-mode without an ELM, then minimizing confinement degradation n =3 RMP ELM suppression" (0.5 day)
- Piggyback planned in Core-edge integration ROF (1 day + 1 LRHO)
  - "Integrate RMP ELM control with divertor detachment in closed divertor" (1 Day+1 LRHO)
- Piggyback being discussed for n=2 RMP ELM suppression in ELM control ROF

Back up: Systematic RMP localization approach

- A systematic approach can minimize core response and maximize edge response by introducing core-null space projection, $\overleftrightarrow{P}_{c,null}$.
- This edge localized RMP shows relatively good efficiency while completely eliminating core resonant response (core δB=0, small penalty in edge δB).

[Calculation of efficient edge-localized RMP]

[S.M. Yang et al., NF, 2020]

$$\overleftrightarrow{C}_{core} \cdot \vec{V}^{x}_{c,null} = 0$$

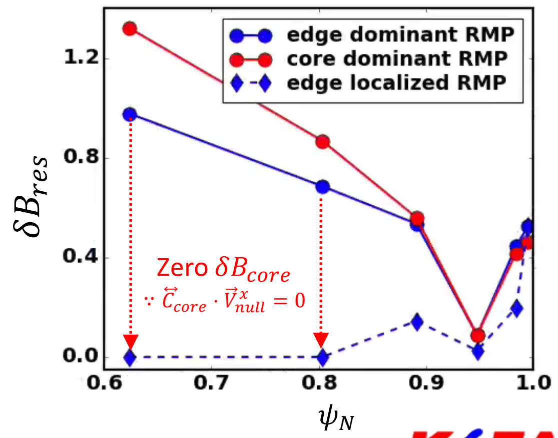
$$\vec{V}^{x}_{c,\mathrm{null}} = \overleftrightarrow{P}_{c,\mathrm{null}} \cdot \vec{V}^{x}_{b}$$

$$\overleftrightarrow{P}_{c,\mathrm{null}} = \overleftrightarrow{N}_{\mathrm{core}} \cdot \left(\overleftrightarrow{N}^{\dagger}_{\mathrm{core}} \cdot \overleftrightarrow{N}_{\mathrm{core}} \right)^{-1} \cdot \overleftrightarrow{N}^{\dagger}_{\mathrm{core}}.$$

$$\vec{B}_{\mathrm{edge}} = \overleftrightarrow{C}_{edge} \cdot \vec{V}^{x}_{c,\mathrm{null}}$$

$$\vec{B}_{\mathrm{edge}} = \overleftrightarrow{C}_{\mathrm{edge}} \cdot \overleftrightarrow{P}_{c,\mathrm{null}} \cdot \vec{V}^{x}_{b}$$

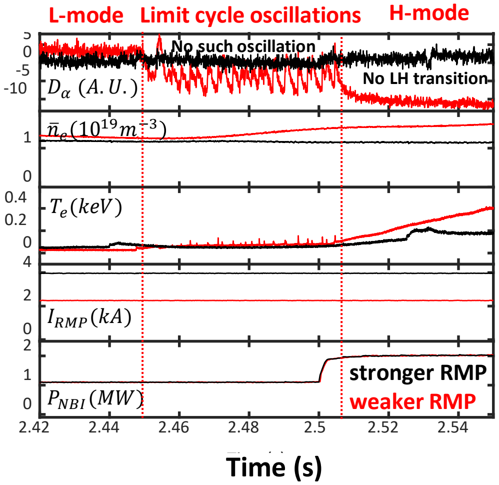
$$\vec{B}_{\mathrm{edge}} = \overleftrightarrow{C}_{e,\mathrm{cnull}} \cdot \vec{V}^{x}_{b}$$



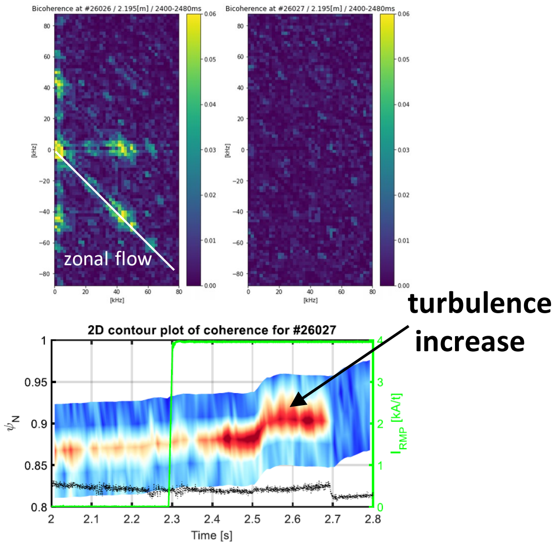
Back up: RMP effect on zonal flow

- Experimental evidence of zonal flow oscillation and its suppression due to RMP is found in KSTAR.
- Experimental results imply a role of RMP in zonal-flow turbulence interaction.
  - With RMP, reduction of nonlinear interaction is shown even with increase turbulence level.
  - With RMP, LCO frequency becomes higher even with lower collisionality, which is counter-intuitive to the linear collisional zonal flow damping rate.

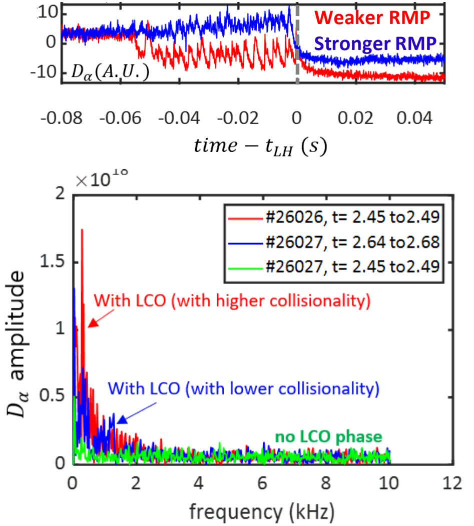
[limit cycle oscillation in KSTAR]



[RMP induced reduction in bi-coherence]



[RMP induced LCO frequency change]



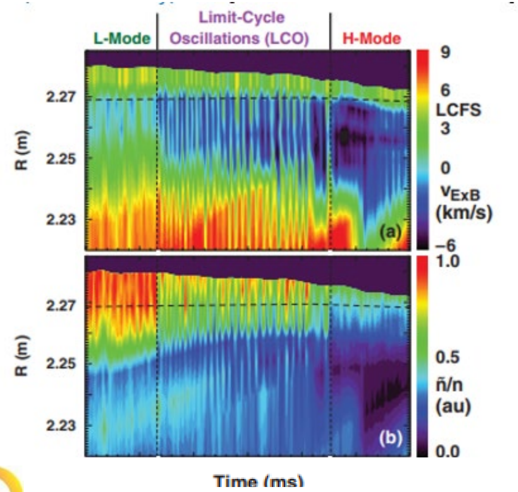
Back up: Limit-cycle oscillation in KSTAR

- Although direct $v_{E\times B}$ is not available, modulation of turbulence ($\delta T_e, \delta n_e$) during the LCO in KSTAR is very similar to zonal flow oscillation in DIIID.
- A δT_e fluctuation shows poloidally elongated structure that indicates that it is m=0 structure.

*plasma is rotating electron diamagnetic direction

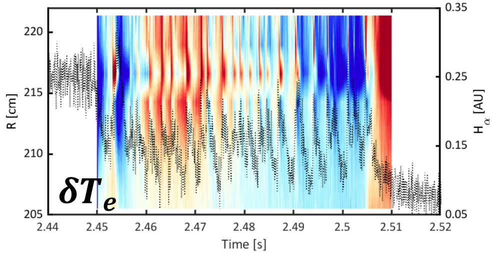
[modulation of fluctuation with LCO]

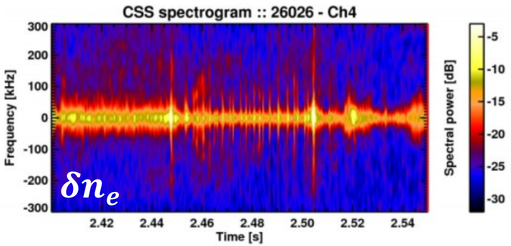
[Zonal flow oscillation in DIIID]



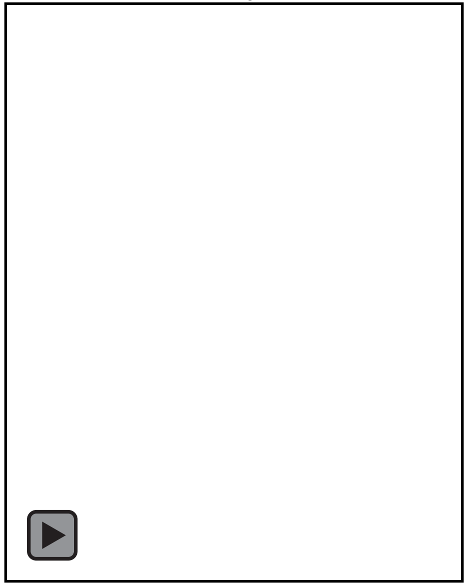
[L. Schmitz et al., PRL 2012]

[during LCO in KSTAR]



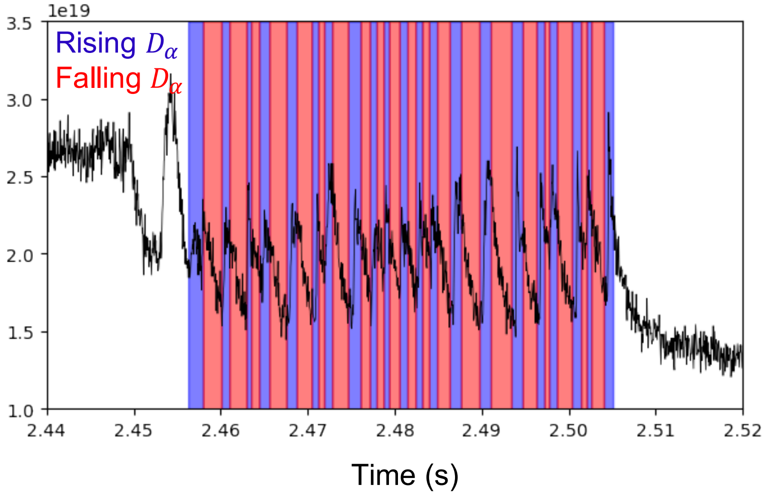


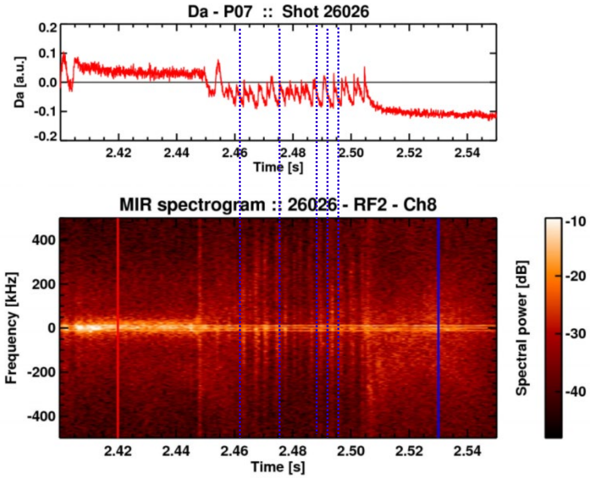
[poloidal δT_e structure]



Back up: Limit-cycle oscillation in KSTAR

- We found that D_α peak is related to the minimum turbulence amplitude. (Rising D_α include zonal flow max)
- We found that nonlinear interaction is much more active during zonal flow grow phase.
- This may imply that Reynolds-stress-driven energy transfer only becomes significant when the turbulence is driving zonal flow.





Rising D_α~ include zonal flow max
Falling D_α~ turbulence grow

Back up: Limit-cycle oscillation in KSTAR

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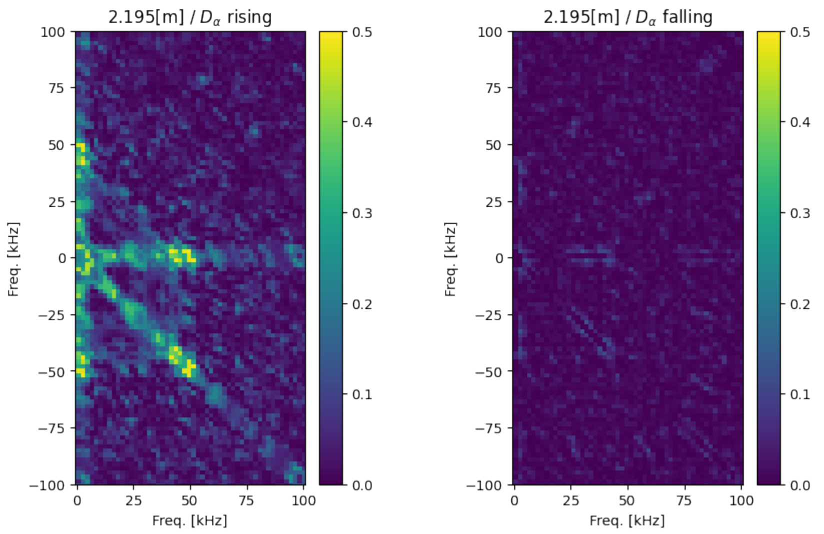
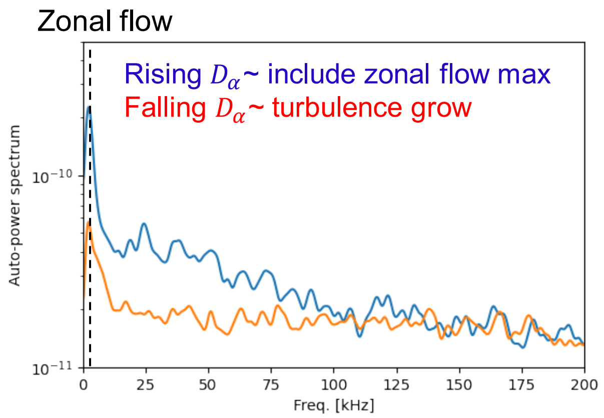
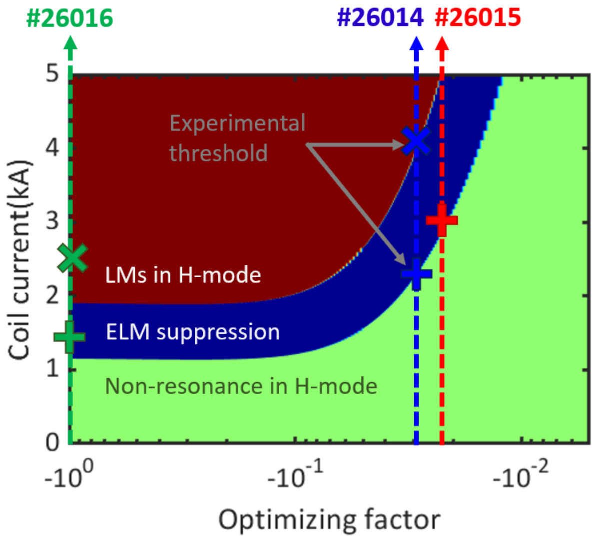




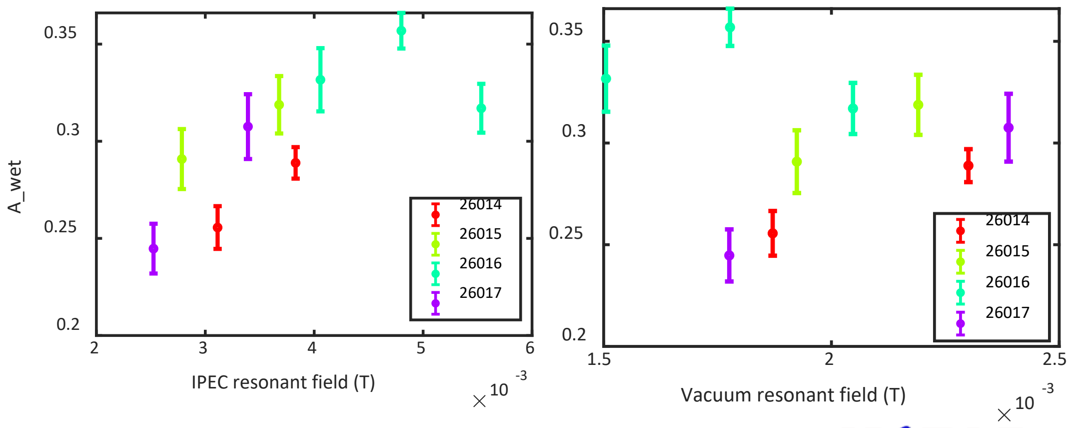
3D optimization with existing coils: Diverter wetted area

- Three different RMP spectrum is investigated by 3D optimization.
  - 90degree phasing (26014): between 26015&26016
  - Largest window (26015): later locking
  - Most efficient RMP (26016): earlier locking
- Diverter wetted area (A_{wet}) is proportional to edge IPEC resonant field?

$$A_{wet}[m^2] \equiv \frac{\int q_\perp dA}{(q_\perp)_{max}}$$

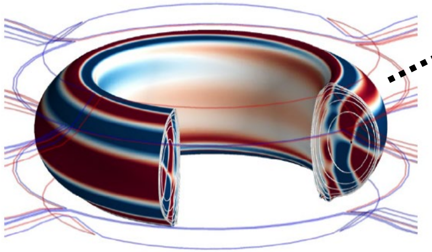


[Diverter wetted area vs edge resonant field]



Introduction

- Optimization of 3D magnetic field needs an understanding of $\delta\vec{B}_{\mathrm{res}}$, $\vec{B}_{\mathrm{pen},th}$ and $\delta\vec{B}_{\mathrm{NR}}$.



[Park et al., Nature Physics, 2018]

$\delta\vec{B}$ consists of $\delta\vec{B}_{\mathrm{res}}$, $\delta\vec{B}_{\mathrm{NR}}$

✓ Resonant field ($\delta\vec{B}_{\mathrm{res}}$) : 3D field resonant with equilibrium field line pitch $q = \frac{m}{n}$.

- $\delta\vec{B}_{\mathrm{res}}$ drives field penetration when $\delta\vec{B}_{\mathrm{res}} \gg \vec{B}_{\mathrm{pen},th}(\mathrm{n_e}, \omega_\phi, \dots)$
- Known to be responsible for ELM suppression and mode locking

✓ Non-resonant field ($\delta\vec{B}_{\mathrm{NR}}$) : 3D field that does not resonant

- $\delta\vec{B}_{\mathrm{NR}}$ is not resonant, but it can change plasma rotation.
- Change of rotation can affect $\vec{B}_{\mathrm{pen},th}(\mathrm{n_e}, \omega_\phi, \dots)$

- This work will mainly cover resonant field $\delta\vec{B}_{\mathrm{res}}$