Tailoring tokamak error fields to optimize plasma instabilities and transport

S.M. Yang[1], J.-K. Park[1], Y.M. Jeon[2], N.C. Logan[3], J. Lee[2], Q. Hu[1], J.H. Lee[2],
S.K. Kim[1], J.W. Kim[2], H.H. Lee[2], Y.-S. Na[4], T.S. Hahm[4], G.J. Choi[4], S. Hahn[2], M. Kim[2] ,
G.-W. Shin[2], Y. In[5], R. Shousha[6], G.Y. Park[4], W.H. Ko[4]

[1] **Princeton Plasma Physics Laboratory,** [2] Korea Institute for Fusion Energy,
[3] Lawrence Livermore National Laboratory, [4] Seoul National University,
[5] Ulsan National Institute of Science and Technology, [6] Princeton University

Outline

- **Tailoring tokamak error field**

- Application of proposed error field correction (EFC)
  - EFC to control edge localized mode instability
  - EFC to control edge plasma transport
  - Other applications

- Summary

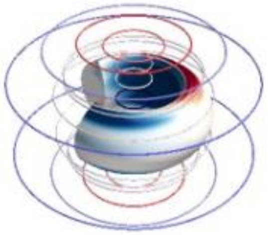
3D Error field in tokamak

- Tokamak confines fusion plasma with its toroidally symmetric magnetic field
- Tokamak is a complex device, and it consists of many magnetic coils to apply tokamak configuration
- However, there are always unwanted magnetic field components in the tokamak, known as **“3D error field”**

3D error field from magnetic coils

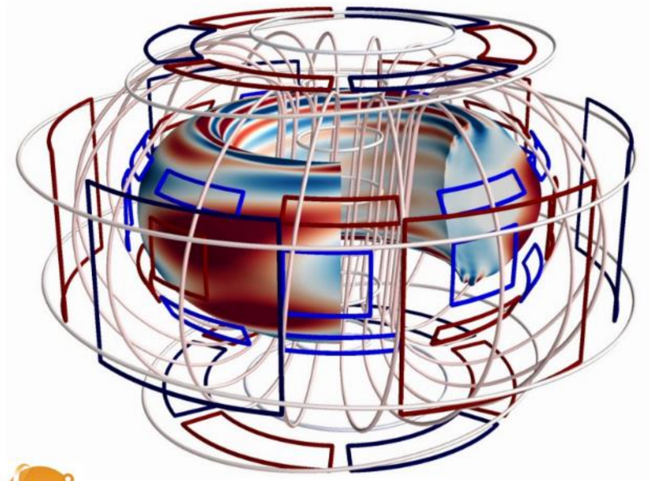
[Logan et al., APS (2021)]

Nominal Windings



Tilts & Shifts

[Park et al., APS (2022)]

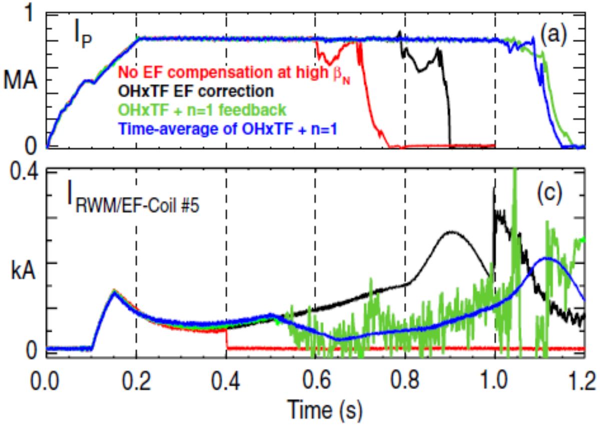


Unfavorable effect of 3D error field in tokamak

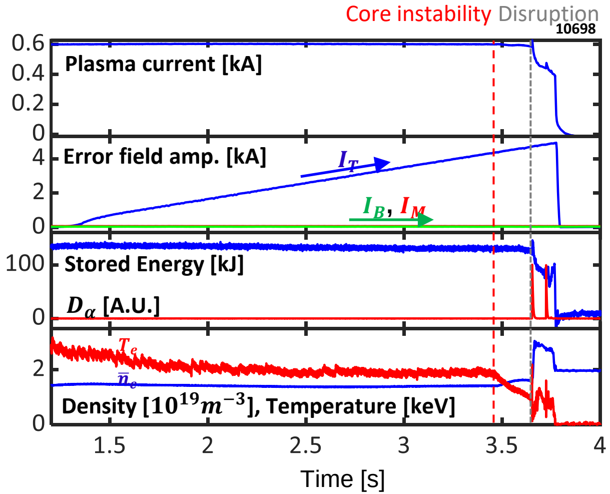
- The **3D error field** level of **even less than 1%** affects the stability and confinement of plasma.
- In particular, the most probable **n=1 3D error field** can drive mode locking and disruption.
- Tokamak construction is designed to minimize the error field.
  - Tokamak is a complex system, so minimizing the error field needs a lot of time and resources.
- Disruption can be avoided by modification of poloidal spectra of n=1 3D error field.

NSTX- error field study

[Menard et al., NF (2010)]



KSTAR- disruption by proxy error field

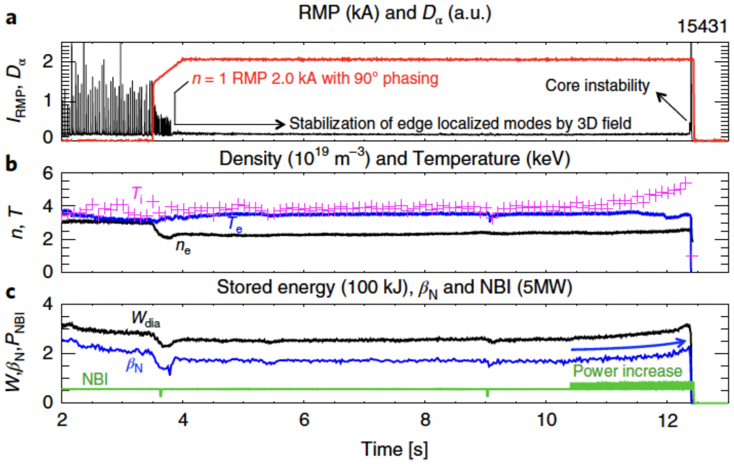


Potential benefit of 3D error field

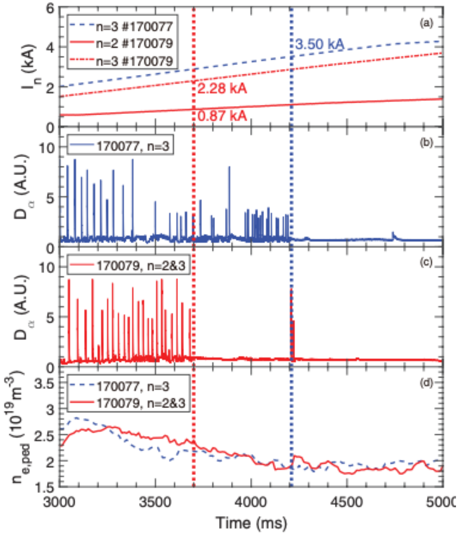
- ITER plans to utilize the edge response of 3D field to control edge localized modes.
- Edge response of **n=1 error field (EF)** can be beneficial for tokamak operation.
  - Edge response of n=1 field can lead to ELM suppression
  - Edge response of n=1 EF can have synergy with applied RMP (e.g. ITER: n=1 EF + n=3 RMP).

n=1 edge 3D field (RMP) for ELM suppression

[J.-K. Park et al., NP (2019)]



Synergy of n=2 and n=3 RMP



[S. Gu et al., NF (2019)]

Benefit of lower (n=2) harmonics in n=3 ELM suppression

3.5 kA vs 2.28 kA

(n=3) (n=3)

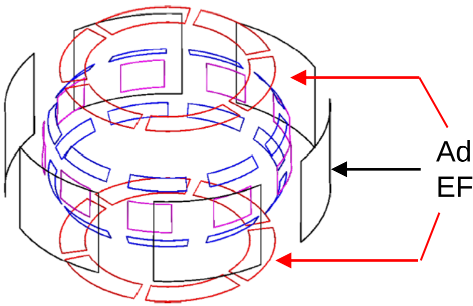
* EF can provide free n=1 or 2

Leveraging edge response of error field

- Standard error field correction focuses on core error field without considering edge response
  - Disruption from core error field is too dangerous
  - ➔ Leveraging error field has been almost prohibited (best option: no EF + RMP)
- But, ITER will have 3 rows of EF correction coils in addition to 3 rows of RMP coils.
  - There will be room to optimize EF spectra in ITER (at least 3 rows)
- High-n RMP will be less efficient in future device as 3D coils need to avoid nuclear degradation of coil.
  - Use multiple toroidal harmonics (e.g., n=1 edge EF + n=3 RMP)
  - Low-n RMP for ELM control will be more efficient

3D coils planned for ITER

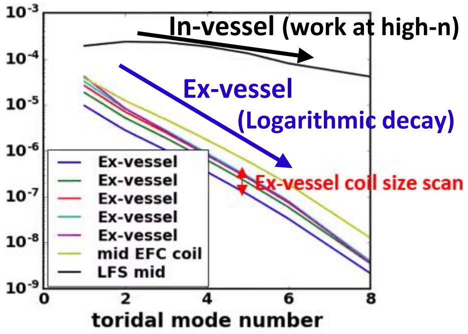
[Weisberg et al., NF 2019]

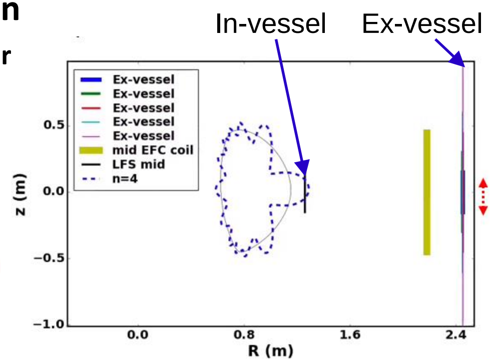


Additional 3 rows EF correction coils

COMPASS-U ex-vessel coil size scan

RMP coupling vs Toroidal mode number





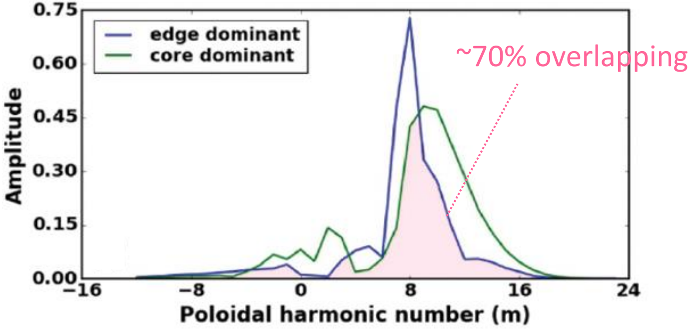
KSTAR

Plasma response is challenge in tailoring error field

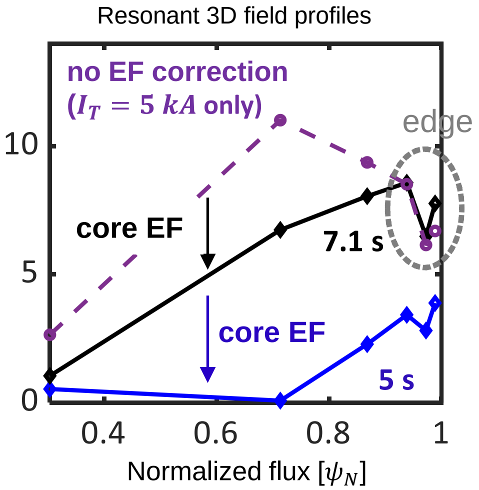
- Core and edge 3D response is highly coupled in tokamak due to plasma response.
  - Core error field reduction ~ edge error field reduction
- A systematic approach can minimize core response and maximize edge response by introducing core-null space projection, $\overleftrightarrow{P}_{c,null}$ [S.M. Yang et al., NF, 2020].
  - Edge and core resonant response as coupled damped oscillators.

Typical core/edge 3D response in tokamak

- Extensive overlap between core and edge



Tailoring error field based on the IPEC response


Resonant 3D field profiles

Outline

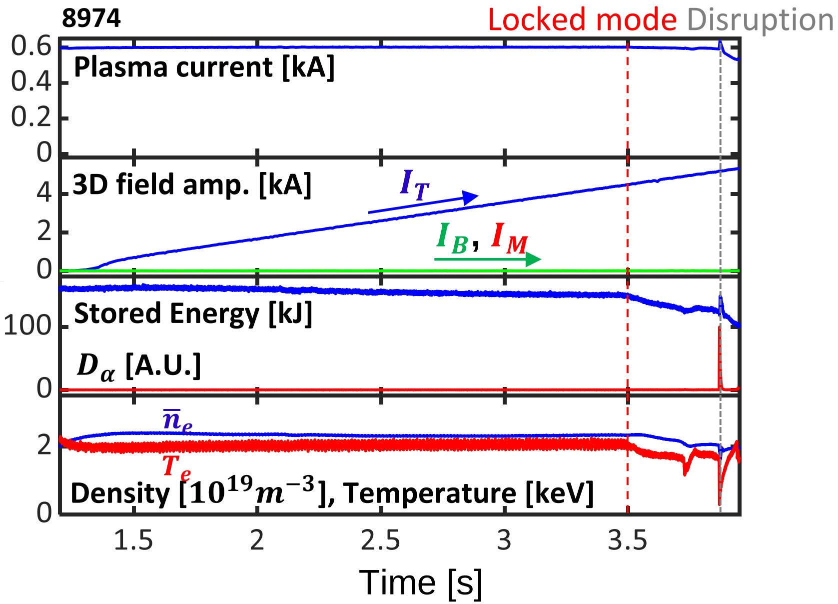
- Tailoring tokamak error field

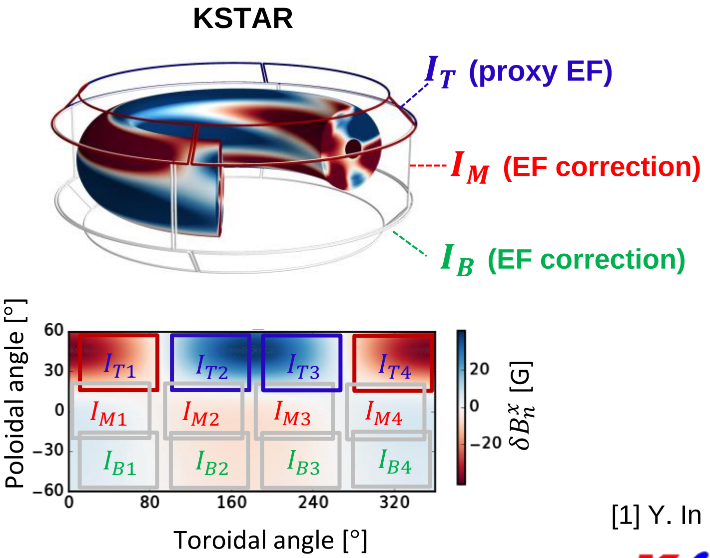
- Application of proposed error field correction (EFC)
  - EFC to control edge localized mode instability
  - EFC to control edge plasma transport
  - Other applications

- Summary

Error field correction for ELM control in KSTAR

- Error field correction to suppress ELMs are tested in KSTAR.
- Due to low intrinsic EF in KSTAR [1], $\boldsymbol{I_T = 5\ kA}$ is used as a proxy n=1 error field.
  - $\boldsymbol{I_T = 5\ kA}$ typically locks low density L-mode KSTAR plasmas.
- Other arrays ($\boldsymbol{I_B}$, $\boldsymbol{I_M}$) are used for n=1 error field correction (more flexibility in ITER)

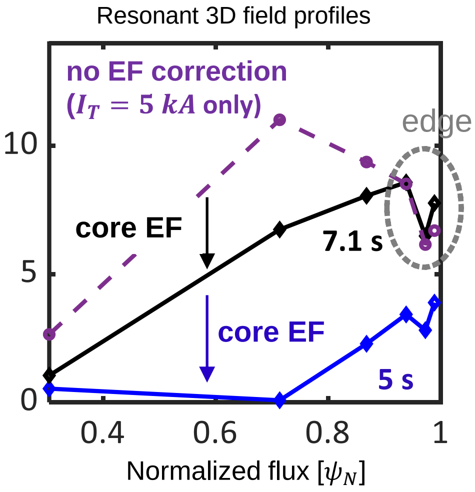


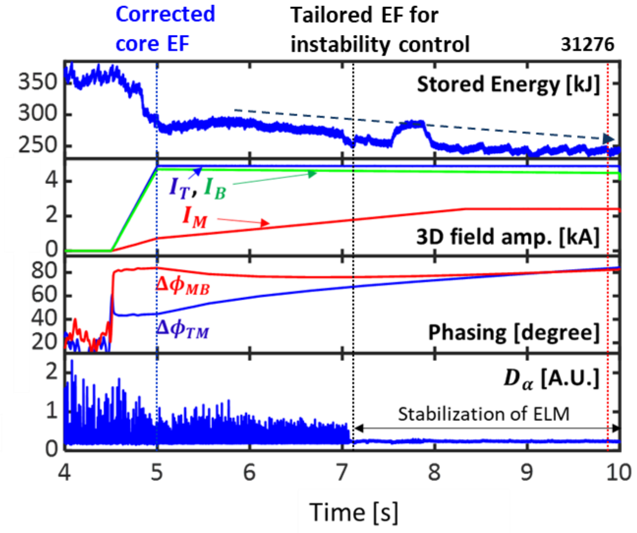


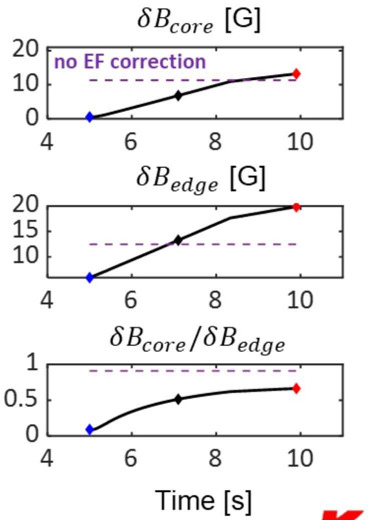
[1] Y. In et al., NF (2015)]

Error field correction for ELM control

- Error field correction is designed to reduce core($\psi_N < 0.9$) while maintaining edge response.
  - Decrease core EF ($\delta B_{core}, \psi_N < 0.9$) to avoid locked mode
  - Increase (maintain) edge RMP (δB_{edge}) for ELM control
- EF correction ($\boldsymbol{I_M}$, $\boldsymbol{I_B}$, $\boldsymbol{\Delta\phi_{MB}}$, $\boldsymbol{\Delta\phi_{TM}}$) adjusted to reduce $\delta B_{core}/\delta B_{edge}$ for ELM control.

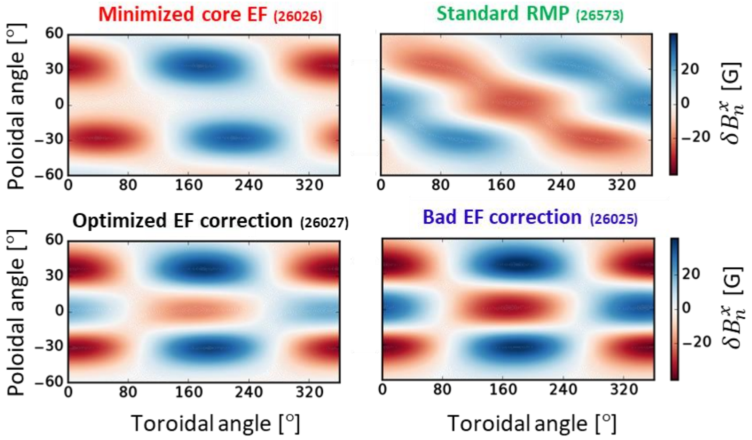


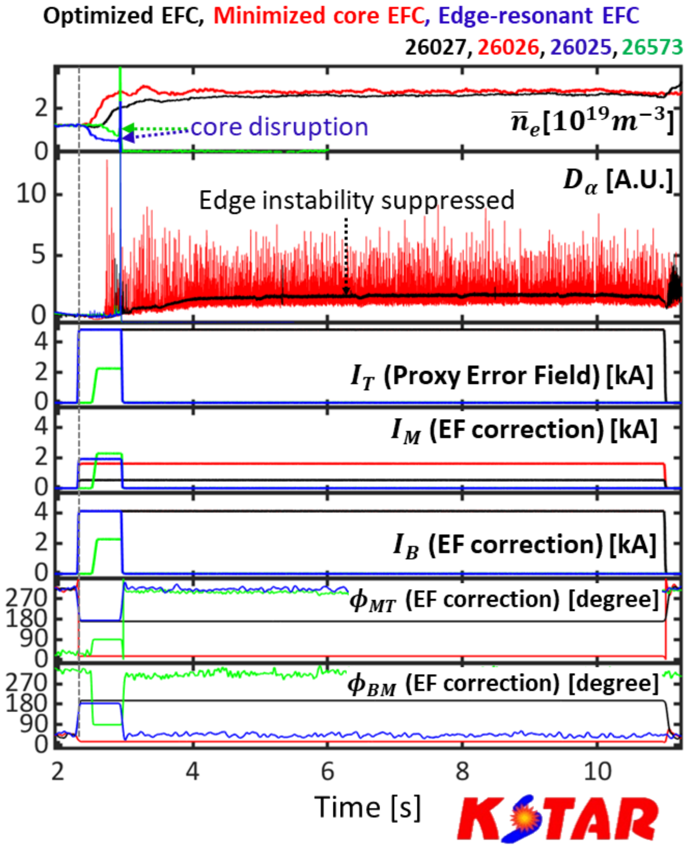




Optimized EFC avoids locking at low density and suppresses ELMs

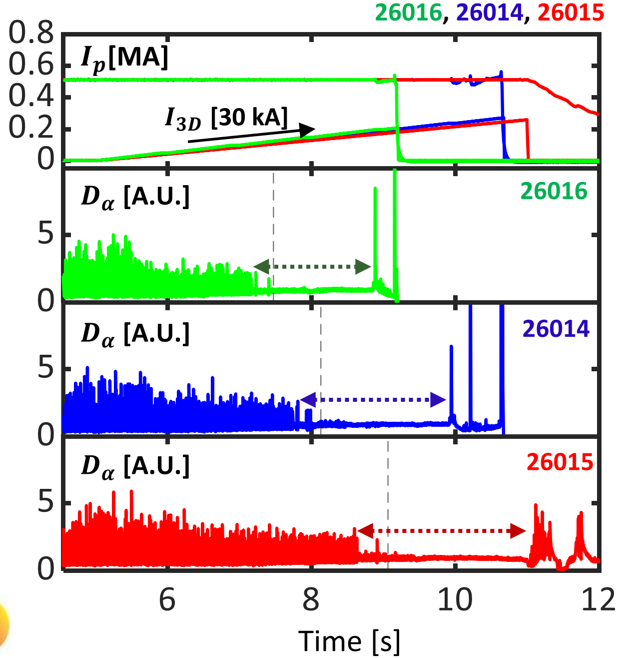
- **Optimized EFC** safely avoid locking at low density $\bar{n}_e \sim 1 \times 10^{19} m^{-3}$, while suppressing ELMs in H-mode.
- Standard EFC does not leave enough edge resonance
  (ELM should be controlled using the additional method)
- Standard RMP and Edge-resonant EFC leave too much core EF -> disruption.
- This error field correction is different from typical RMP

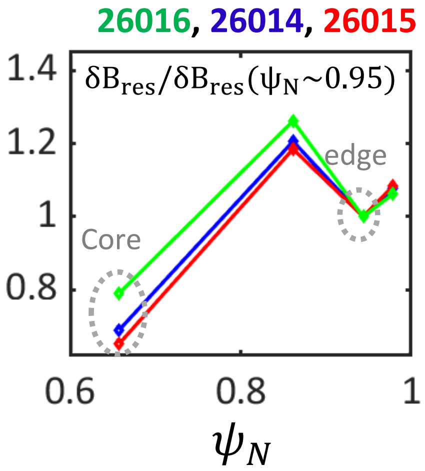


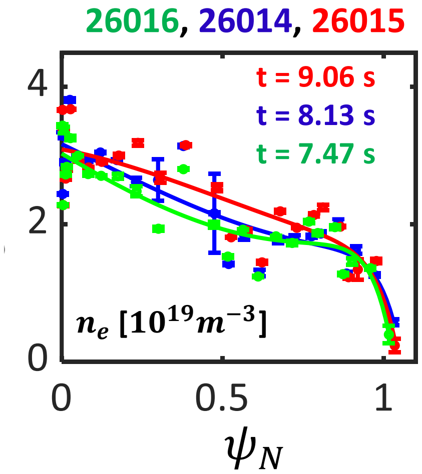


Improved confinement of RMP-ELM suppression

- Also, three different 3D spectra with different edge localization are applied for ELM suppression
==> Slowly ramped to compare profile after ELM suppression
- Edge localization (26015) leads less confinement degradation than other cases (26016)

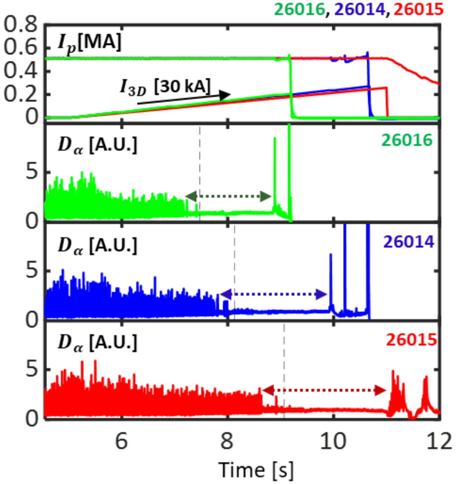


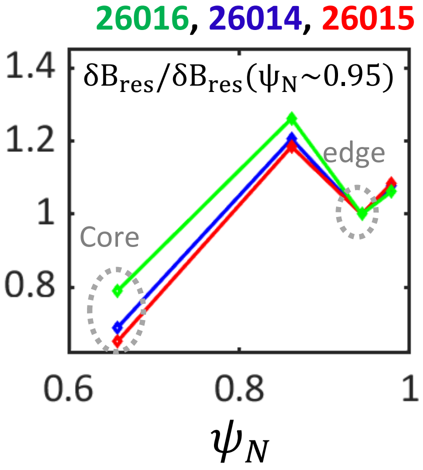


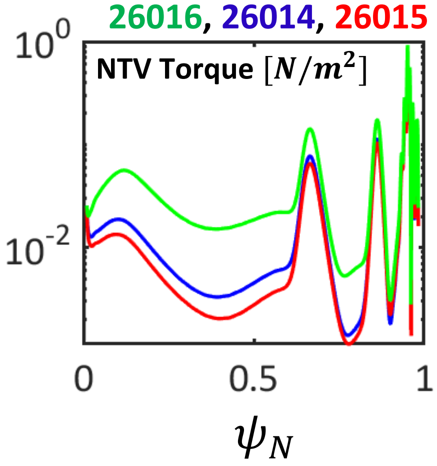


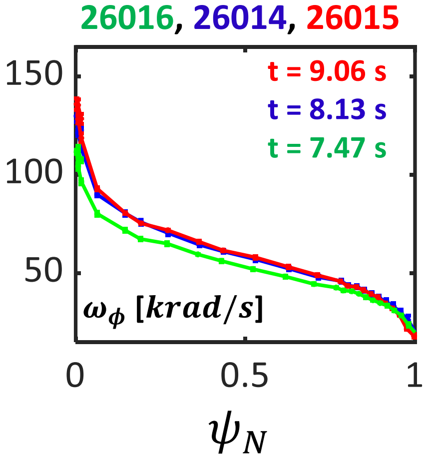
Improved confinement of RMP-ELM suppression

- Also, three different 3D spectra with different edge localization are applied for ELM suppression
  ==> Slowly ramped to compare profile after ELM suppression
- Edge localization (26015) leads less confinement degradation than other cases (26016)



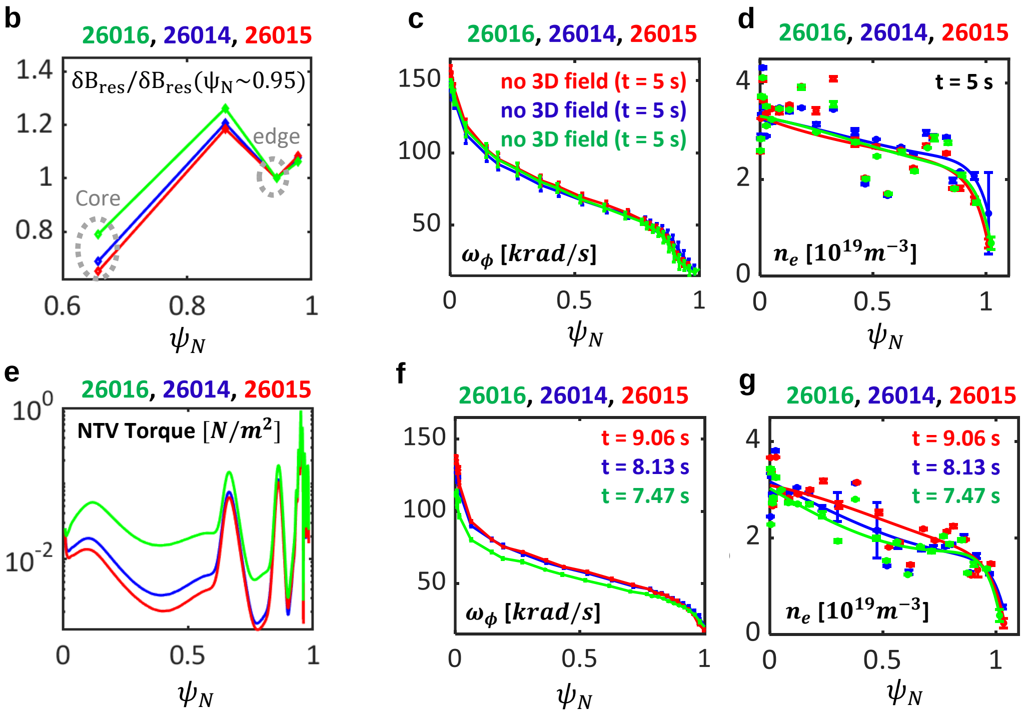






Back up: Improved confinement of RMP-ELM suppression

- Also, three different 3D spectra with different edge localization are applied for ELM suppression
  ==> Slowly ramped to compare profile after ELM suppression
- Edge localization (26015) leads less confinement degradation than other cases (26016)

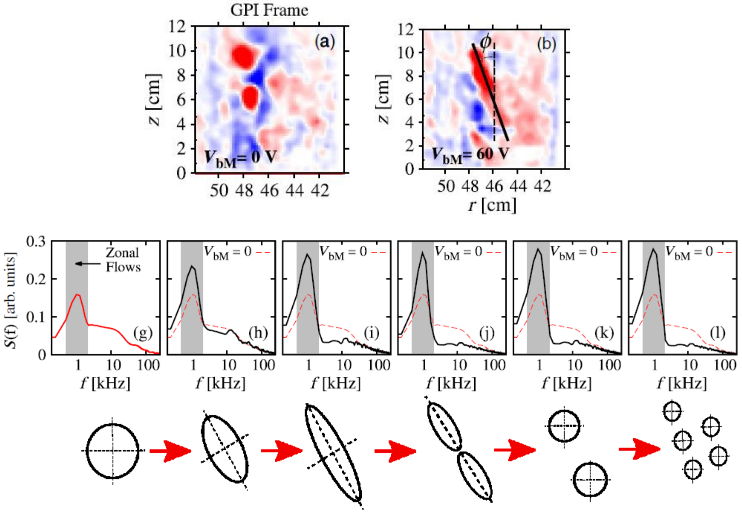


Outline

- Tailoring tokamak error field
- Application of proposed error field correction (EFC)
  - EFC to control edge localized mode instability
  - **EFC to control edge plasma transport**
  - Other applications
- Summary

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.

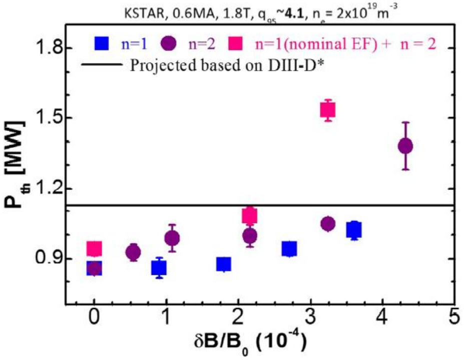


[I. Shesteikov et al., PRL, 2013].

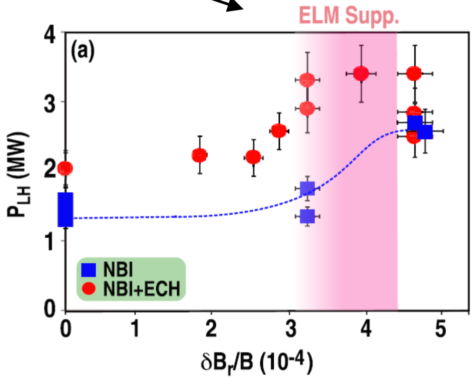
[3D field VS L-H power threshold]

KSTAR

DIII-D



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

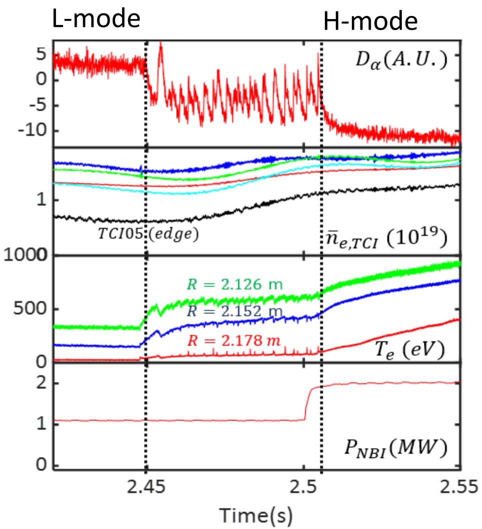


[L. Schmitz et al., NF, 2019]

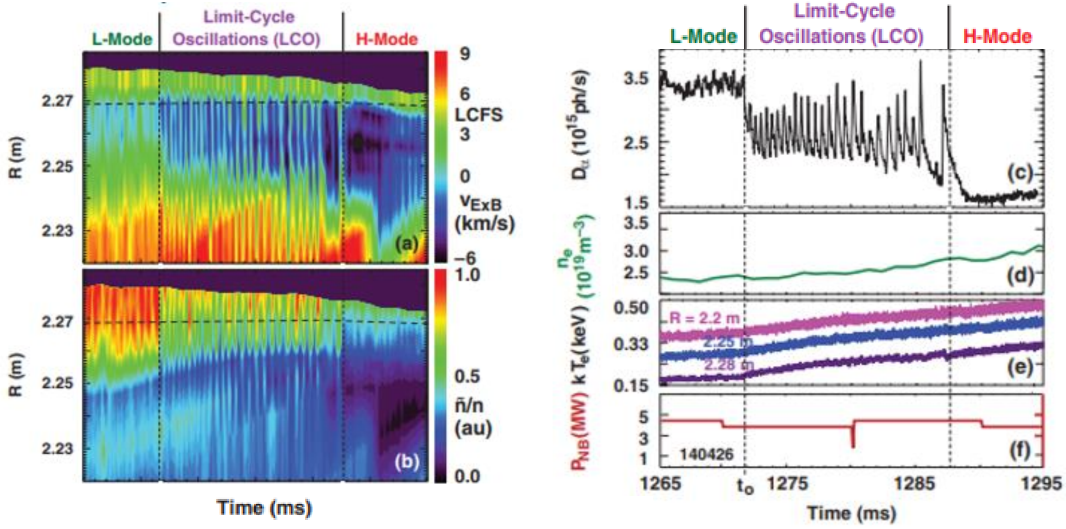
Observation of limit-cycle oscillation before L-H transition

- 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]



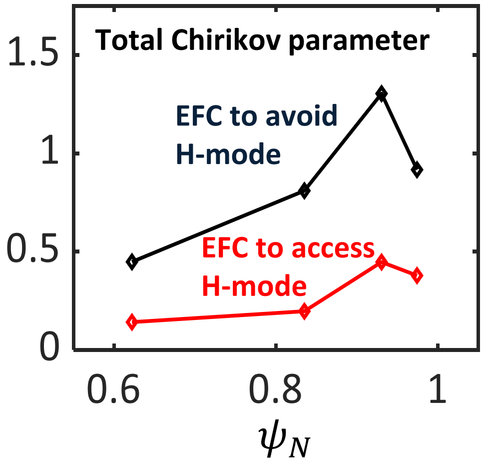
[Zonal flow oscillation in DIIID]



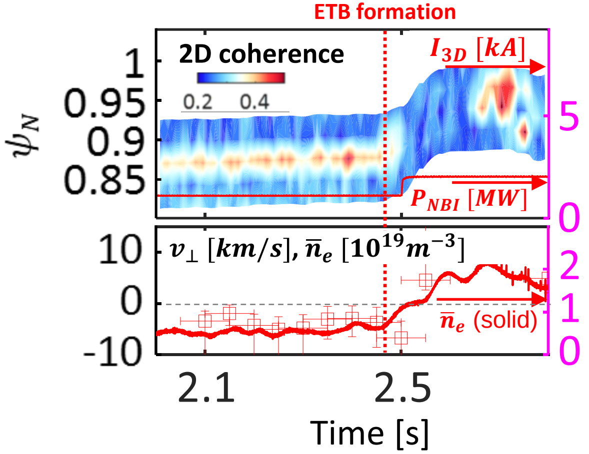
[L. Schmitz et al., PRL 2012]

Tailoring error field to access/avoid H-mode

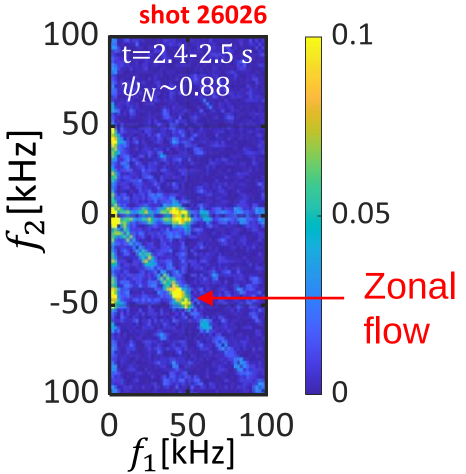
- Tailoring n=1 error field can lead to efficient H-mode transition with zonal flow/turbulence interaction
  - **At 1.1 MW,** by removing edge/core error field in the error field correction
- Tailoring error field can prevent H-mode transition with increased turbulence, less zonal flow.
  - At 2.0 MW, by leaving edge error field in the error field correction
- Error field correction (EFC) should consider plasma response to control H-mode access. (Vacuum vs total)



EFC to access H-mode (26026, at 1.1 MW)

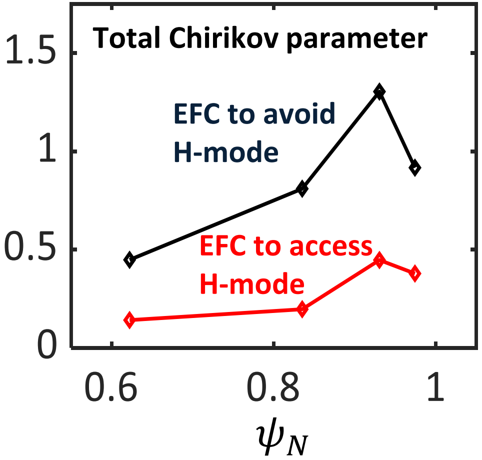


Zonal-flow turbulence interaction



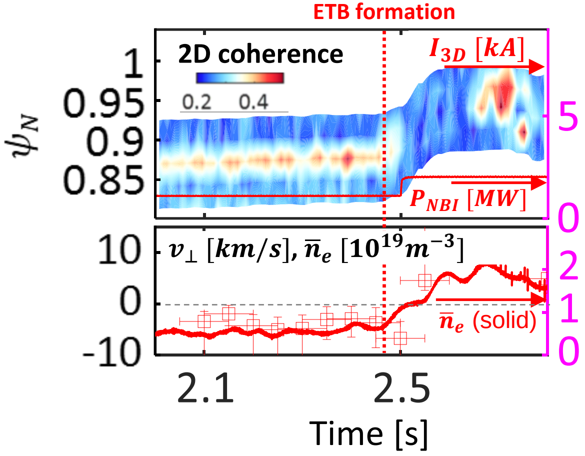
Tailoring error field to access/avoid H-mode

- Different error field correction applied at 2.2 s (EFC to access vs avoid H-mode)
- Tailoring n=1 error field can lead to efficient H-mode transition with zonal flow/turbulence interaction
  - **At 1.1 MW,** by removing edge/core error field in the error field correction
- Tailoring error field can prevent H-mode transition with increased turbulence, less zonal flow.
  - At 2.0 MW, by leaving edge error field in the error field correction



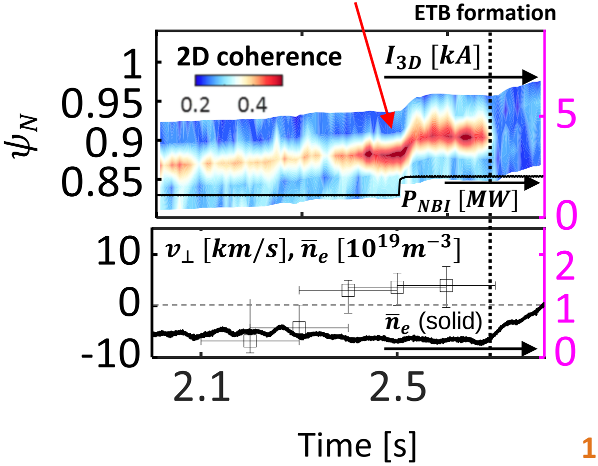
H-mode at lower heating (1.1 MW)

- No edge turbulence change



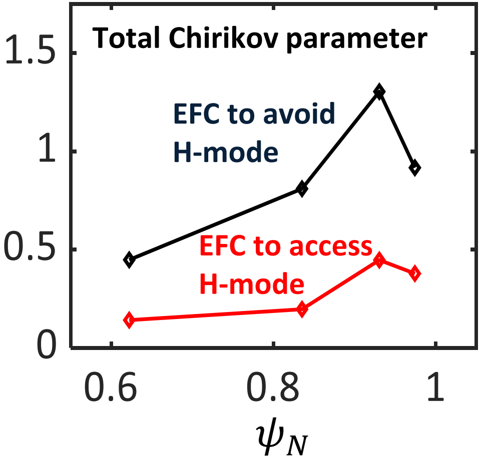
H-mode at higher heating (2.0 MW)

- Edge turbulence increased

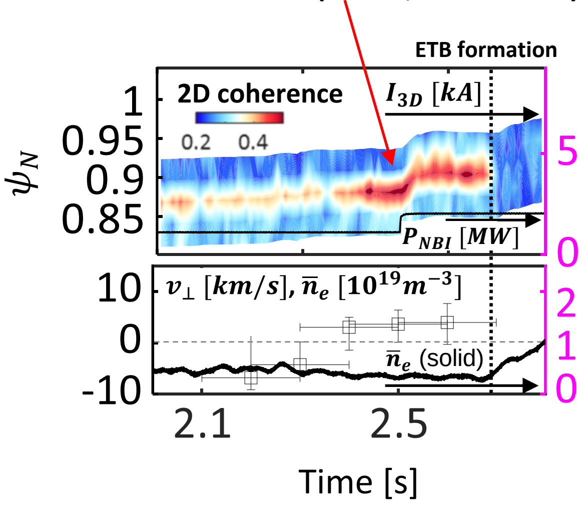


Tailoring error field to access/avoid H-mode

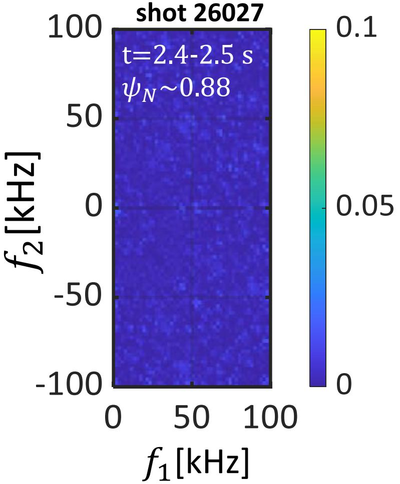
- Different error field correction applied at 2.2 s (EFC to access vs avoid H-mode)
- Tailoring n=1 error field can lead to efficient H-mode transition with zonal flow/turbulence interaction
  - **At 1.1 MW,** by removing edge/core error field in the error field correction
- Tailoring error field can prevent H-mode transition with increased turbulence, less zonal flow.
  - At 2.0 MW, by leaving edge error field in the error field correction



EFC to avoid H-mode (26027, at 1.1 MW)



No zonal-flow turbulence interaction

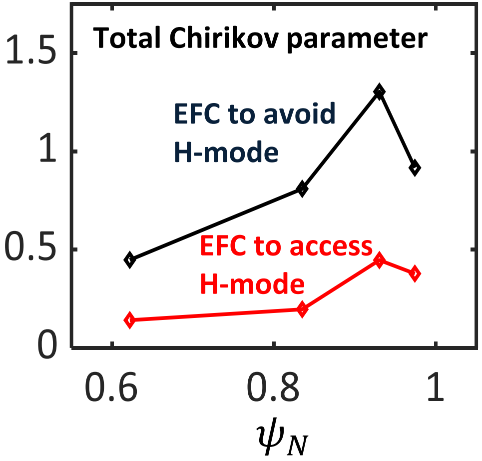


Tailoring error field to access/avoid H-mode

- The experiments shows importance of edge response of error field in error field correction (EFC).
  - EFC to access H-mode: edge response should be minimized in EFC
  - EFC to avoid H-mode: edge response should be maximized in EFC
- Note that plasma response should be considered in this error field correction (EFC)

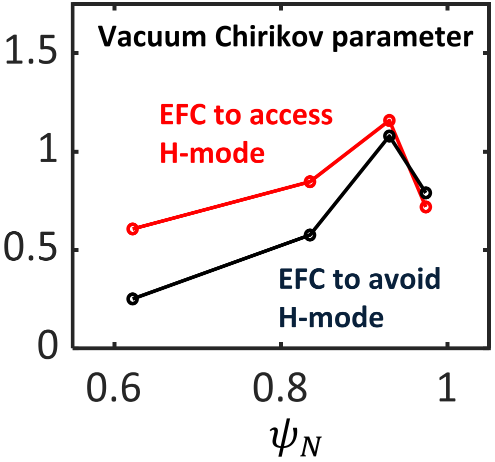
With plasma response

- Stronger edge response to avoid H-mode
  => Agrees with experiment



Without plasma response

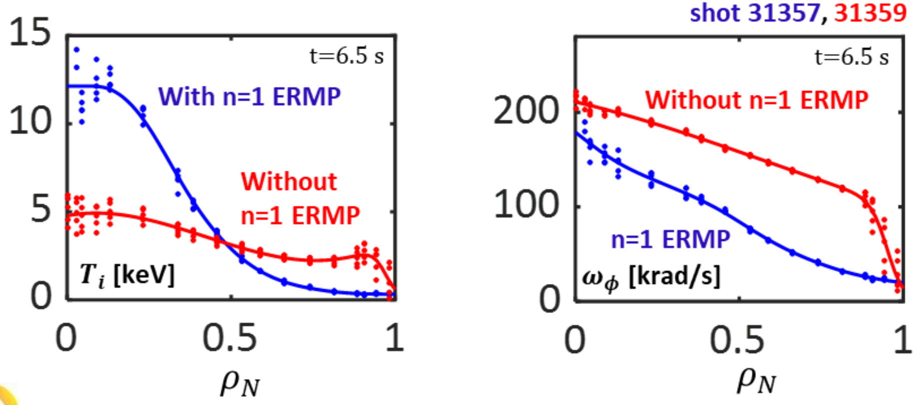
- Weaker edge response to avoid H-mode
  => Does not agree with experiment



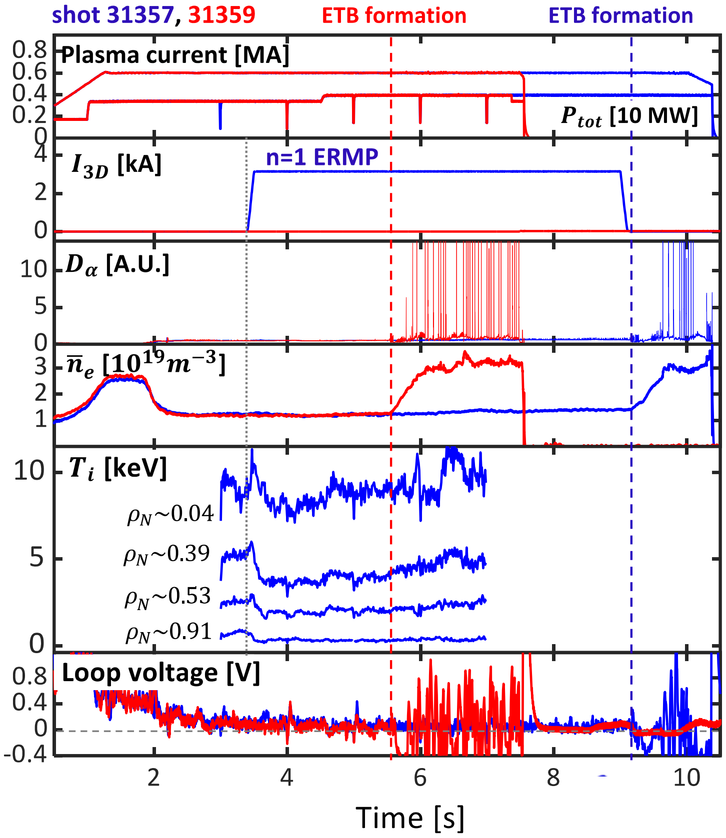
Application: H-mode avoidance to sustain high T_i regime

- There are alternative scenarios that needs to avoid H-mode transition.
  - (e.g. FIRE mode, negative-D, ITB, etc…)
- N=1 ERMP is applied in KSTAR to avoid the L-H transition with improved core confinement.
  - Operates at low density without locking

    $(\bar{n}_e \sim 1.2 \times 10^{19} m^{-3})$
  - Avoid H-mode transition



[Courtesy of Y.M. Jeon (KFE)]



Outline

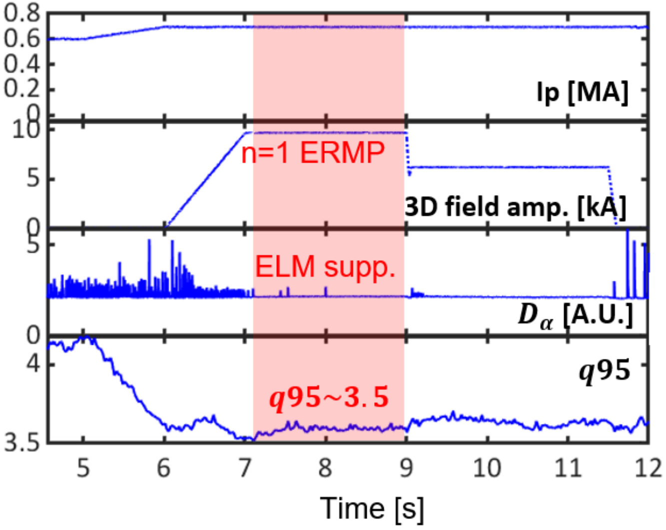
- Tailoring tokamak error field
- Application of proposed error field correction (EFC)
  - EFC to control edge localized mode instability
  - EFC to control edge plasma transport
  - Other applications
- Summary

Application: Extending operation window of n=1 ELM suppression

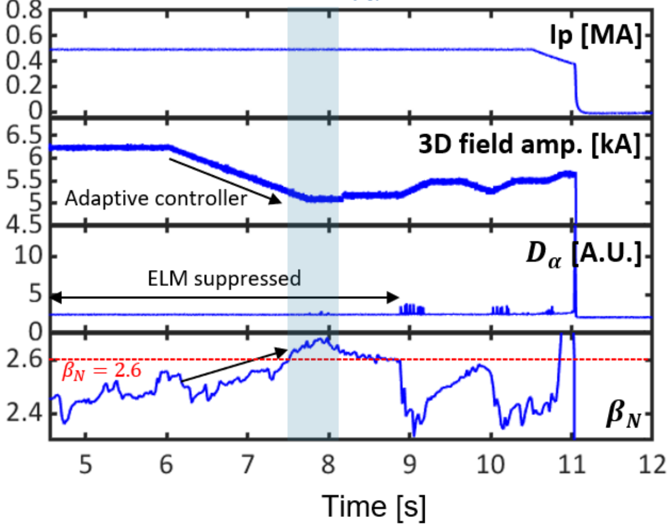
- Edge localization also expanded operation of n=1 RMP-ELM suppression in β_N and q_{95} in KSTAR

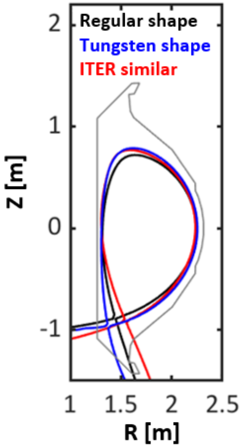
- ITER relevant q_{95} around 3.5 for the first time [Courtesy of S.K. Kim and S.H. Hahn (KFE)]
- β_N above 2.6 [M. Kim et al., submitted to Nuclear fusion]

n=1 ELM suppression



Record β_N

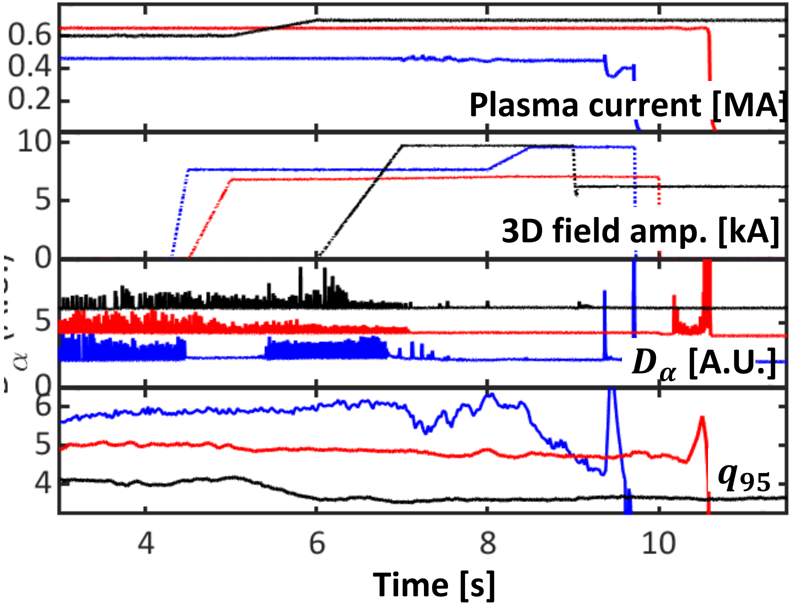




Application: Extending operation window of n=1 ELM suppression

- Edge localization also expanded operation of n=1 RMP-ELM suppression in β_N and q_{95} in KSTAR

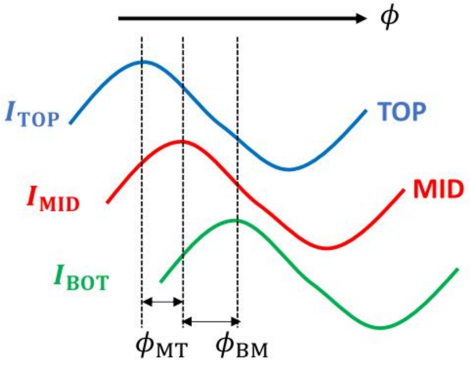
  - n=1 ELM suppression at various q_{95} ($\boldsymbol{q_{95}\sim3.5}$, $\boldsymbol{5}$, $\boldsymbol{6}$)

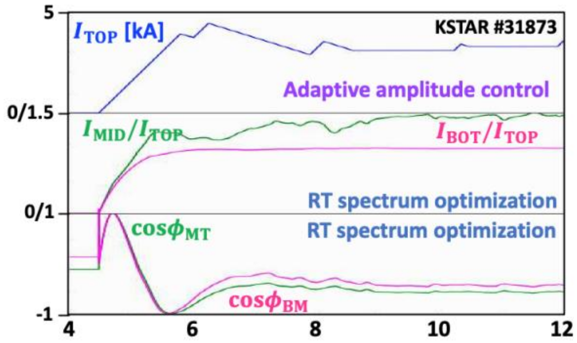


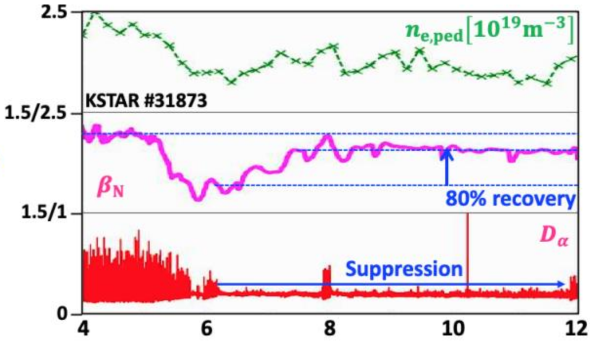
Application: Physics basis of real-time ELM controls

- The proposed scheme becomes physics basis of machine learning
  -> Accelerates 3D spectrum optimization for real-time RMP-ELM control.
- The real-time controller successfully controls ELM with recovered confinement

[Courtesy of S.K. Kim]

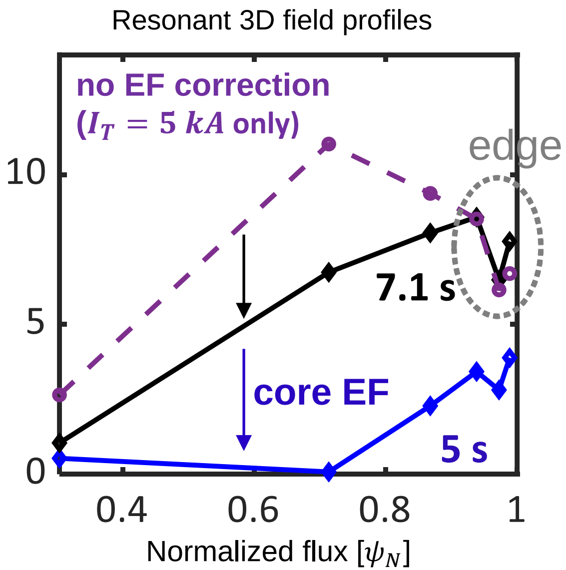






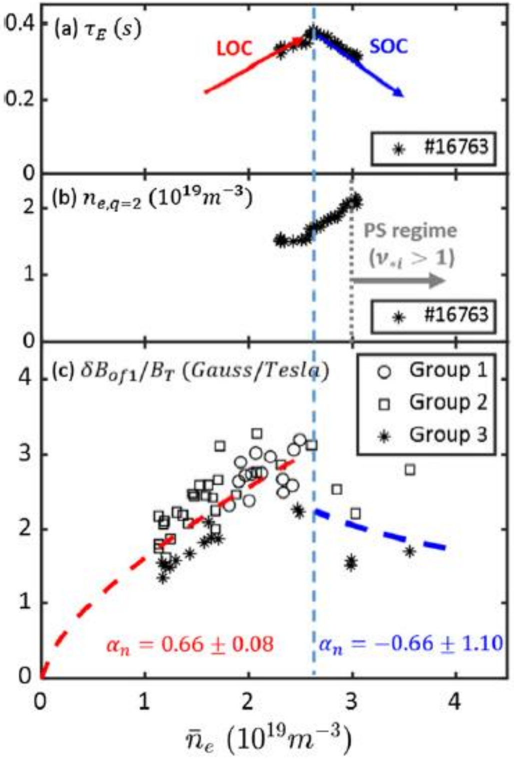
Conclusion

- Systematic scheme tailors tokamak error field to control instability and transport.
  - Add additional edge 3D response for ELM control
  - Controls H-mode access/avoidance
- Proposed edge localization is also beneficial in RMP
  - Safer low-n RMP ELM suppression to extend operation windows
  - Optimizes confinement ELM suppressed H-mode
- This implies that error field can be favorably used in tokamak as long as we have flexibility to control spectrum of error field.


Resonant 3D field profiles

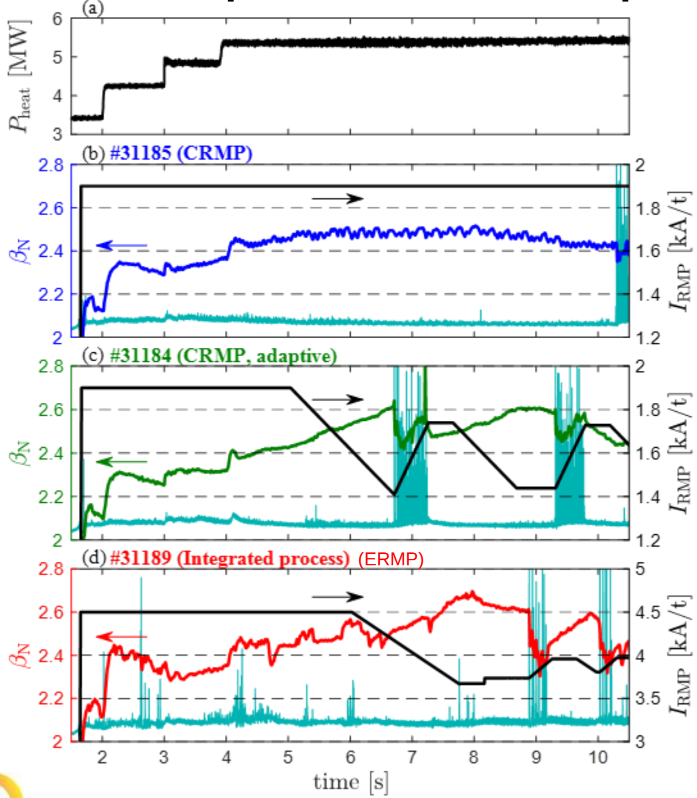
END

[Density dependence of error field thresholds in KSTAR]

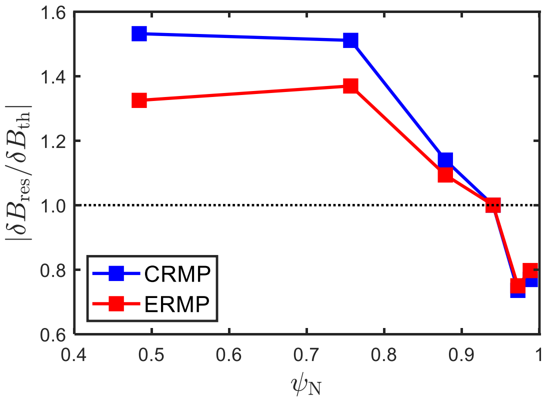


[Yang et al., NF (2021)]

Improved plasma confinement with edge localization



[M.W. Kim et al., NF submitted]

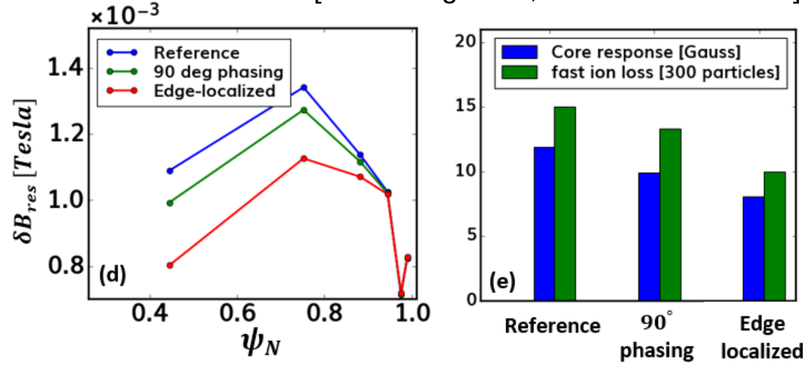


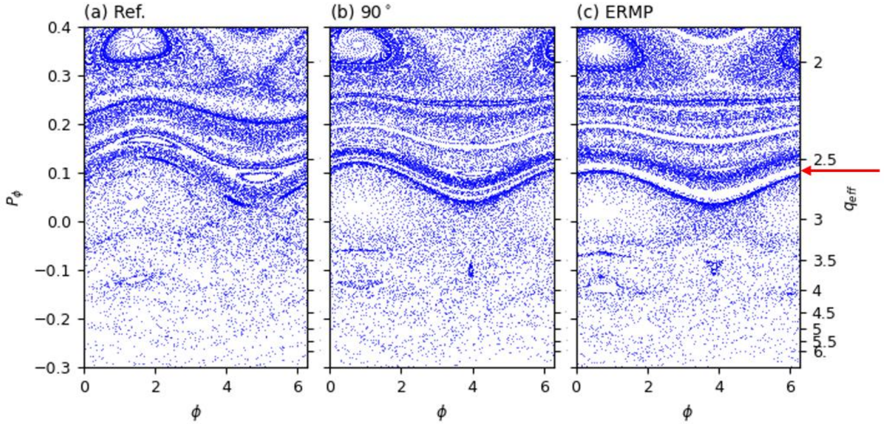
- Comparison of CRMP and ERMP shows confinement improvement with ERMP

  - $\boldsymbol{\beta_N = 2.6}$ achieved only with ERMP
  - CRMP couldn't get this β_N
  - Edge localization improved at high β_N
  - Physics can be related to fast ion

Improved fast particle confinement with edge localization

[S.M. Yang et al., NF to be submitted]





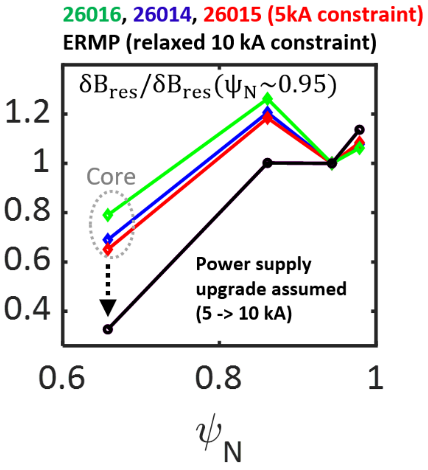
KAM surface that improves fast particle confinement

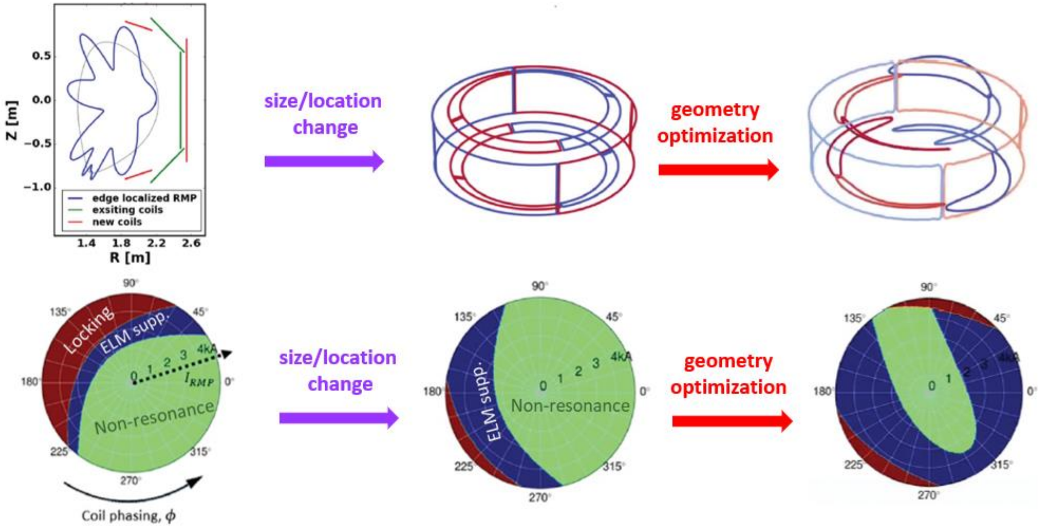
- With a reduced core RMP response, the simulation shows a reduction of fast ion loss.
  - Due to good KAM surface with ERMP

- Simulation implies that ELM suppression can be maintained with improved fast ion confinement by core RMP reduction.

Edge localized RMP guides 3D coil design

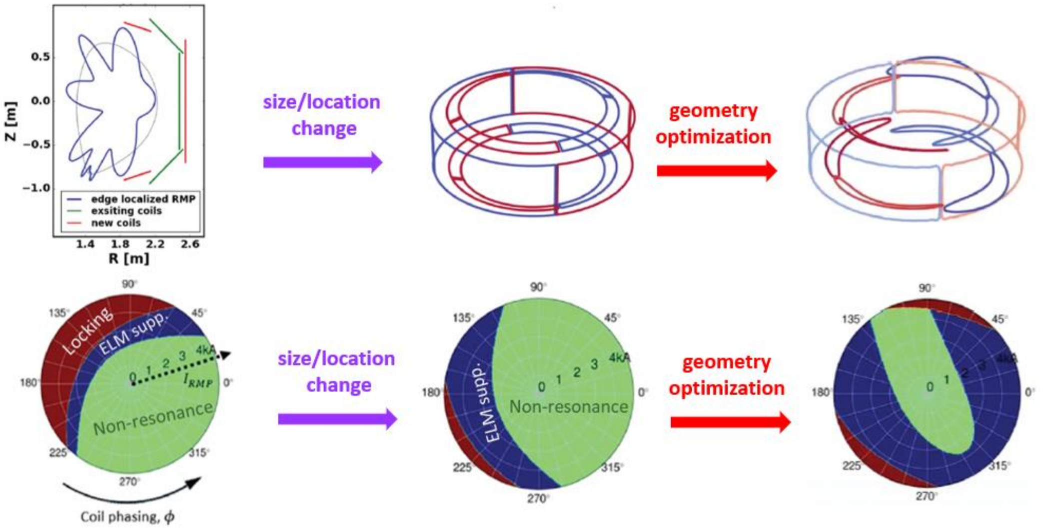
- Edge localization provides a physics basis for designing EFC and RMP coils.
  - Due to engineering constraints of 3D coils, there are still remaining core resonant fields even with systematic edge localization.
  - Coil power supply upgrade from 5 to 10 kA can reduce this unnecessary component.





Edge localized RMP guides 3D coil design

- Edge localization provides a physics basis for designing EFC and RMP coils.
- For example, improvement of confinement and safety of ELM suppression can be possible.
  - Modified coil size and location of existing KSTAR coils (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)



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)