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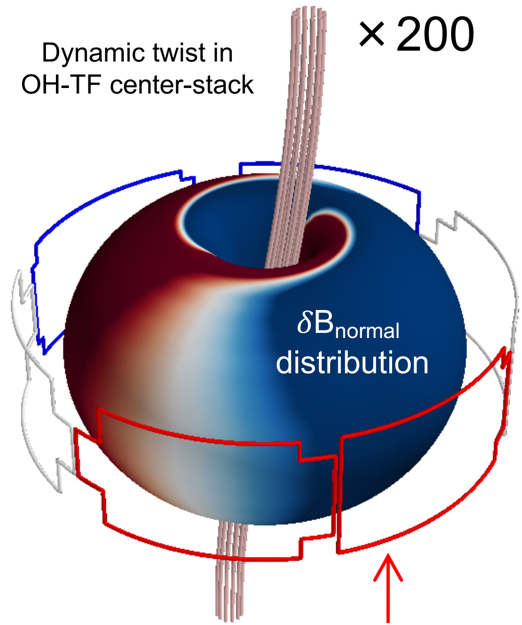
A small non-axisymmetric magnetic field can greatly change tokamak performance and thus must be under control

- 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
  → Error Field Correction (EFC)

NSTX Example

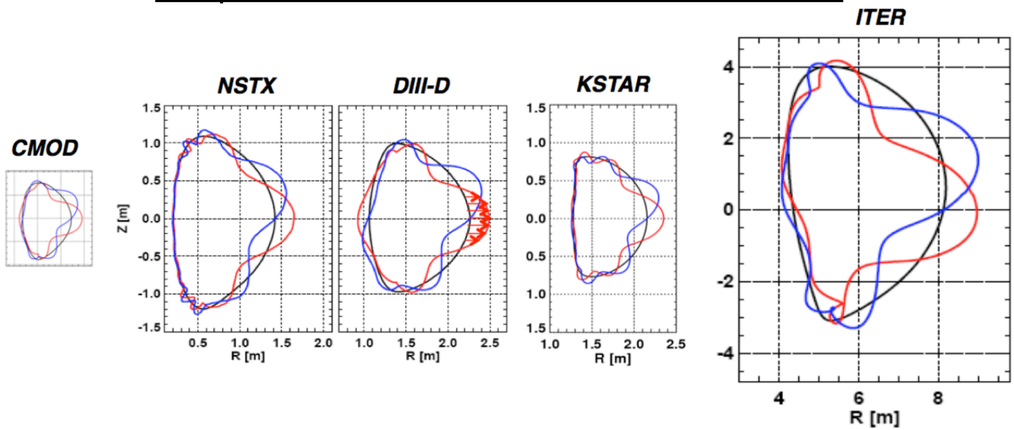
Error fields driving locked modes



Error field correction leading to better performance

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

<u>Shape of dominant resonant field distribution</u>

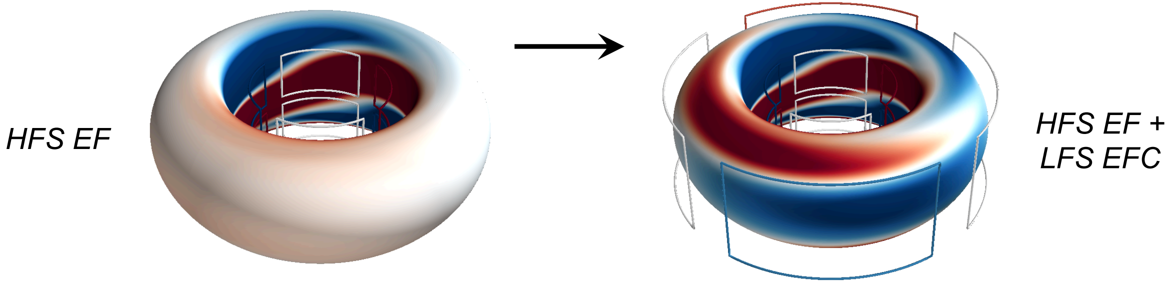


- Ideal MHD clearly shows which 3D field is most resonant with tokamak plasmas and thus must be compensated if not necessary
  - Leading to a major change in EFC approach, via “resonant overlap” field
    - Extensively validated in tokamak devices including DIII-D [LanctotPOP10, Paz-SoldanPOP14]
- Present 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]

<u>Needs a complementary EFC approach</u>
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 $\left|\delta\vec{B}\right|_{particles} \to 0$ [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

$$\left|\delta\vec{B}\right| \sim \hat{b}\cdot\left(\vec{\nabla}\times\left(\vec{\xi}\times\vec{B}_0\right) + \vec{\xi}\cdot\vec{\nabla}B_0\right) \to 0 \quad \longleftrightarrow \quad \delta\vec{F}\left[\vec{\xi}\right] = 0$$

Eulerian
changes in a fixed space

Lagrangian
changes with field lines

- 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

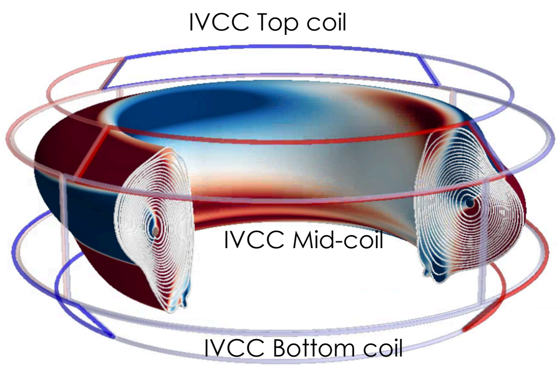
Torque response matrix contains all the information of neoclassical torque that a tokamak can drive with available coils

- 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

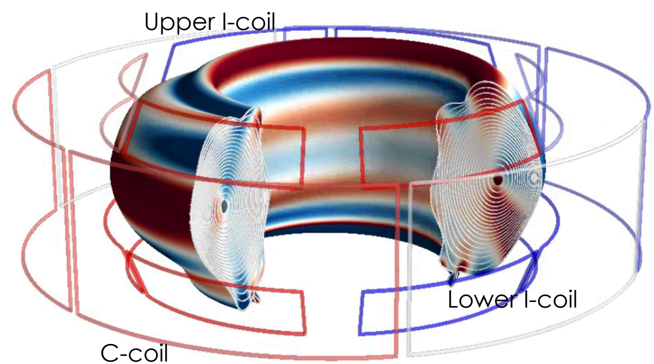
$$\tau(\psi) = \begin{pmatrix} I_T e^{-i\phi_T} & I_M e^{-i\phi_M} & I_B e^{-i\phi_B} \end{pmatrix} \cdot \begin{pmatrix} T_{TT}(\psi) & T_{TM}(\psi) & T_{TB}(\psi) \\ T_{MT}(\psi) & T_{MM}(\psi) & T_{MB}(\psi) \\ T_{BT}(\psi) & T_{BM}(\psi) & T_{BB}(\psi) \end{pmatrix} \cdot \begin{pmatrix} I_T e^{i\phi_T}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

- 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

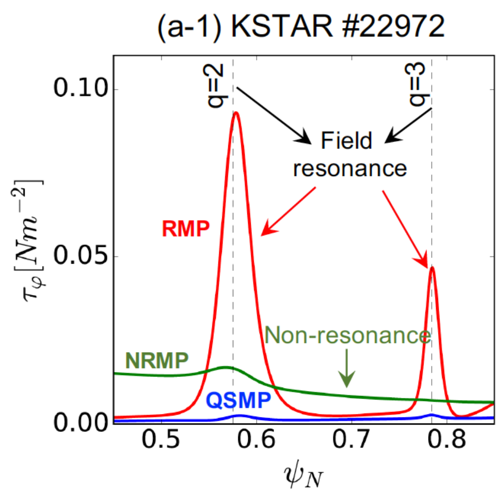


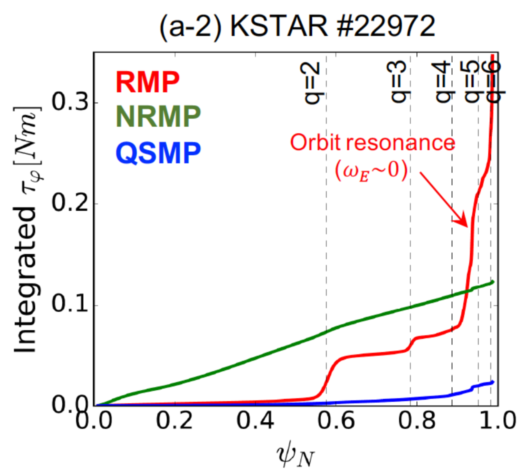
DIII-D n=1 QSMP



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

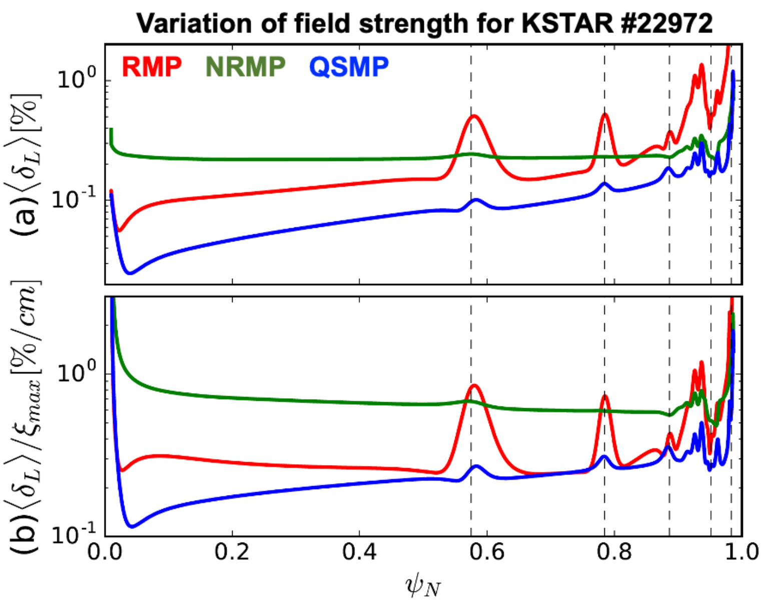




QSMP optimized by GPEC indeed minimizes variation in the field strength at best upon constrained by force balance and torque

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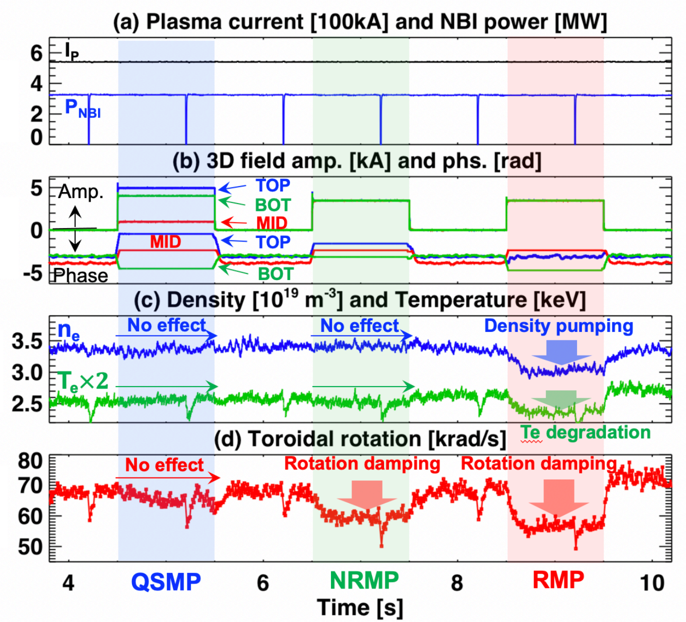
QSMP designed and tested in KSTAR indeed did not bring any meaningful effects despite the large amplitudes

- 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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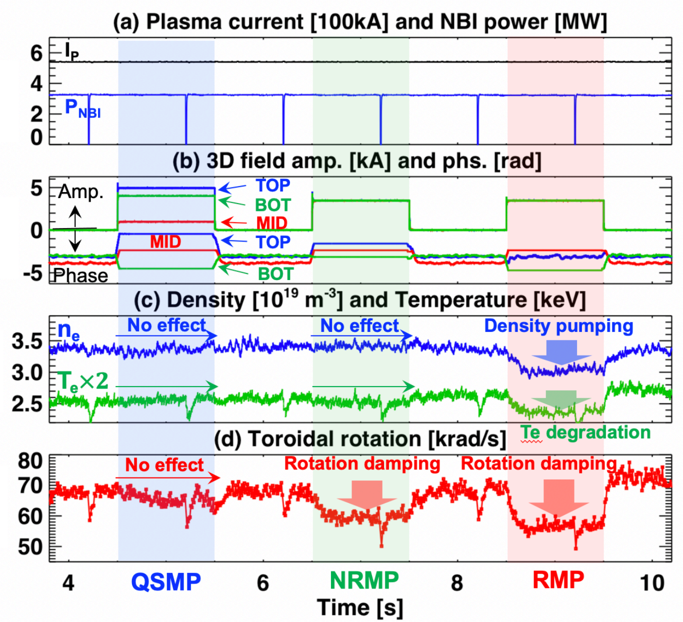

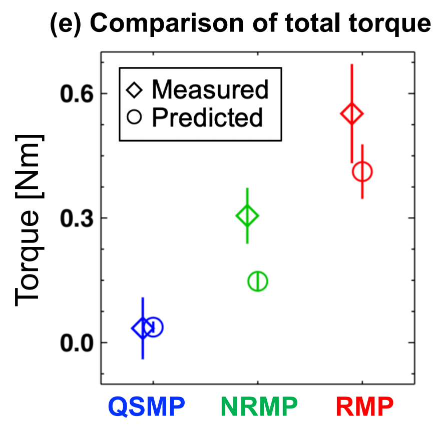

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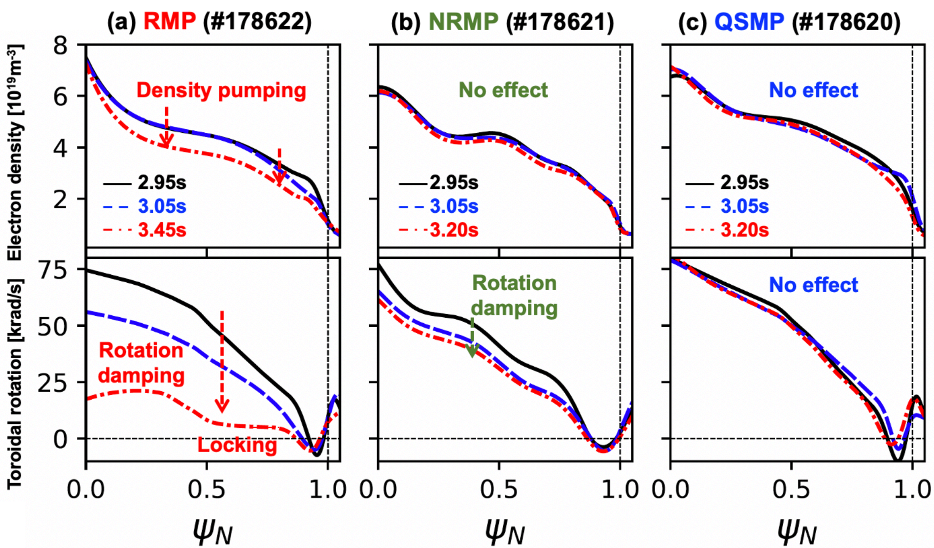
QSMP did not induce any visible effects in DIII-D either despite strong 3D response expected otherwise

- 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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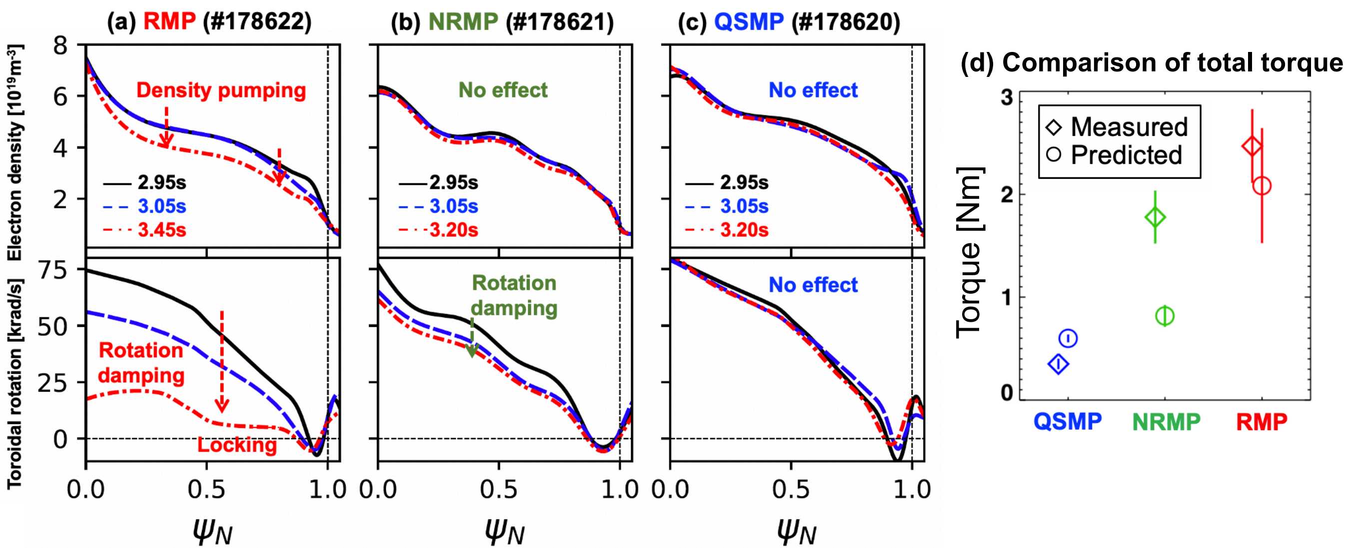
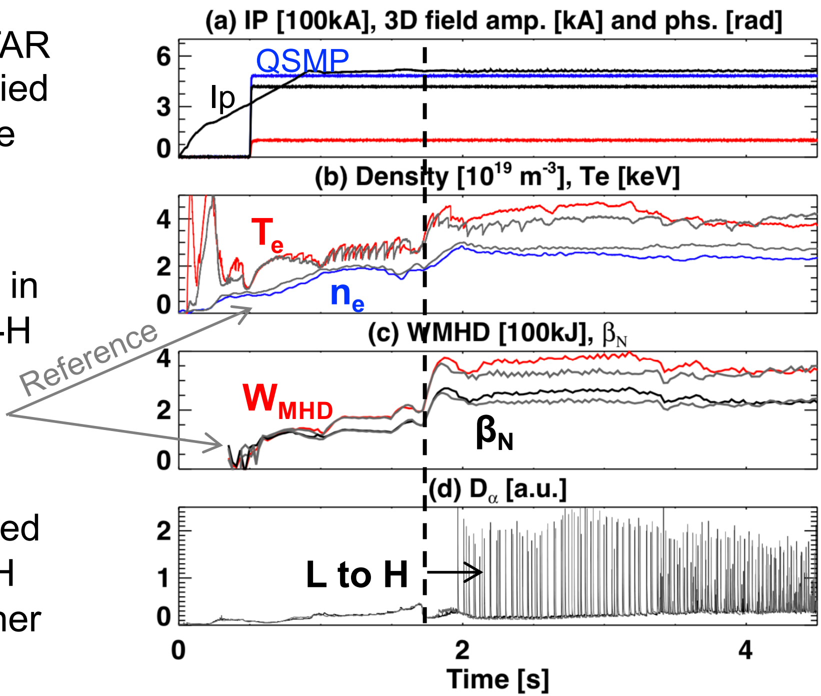


QSMP remains also safe through early ramp-up and L-H transitions

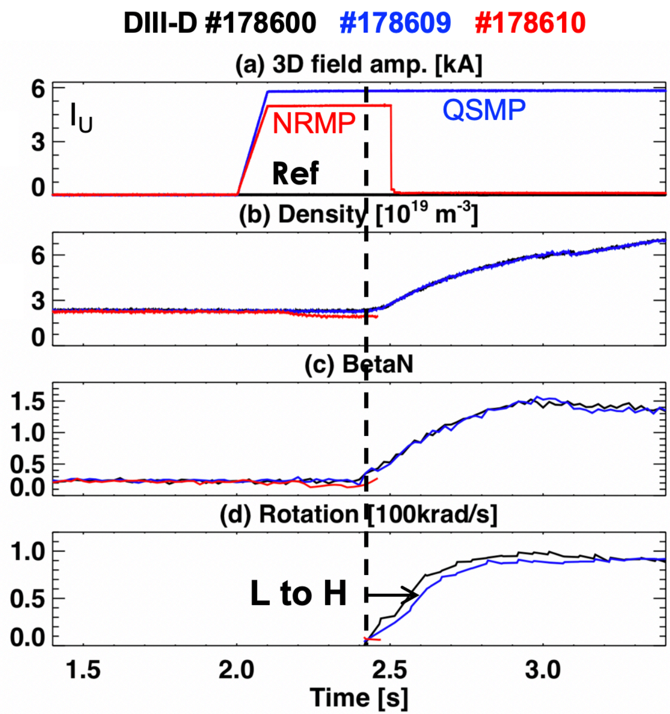
- QSMP for a new 2020 KSTAR target is designed and applied during the ramp-up, with the maximum amplitude
- Did not leave any influence in the ramp-up and through L-H transition, compared to the reference without 3D fields
- QSMP plasma in fact showed better confinement after L-H transition which will 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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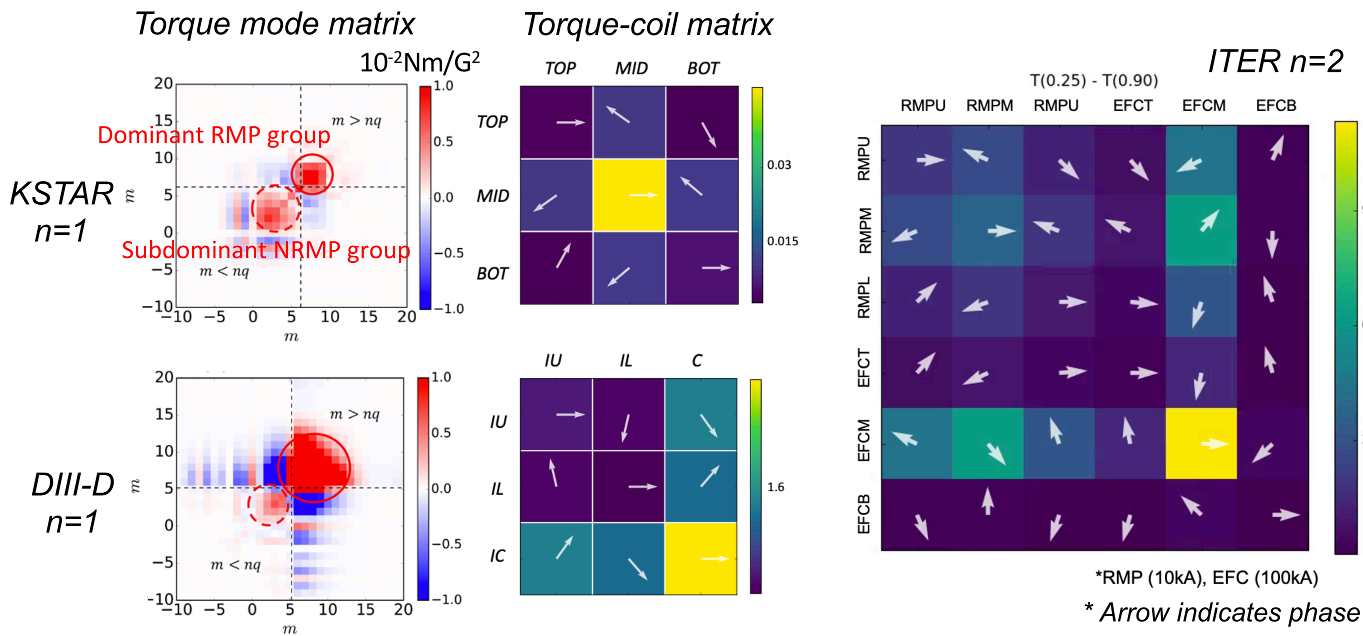
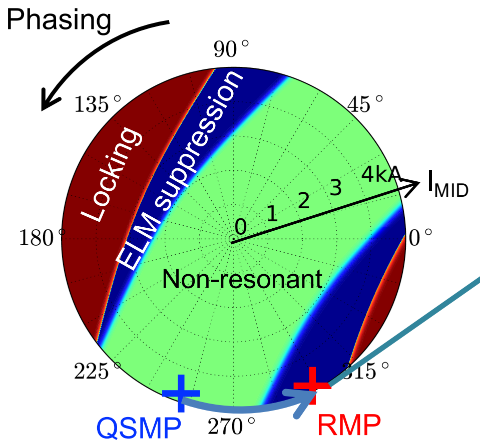
Torque response matrix offers fundamental approaches to design coils and create large quasi-symmetric tokamak deformation

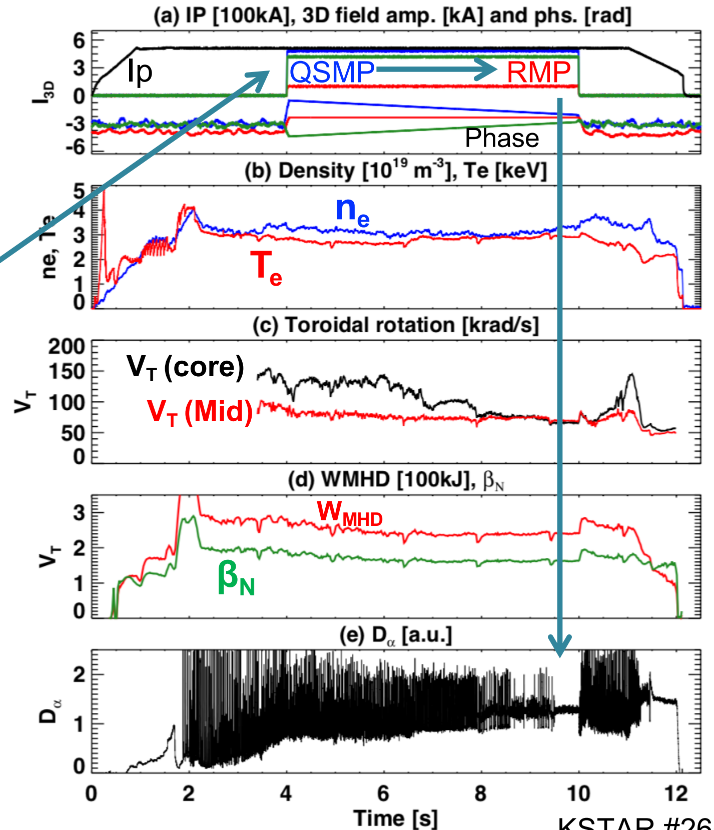
- Torque mode matrix reveals the second dominant group which should be targeted in subsidiary residual EF correction
- If coils are already designed, torque-coil matrix can be used to deform EF to a quasi-symmetric residual using the correction coils



QSMP can also be used to find and investigate the effective RMP with minimized transport

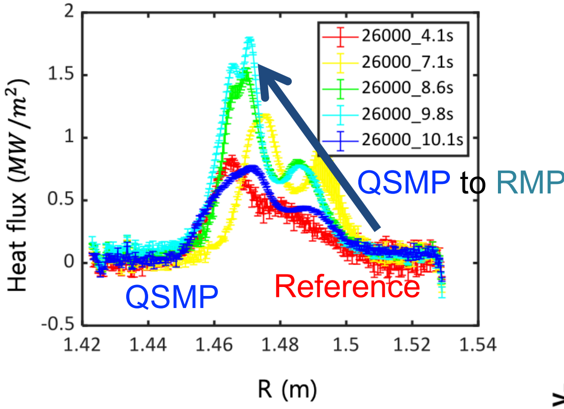


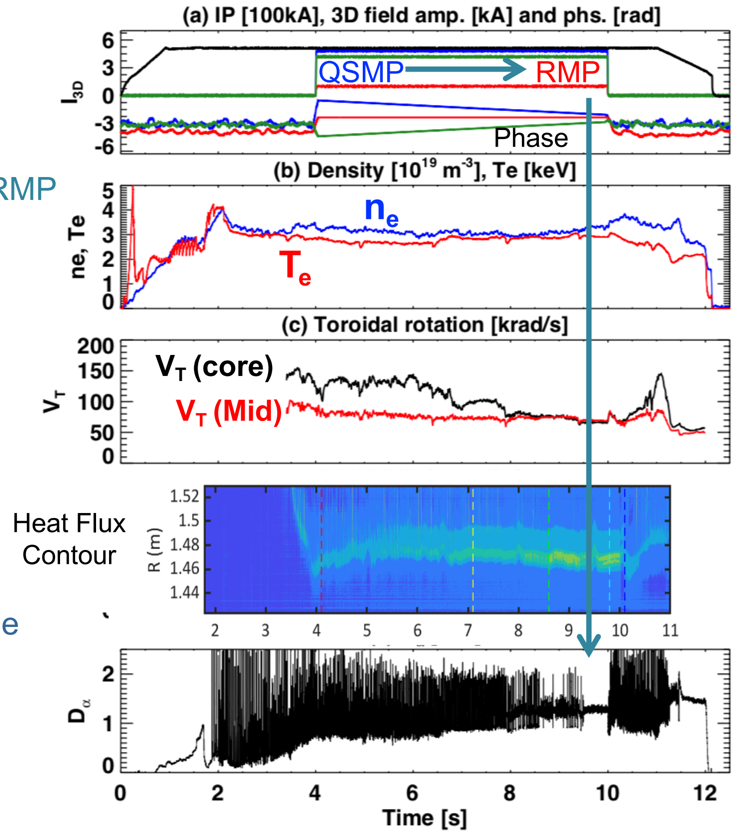
- GPEC + empirical RMP thresholds reveals a shortest path between QSMP and ELM-suppressing RMP
- Benefits of such near-QSMP suppressing ELMs must be confirmed by comparison study



KSTAR #26000

QSMP will be used to find a 3D field that can create heat flux spreading without degrading plasma performance





- Heat flux gradually spreads and then increases from QSMP to an ELM-suppressing RMP
  - As expected from increased edge resonance
  - QSMP could be used to find an optimum trade-off between heat flux spreading and performance

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