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Quasi-symmetric error field correction in tokamaks

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Overview

- Background: Non-axisymmetric error field control (EFC) in tokamaks
  - Recent progress on resonant EFC
  - Issue with residual magnetic perturbations after resonant EFC

- Modeling: EFC optimization towards quasi-symmetric (QS) residuals
  - Minimization of variation in field strength and 3D neoclassical transport
  - Optimization via torque response matrix

- Experiment: Testing quasi-symmetric magnetic perturbations (QSMP)
  - In comparison with RMPs and NRMPs in KSTAR and DIII-D
  - Safety of QSMPs during transient phase

- Summary and outlook

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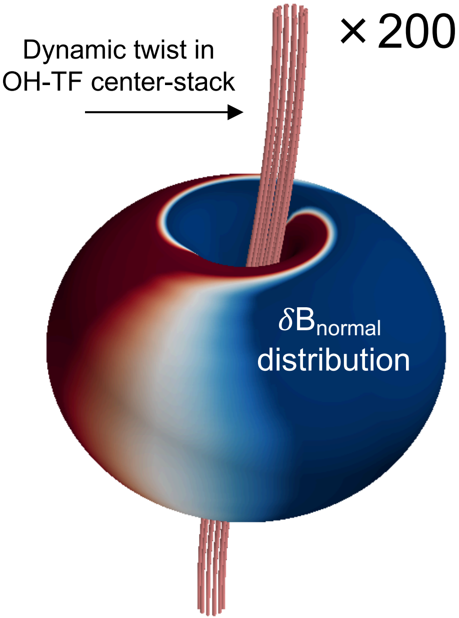
A small non-axisymmetric magnetic field can greatly change tokamak performance and thus must be under control

- A tokamak has always intrinsic non-axisymmetric (3D) error fields (EF)
  - Due to imperfect magnets and components
- A 3D field can also be introduced on purpose
  - Mostly for instability control, as highlighted by ”RMP ELM control” in tokamaks
- In either case, a 3D field as small as $\delta B/B=10^{-3}\sim10^{-4}$ can greatly degrade or even disrupt tokamak plasmas, if not properly controlled or judiciously used
- Any dangerous or unnecessary 3D field components must be compensated

NSTX Example

Error fields driving locked modes



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  → Error Field Correction (EFC)

<u>NSTX Example</u>

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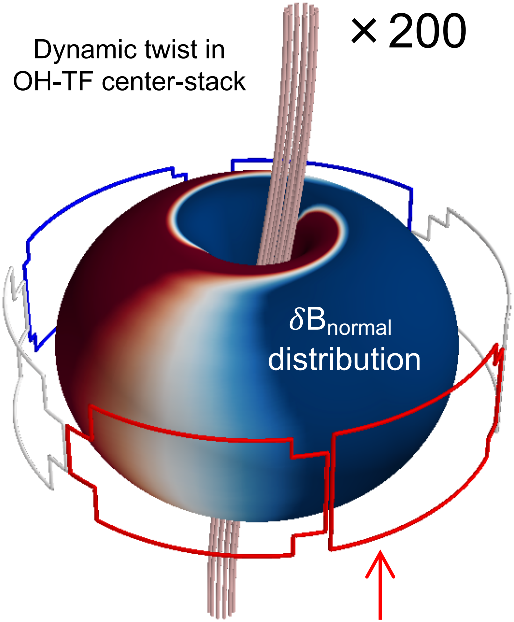
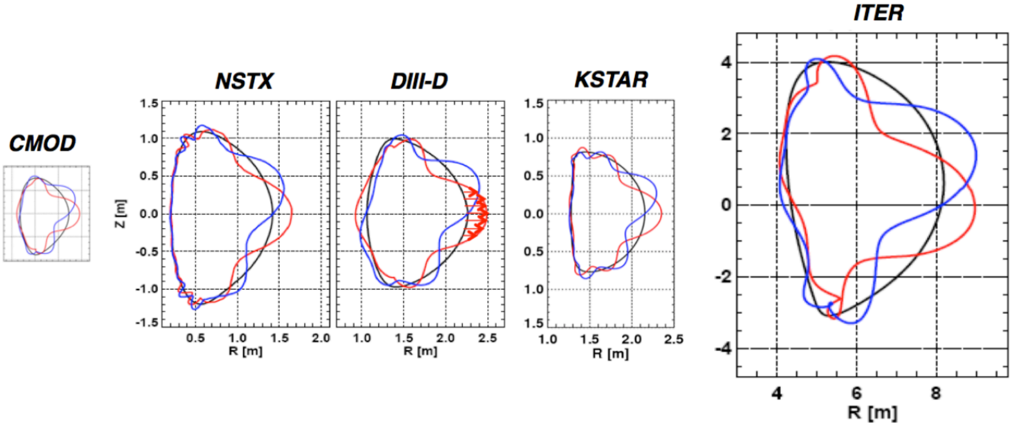


Error field correction leading to better performance

Recent progress on plasma response and MHDs is offering a reliable leading-order EFC scheme

Shape of dominant resonant field distribution

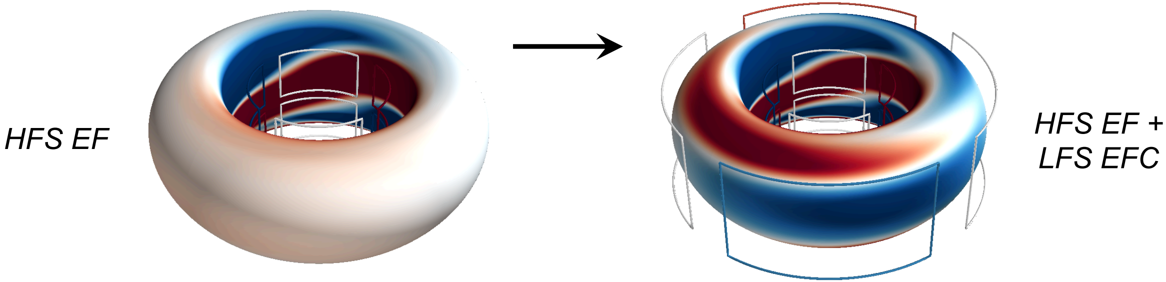


- Ideal MHD clearly shows which 3D field is most resonant with tokamak plasmas and thus must be compensated if not necessary
  - Leading to a major change in EFC approach, via “resonant overlap” field
    - Extensively validated in tokamak devices including DIII-D [LanctotPOP10, Paz-SoldanPOP14]
- Present ITER EFC strategy: Reduce overlap with dominant resonant field below “EF penetration” threshold
  - Two-fluids MHDs then can offer prediction of EF penetration threshold in practice
    - See N. Logan’s poster for resonant EFC summary [TM1 (Hu), EPEC (Fitzpatrick)]

Residual EFs may not be disruptive in stable operating conditions but shown to be still problematic transiently

- COMPASS studies with the high-field-side proxy-EF show
  - Locked modes could indeed be avoided by resonant EFC, but large non-resonant residual EFs could still be disruptive during L-H transition [MarkovicEPS2018]

Successful EFC against locked modes but not for L-H transition



- NSTX-U and DIII-D also showed that NTV rotational damping by residual EFs which can eventually cause instability issues [Paz-SoldanPOP14, ParkAPS18]

Needs a complementary EFC approach

for residual EFs which often have greater non-axisymmetry and create non-linear effects

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Minimizing all the prominent residual EF effects reminisces optimization towards a quasi-symmetry

- Eliminating all static EF effects in guiding center plasmas is in principle achievable by:

Variation in the field strength $\left|\delta\vec{B}\right|_{particles} \rightarrow 0$ [NurenbergPLA88,BoozerPPCF95]

- Ideally, there is a linear path to perturb a tokamak while holding this condition:
- However, it is the force balance in plasma that dictates the $\vec{\xi}$ profiles

$$\left|\delta\vec{B}\right| \sim \hat{b}\cdot\left(\underbrace{\vec{\nabla}\times\left(\vec{\xi}\times\vec{B}_0\right)}_{\substack{\textit{Eulerian}\\ \textit{changes in a fixed space}}} + \vec{\xi}\cdot\underbrace{\vec{\nabla}B_0}_{\substack{\textit{Lagrangian}\\ \textit{changes with field lines}}}\right) \rightarrow 0 \quad \longleftrightarrow \quad \delta\vec{F}\left[\vec{\xi}\right] = 0$$

- These two are NOT compatible in general

as well known [Garron&BoozerPFB9]
from more general 3D geometry

Nonetheless, quasi-symmetric optimization can be performed in average

Self-consistent perturbed equilibria with neoclassical transport offers a unique QS optimizing scheme, via torque response matrix

- Perturbed equilibria with non-adiabatic pressure (including 3D coils):

$$\delta\vec{F}\left[\vec{\xi}\right] = \delta\vec{F}_{ideal}\left[\vec{\xi}\right] - \vec{\nabla}\cdot\Pi[\vec{\xi}] = 0$$

- Neoclassical torque is also given by integrating:

$$\tau_{\varphi} = Im\left[n\int_{plasma} dx^{3}\left(\vec{\xi}\cdot\delta\vec{F}[\vec{\xi}]\right)\right]$$

- Torque minimization leads minimized 3D neoclassical particle, momentum, heat transport, although its momentum part (called NTV) is mostly pronounced in tokamaks

$$\tau_{\varphi} \propto \Gamma_{NTV} \propto Q_{NA} \sim 0$$

- Full solutions provide torque response matrices to given 3D fields or coils

$$\tau_{\varphi}(\psi) = (Fourier\ modes)^{+}\cdot \boldsymbol{T}(\psi)\cdot(Fourier\ modes)$$

$$= (Coil\ currents)^{+}\cdot \boldsymbol{T_{C}}(\psi)\cdot(Coil\ currents)$$

- Method above has been implemented in general perturbed equilibrium code (GPEC) which has been used as a primary tool to design QSMP configurations

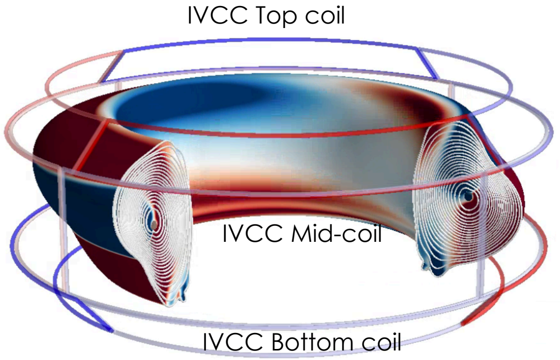
Torque response matrix contains all the information of neoclassical torque that a tokamak can drive with available coils

- All possible neoclassical torque that a tokamak (e.g. KSTAR) can drive using their 3 rows of coils are given by
  - 3x3 matrix, per each n, per a target equilibrium and its kinetic profiles

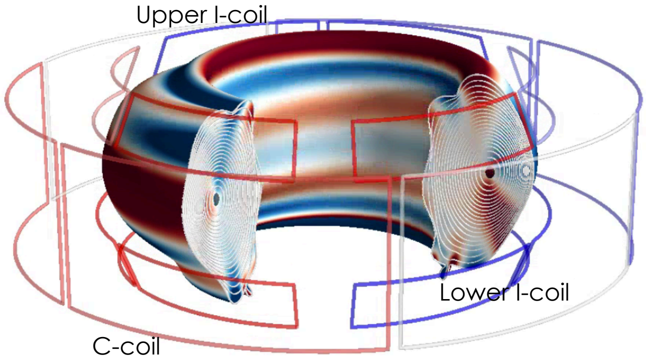
$$\tau(\psi) = \begin{pmatrix} I_T e^{-i\phi_T} & I_M e^{-i\phi_M} & I_B e^{-i\phi_B} \end{pmatrix} \cdot \begin{pmatrix} T_{TT}(\psi) & T_{TM}(\psi) & T_{TB}(\psi) \\ T_{MT}(\psi) & T_{MM}(\psi) & T_{MB}(\psi) \\ T_{BT}(\psi) & T_{BM}(\psi) & T_{BB}(\psi) \end{pmatrix} \cdot \begin{pmatrix} I_T e^{i\phi_T} \\ I_M e^{i\phi_M} \\ I_B e^{i\phi_B} \end{pmatrix}$$

- Its eigenvector for the minimum eigenvalue of the torque-coil response matrix: The best possible quasi-symmetric magnetic perturbation (QSMP) in a tokamak

KSTAR n=1 QSMP



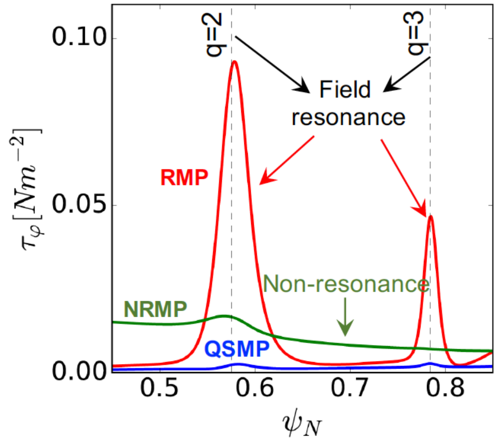
DIII-D n=1 QSMP



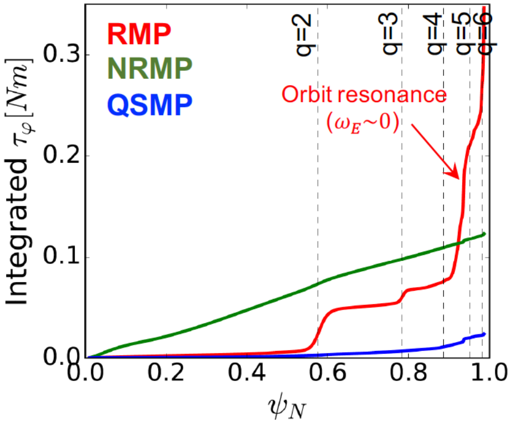
QSMP is clearly contrasted to two other categories of small 3D fields in tokamaks

- RMP creates strong resonant response (at the rational surfaces)
- NRMP can drive substantial non-resonant NTV, but without resonant response
- QSMP suppressed both resonant and non-resonant response
while maintaining the same power norm of field amplitudes or currents

(a-1) KSTAR #22972



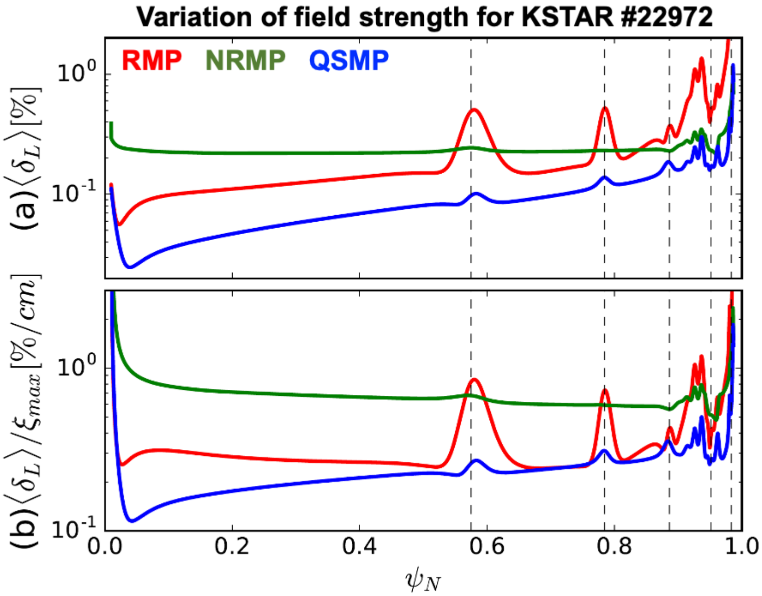
(a-2) KSTAR #22972



QSMP optimized by GPEC indeed minimizes variation in the field strength at best upon constrained by force balance and torque

- GPEC finds the best possible QSMP by minimizing total torque, within force balance
- Resulting in minimization of plasma response and variation in the field strength
- Resulting in optimization of displacement spectrum

$$\delta_L \equiv \frac{|\delta B|}{B_0} = \hat{b} \cdot \vec{\nabla} \vec{\xi} \cdot \hat{b} - \vec{\nabla} \cdot \vec{\xi} \sim 0$$



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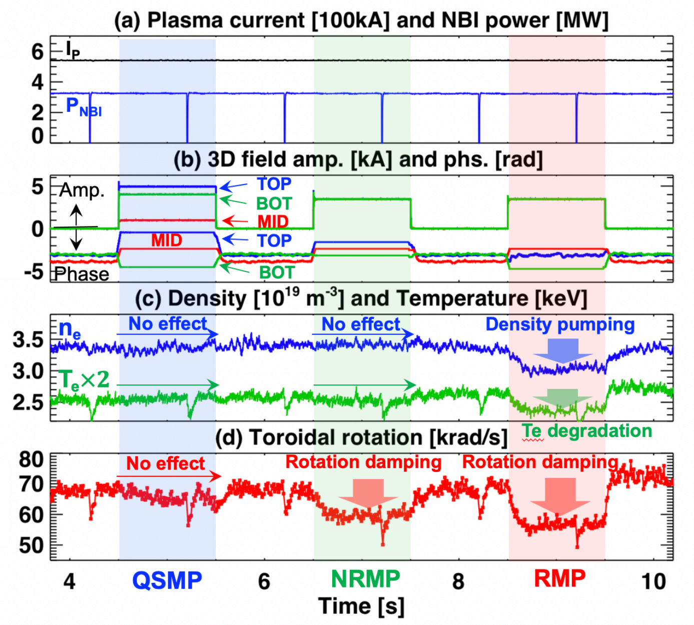
QSMP designed and tested in KSTAR indeed did not bring any meaningful effects despite the large amplitudes

- RMP caused density pumping, confinement degradation, and rotational damping
  - Could suppress ELMs if further optimized
- NRMP induced rotational damping only (without density pump-out)
- QSMP did not show any degradation, even with the maximum currents applied (10kAt)



P_{NBI}~3MW,
T_{NBI}~2.9Nm,
I_P=0.5MA, B_T=1.8T,
β_N~1.8, q_{95}~5,
n_e~3.4e19m^{-3},
T_i(Core)~ 2.2keV,
T_e(Core)~2.3keV,
ω_ϕ~100krad/s

[S. M. Yang, 2019 KSTAR Campaign]

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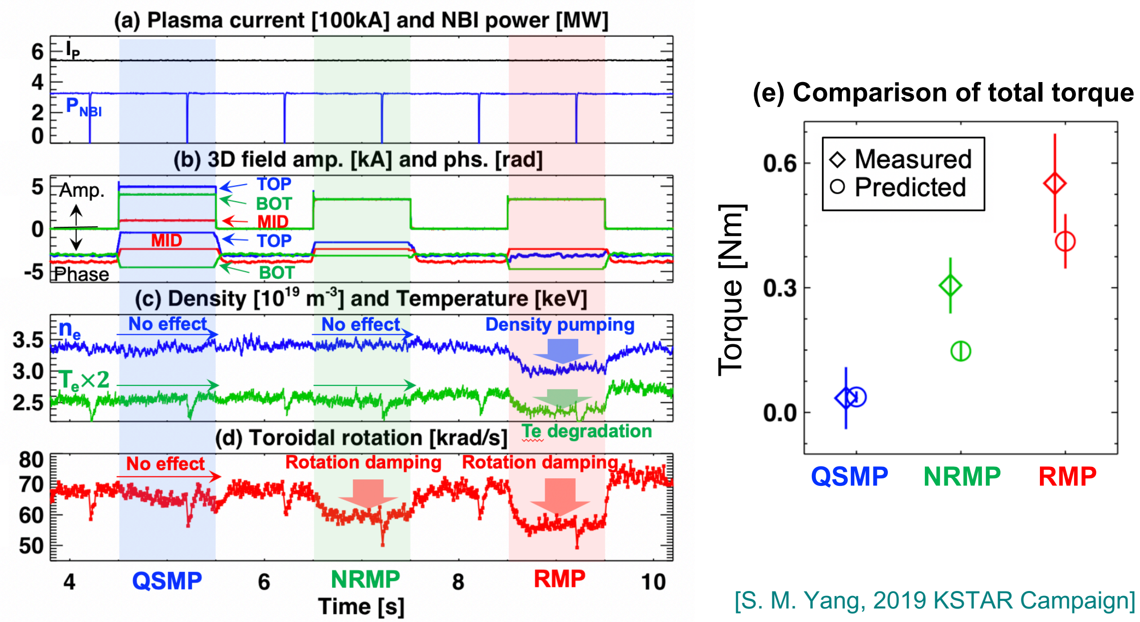
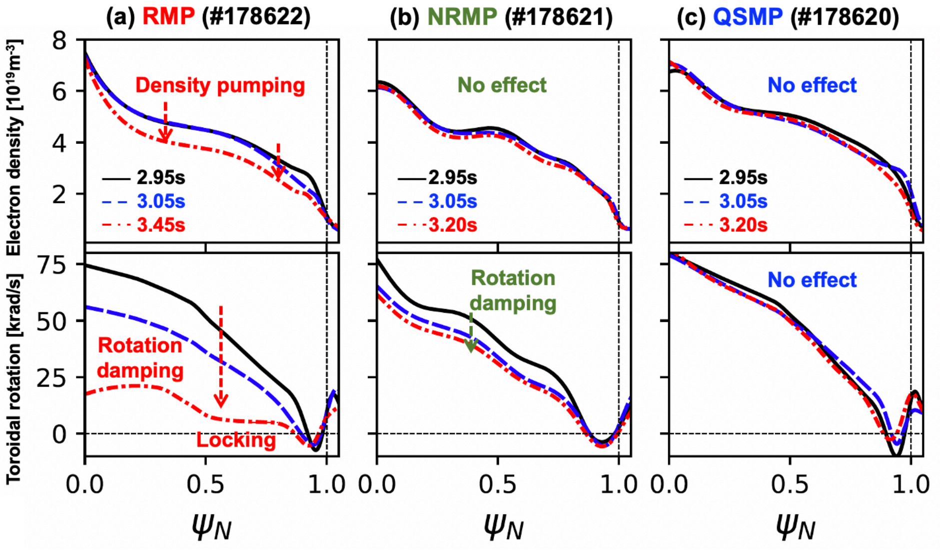


[S. M. Yang, 2019 KSTAR Campaign]

QSMP did not induce any visible effects in DIII-D either despite strong 3D response expected otherwise

- RMP caused density pumping, confinement degradation, and rotational damping
  - Eventually caused a locking due to strong resonant response
- NRMP induced rotational damping only
- QSMP did not show any degradation, despite maximum currents applied (5kAt)



P_{NBI}~8.5MW,
T_{NBI}~6.7Nm,
I_P=1.2MA,
B_T=1.8T,
β_N~3.1,
q_{95}~4.3,
n_e~5.0e19m^{-3},
T_i~6.0keV,
T_e~4.3keV,
ω_ϕ~80krad/s

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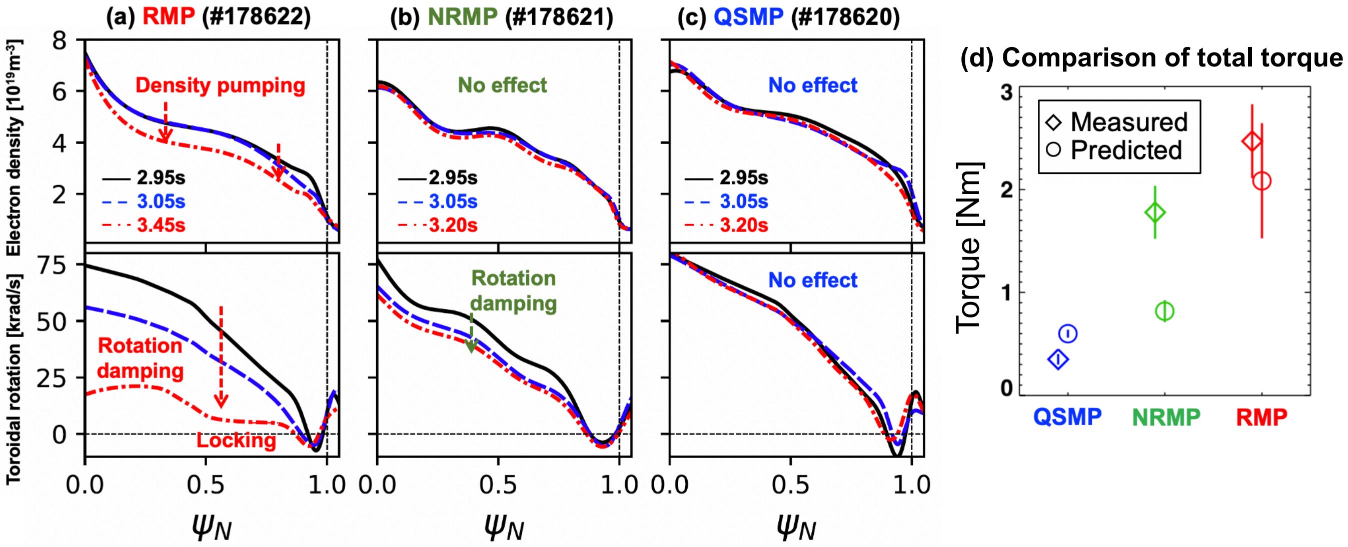
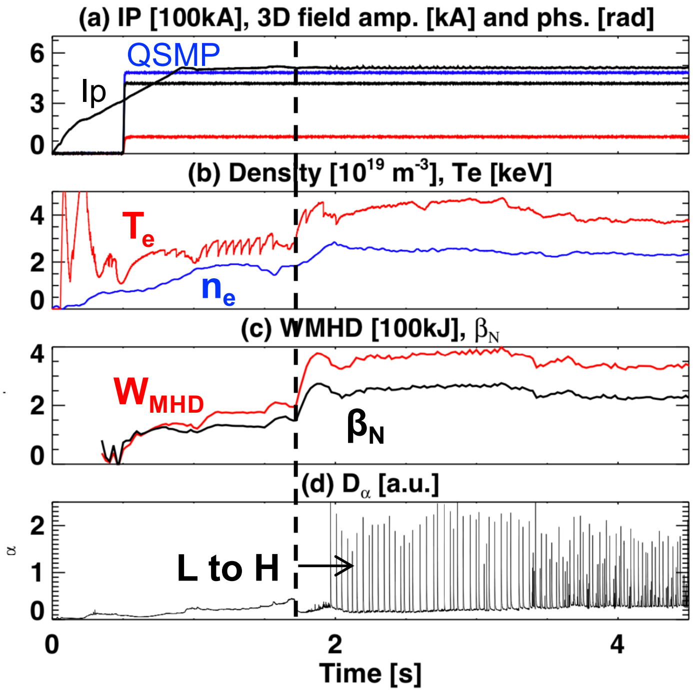


QSMP remains also safe through early ramp-up and L-H transitions

- QSMP for a new 2020 KSTAR target is designed and applied during the ramp-up, with the maximum amplitude

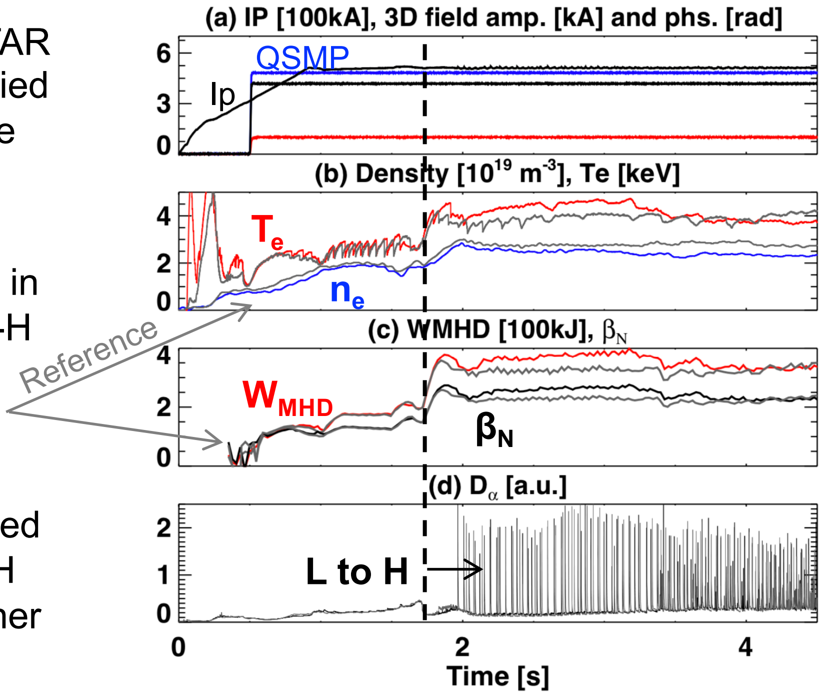


QSMP remains also safe through early ramp-up and L-H transitions

- QSMP for a new 2020 KSTAR target is designed and applied during the ramp-up, with the maximum amplitude

- Did not leave any influence in the ramp-up and through L-H transition, compared to the <u>reference</u> without 3D fields

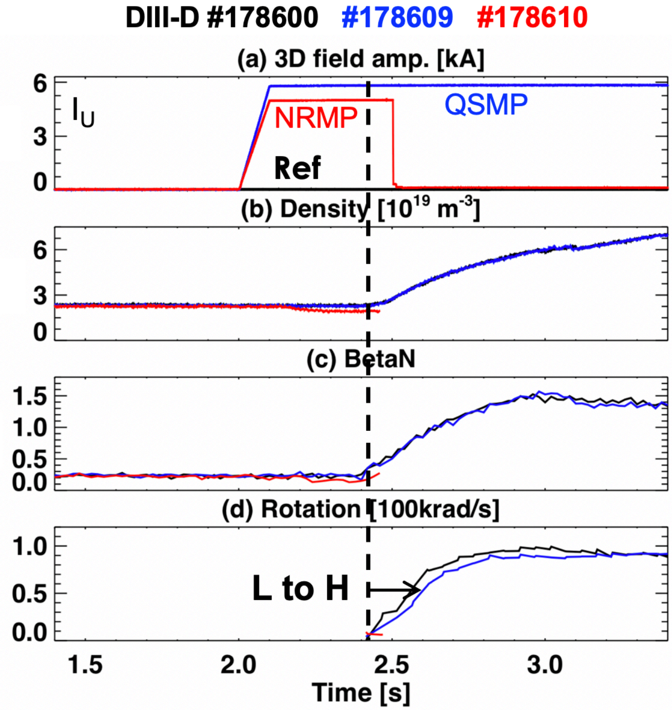
- QSMP plasma in fact showed better confinement after L-H transition which will be further investigated



L-H transition with marginal power remained intact by QSMP, although disrupted by NRMP

- QSMP applied also to a marginal H-mode in DIII-D
- @ L-H:
  - P_{NBI}~1MW, T_{NBI}~0.83Nm,
  - I_P=1.2MA, B_T=1.8T,
  - **β_N=0.24~1.5**, q_{95}~4.0,
  - n_e~2.2e19m^{-3}, T_e~1.7keV, ω_ϕ~17krad/s

- No impact by QSMP, although NRMP disrupted plasma through L-H
  - As observed in COMPASS
  - In DIII-D, locked modes were observed before L-H transitions
    - Indicating NRMP is not entirely optimized
    - Still, showing value of QS optimization



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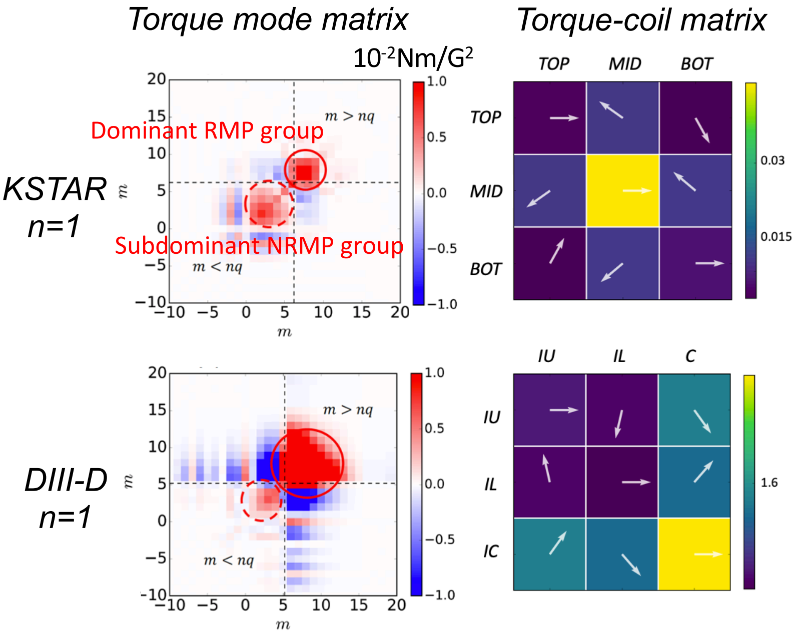
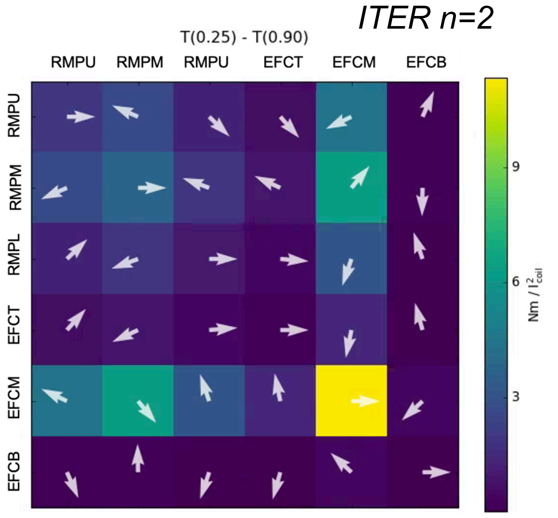
Torque response matrix offers fundamental approaches to design coils and create large quasi-symmetric tokamak deformation

- Torque mode matrix reveals the second dominant group which should be targeted in subsidiary residual EF correction
- If coils are already designed, torque-coil matrix can be used to deform EF to a quasi-symmetric residual using the correction coils





*RMP (10kA), EFC (100kA)

* *Arrow indicates phase*

Summary

- Residual non-axisymmetry after EFC against dominant resonant mode can still cause a significant impact depending on cases (e.g. NSTX-U or COMPASS)
- As a complementary approach, residual non-resonant EF can be further optimized towards quasi-symmetry
- Such a quasi-symmetric magnetic perturbation (QSMP) has been designed using GPEC torque matrix and tested in KSTAR and DIII-D using its available coils
- No negative effects were found with QSMPs in the studied cases in contrast to RMP or NRMP, despite the large overall amplitudes of perturbations
- The results indicate QSMP renders a group of safe non-axisymmetric fields, showing the feasibility of QS even in a perturbed tokamak