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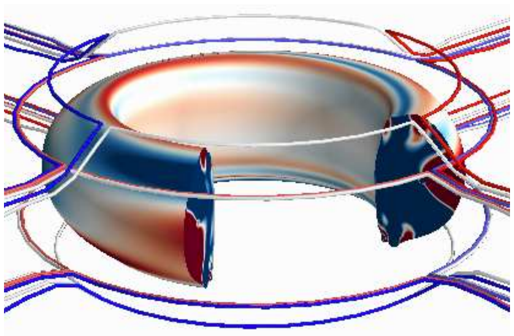
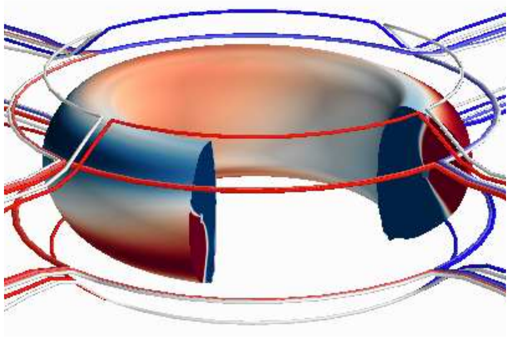
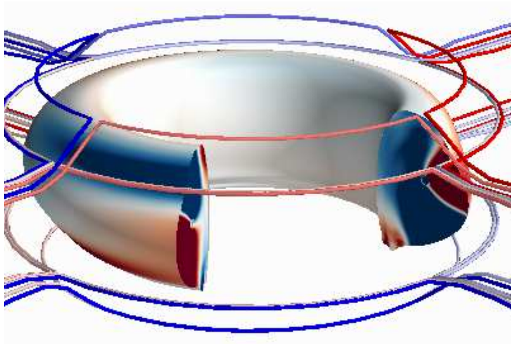
3D field physics collaborations with KSTAR: Physics Basis, optimization and control of RMPs and NRMPs







PI: Jong-Kyu Park (PPPL)
Co-PI: Carlos Paz-Soldan (GA)
Institutional PIs: Heinke Frerichs (UW), Egemen Kolemen (PU),Zihong Lin (UCI)
Key Contributors: N. Logan, C. Zhu, Q. Hu (PPPL), T. Evans, Y. Liu, D. Weisberg (GA), O. Schmitz (UW) et al.

Magnetic Fusion Meeting
December 16, 2019

Background and Motivation

- New international project on 3D tokamak physics
  - To develop a unified physics basis and predictive capability for RMP ELM control
  - Leveraging unique capabilities of international tokamaks (KSTAR, AUG, EAST)
  - Complementing work on US domestic facilities (DIII-D & NSTX-U)
  - Continuing 3D coil optimization for RMP & NRMP (KSTAR, COMPASS-U)

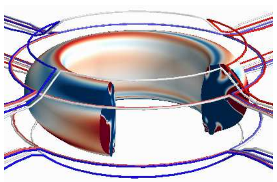
- KSTAR as a focus device
  - To demonstrate long-pulse high performance scenarios with RMP ELM control
  - To demonstrate reactor-relevant RMP schemes
    - Low-n RMP with long penetration, taking advantages of low intrinsic error fields
  - Using high-tech diagnostics such as ECEI

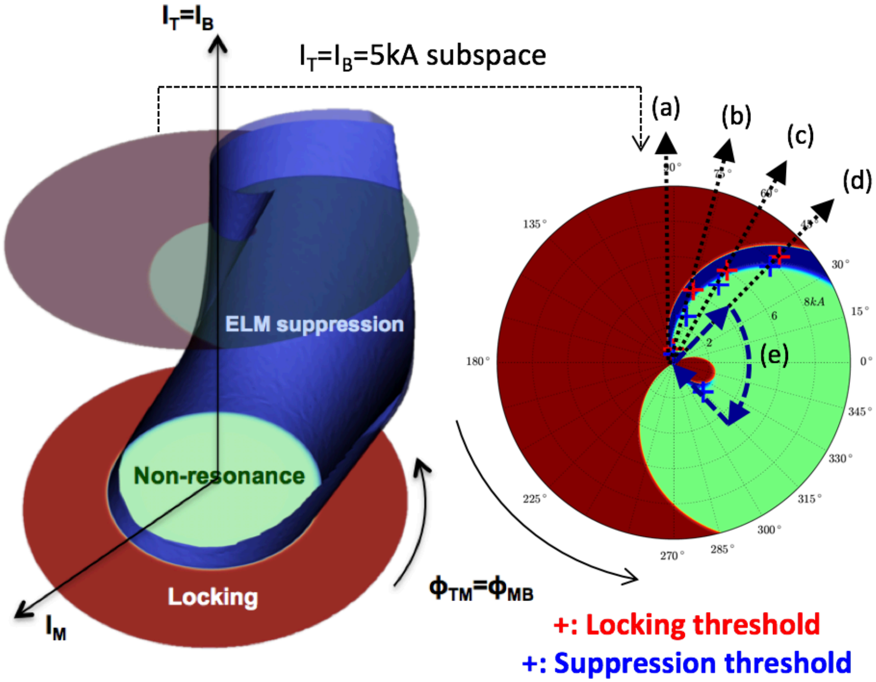
- 9 US researchers joined to 2019 KSTAR campaign (11/11-15)
  - As will be briefly summarized in this talk
  - While Y. M. Jeon (sabbatical) will cover the detail on RMP issues in KSTAR

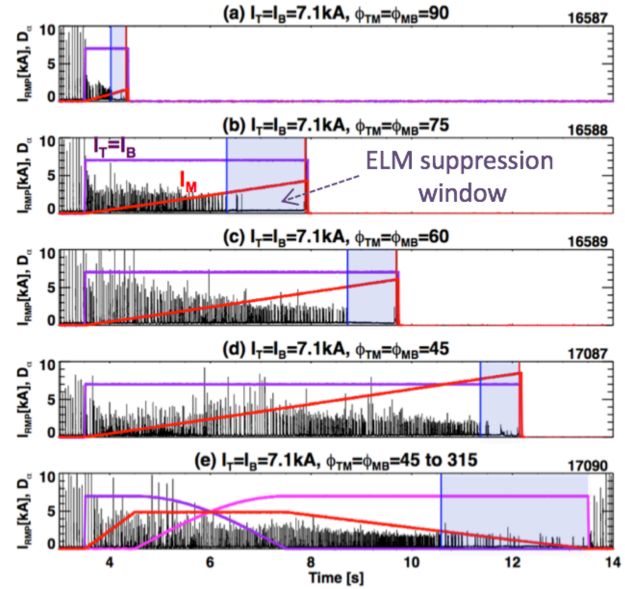
Outline

- Basic strategy and hypothesis of new RMP project
- Collaboration on KSTAR for RMP
  - [Task1] Study of accessibility to RMP ELM suppression (will be covered by Y. M. Jeon's talk for KSTAR)
  - [Task2] Parametric scaling study of RMP thresholds (N. Logan, Q. Hu)
  - [Task3-4] Initiation of turbulence transport under RMP (T. Evans & UCI) and heat flux optimization (Univ. W-Madison)
  - [Task5] Implementation and first test of RT RMP controller (E. Kolemen and Princeton. U)
  - [Task6] 3D coil design and optimizer (N. Logan, C. Zhu, S. Yang)
- Collaboration on KSTAR for NRMP
  - Extreme-case study on QSMP (S. M. Yang)
- Summary

First basic strategy is to remove 3D complexities by ideal or kinetic perturbed equilibria (only by outer-layer response)







[Park, Nat. Phys (2018)]

- KSTAR collaboration has indicated:
  – Ideal MHD precisely describes edge/core RMP variations due to complicated 3D coils
  – So, RMP operating windows can be predicted in entire 3D field space, if edge RMP threshold for ELM suppression and core RMP threshold for locked modes are known
  – Reducing the RMP problem to a local, without confusion due to different 3D coils in devices

Next, edge RMP thresholds for ELM suppression must be predicted with parametric scaling, when accessible

- We are planning to develop empirical database and parametric scaling of edge RMP thresholds (by estimating it with IPEC/GPEC) for ELM control
- While studying accessibility condition
- Based on hypothesis for local island bifurcation in the edge
- In comparison to numerical scaling:
  *e.g. TM1 scaling by Q. Hu

$$\frac{\delta B_{mn=2,edge}}{B_{T0}} \cong 3.5\times10^{-2} n_e^{0.7} |\omega_{\perp e}|^{0.9} B_{T0}^{-1}$$

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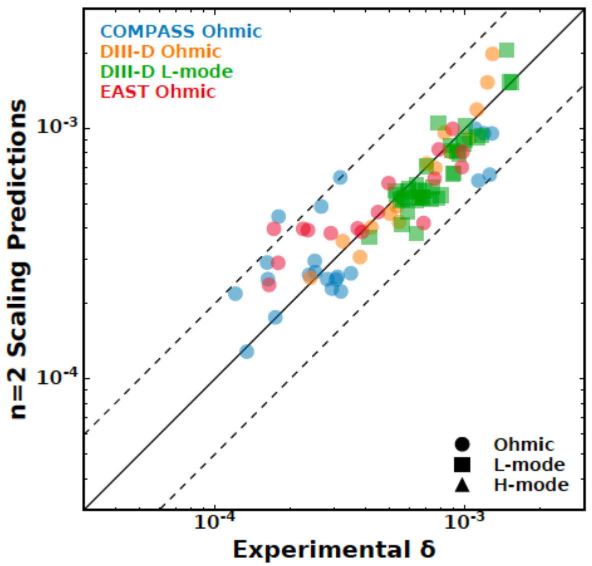
- Together with core RMP scaling:
  *e.g. Empirical scaling by N. Logan

$$\frac{\delta B_{mn=2,core}}{B_{T0}} \cong 4.4\times10^{-4} n_e^{1.1} B_{T0}^{-1.5} R_0^{1.5} \left(\frac{\beta_N}{l_i}\right)^{0.4}$$



- Accessibility? Experience tells us RMP ELM suppression is almost impossible when certain conditions such as shaping or q_{95} is not optimal

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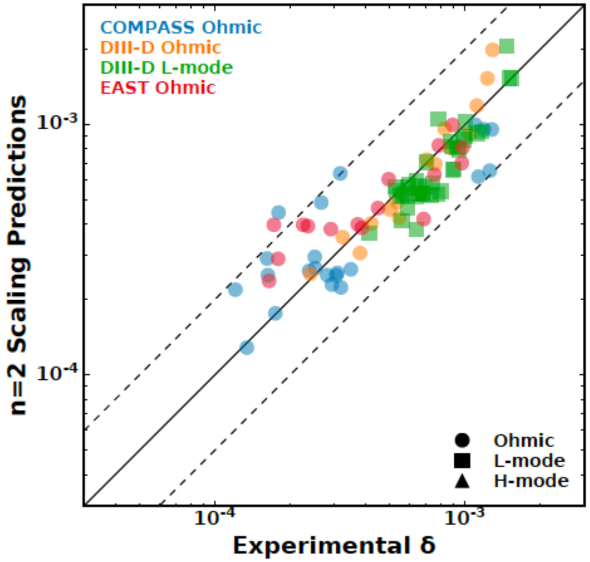

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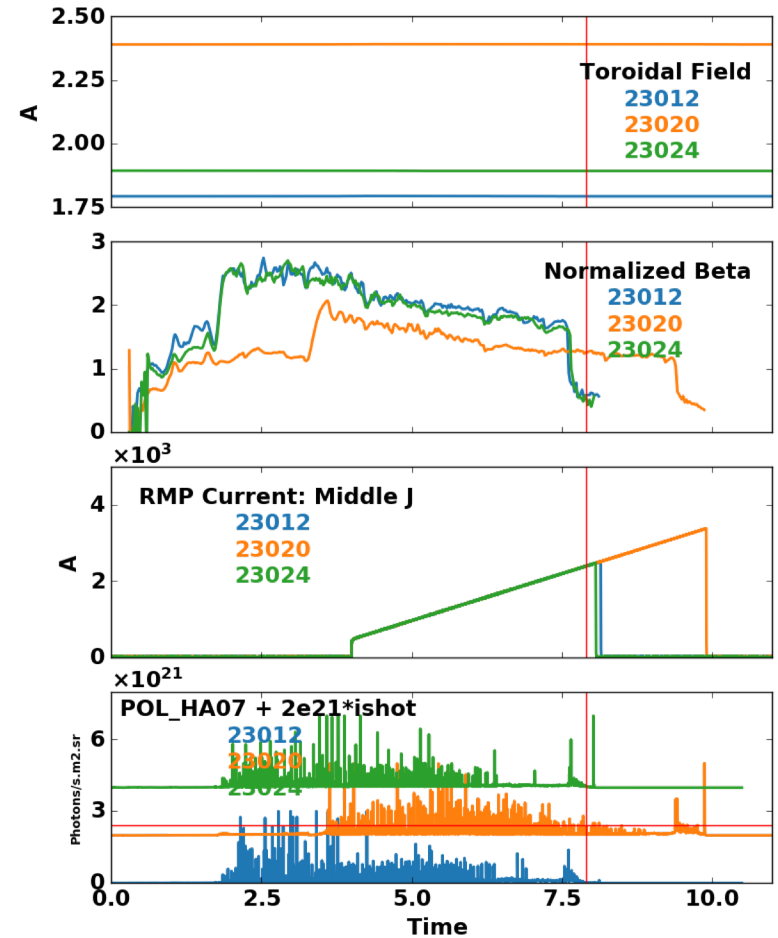
- Accessibility? Experience tells us RMP ELM suppression is almost impossible when certain conditions such as shaping or q_{95} is not optimal

➡ See Y. M. Jeon's talk for empirical observations on this in KSTAR

Initial data for n=1 RMP thresholds obtained for different B_Ts, expecting more runs with power scan

- N. Logan is leading RMP scaling experiments in KSTAR
- Clear ELM suppression with B_T=1.8T, 1.9T, and 2.4T



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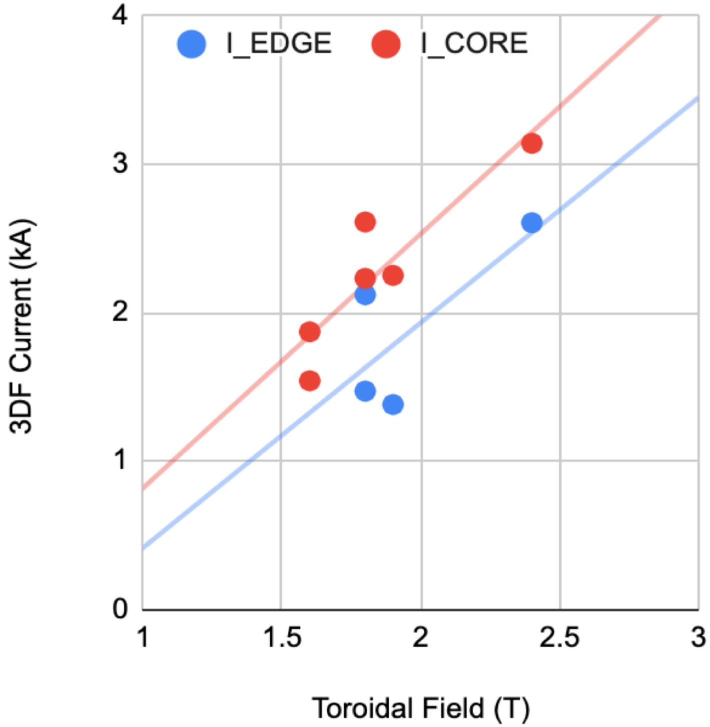
- N. Logan is leading RMP scaling experiments in KSTAR
- Clear ELM suppression with B_T=1.8T, 1.9T, and 2.4T
- Initial results do not indicate expected negative B_T scaling
  - However, n_e & β_N were not successfully isolated and normalized properly in interpretation
  - Will also need kinetic EFITs and response to calculate RMP strength
- Power (β_N) scaling will be tested on January

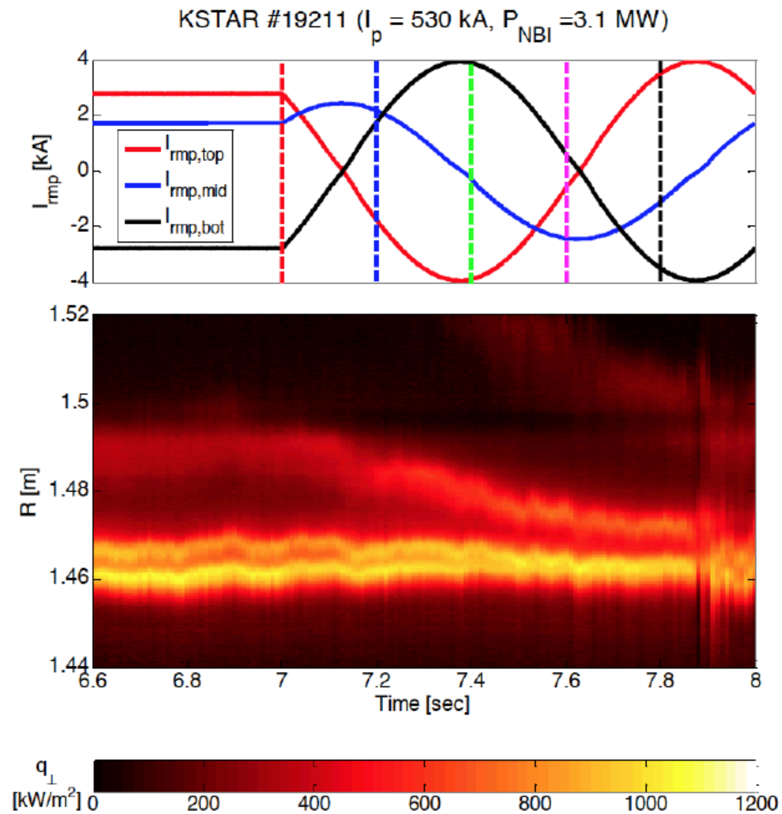


New collaboration for RMP transport physics planned and discussed during the trip

- Island dynamics and transport studies have also been initiated:
  - Q. Hu will study classical Branginskii's
    - Largely explained particle transport (in DIII-D)
  - Y. Liu will study neoclassical (NTV)'s
  - T. Evans and Z. Lin will study turbulence
    - Carried out SMBI, ECH modulation experiments
    - Will work with KSTAR for ECEI, high-K, BES across RMP ELM suppression boundaries

- Heat flux optimization under RMP ELM suppression window will also be studied
  - H. Frerichs and O. Schmitz will use EMC3-EIRENE with KSTAR IR

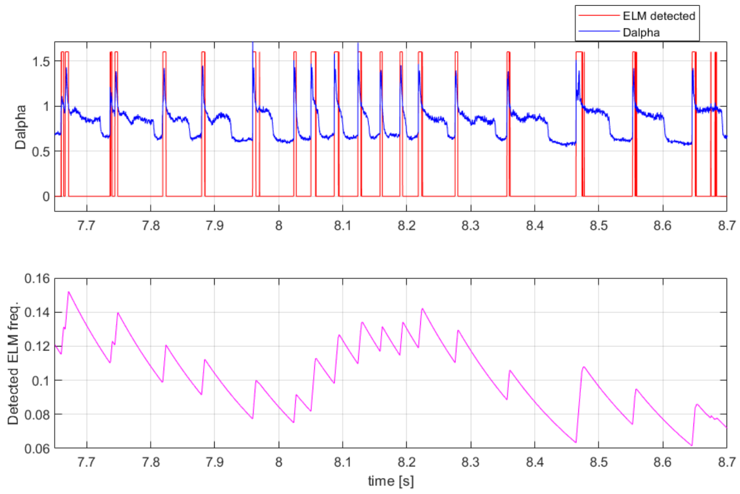
While maintaining
full RMP ELM suppression

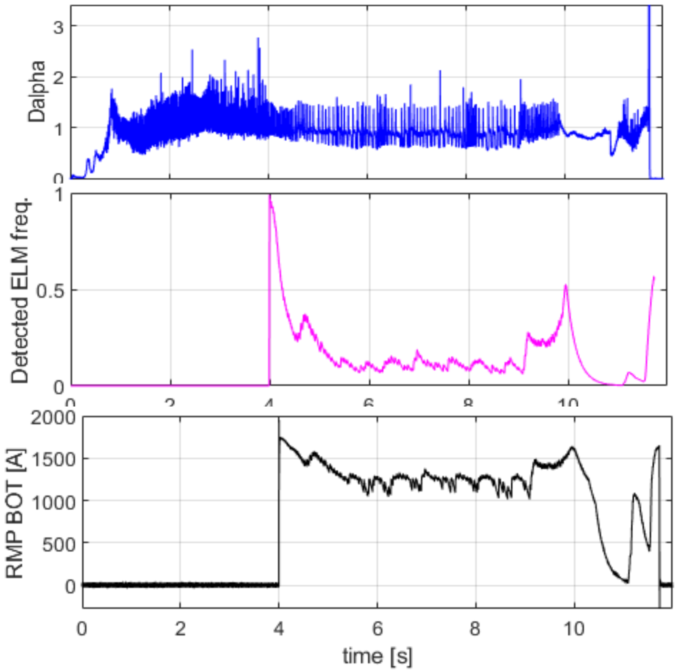


New real-time adaptive RMP controller and demonstrated expected response

- E. Kolemen and Ph. D students implemented real-time (RT) RMP controller based on D-alpha ELM interpreter
- Achieved RT reduction ELM frequency
  - Offset increases when ELM frequency temporarily increases
  - Without false negatives and low number of false positives
- This controller should be guided by predicted window and scaling

Real-time ELM interpreter

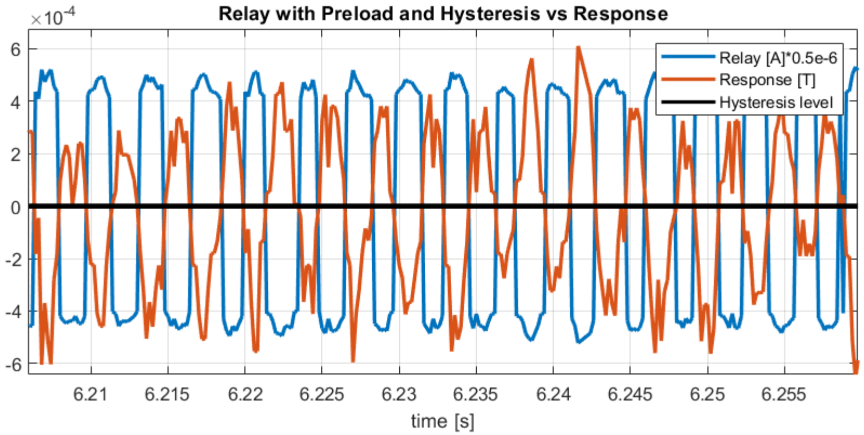




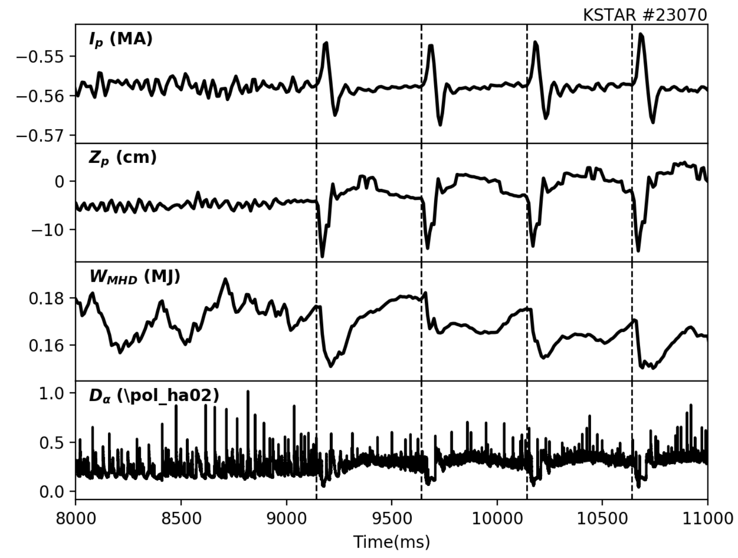
New RT MHD spectroscopy and control for pedestal physics studies have been implemented and tested

- R. Shousha (Princeton U.) implemented advanced relay feedback MHD spectroscopy
- A. Neilson (Princeton. U) successfully control large and fast vertical jogs for the first time in KSTAR

Example from KSTAR shot #23070 (hyst band: ±3e-6):

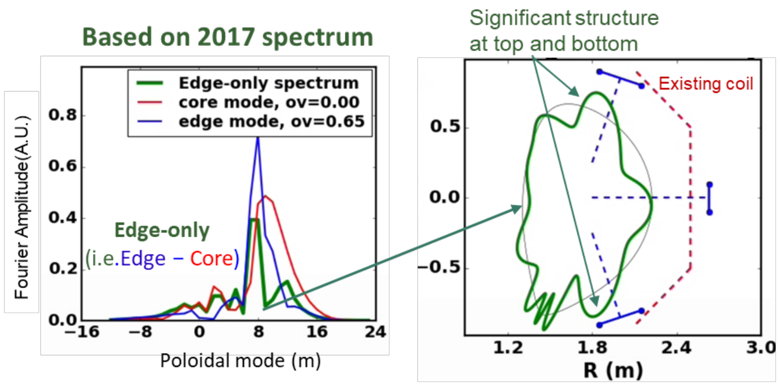


Piggyback at later time:



New reactor-relevant 3D coil concepts will be studied based on improved RMP (and NRMP/QSMP) physics understanding

- Core/Edge RMP metrics can be used to find the best edge RMP:



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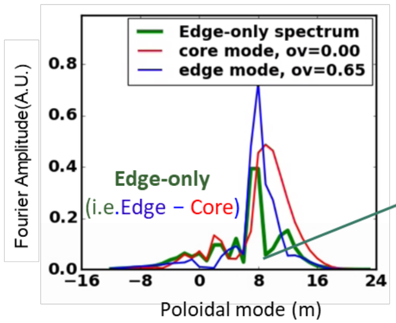
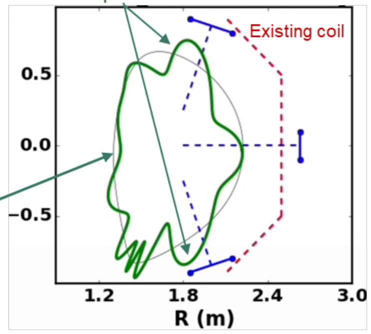
- Core/Edge RMP metrics can be used to find the best edge RMP:
- Accessibility + scaling will be used to predict RMP windows in new targets and new 3D coils

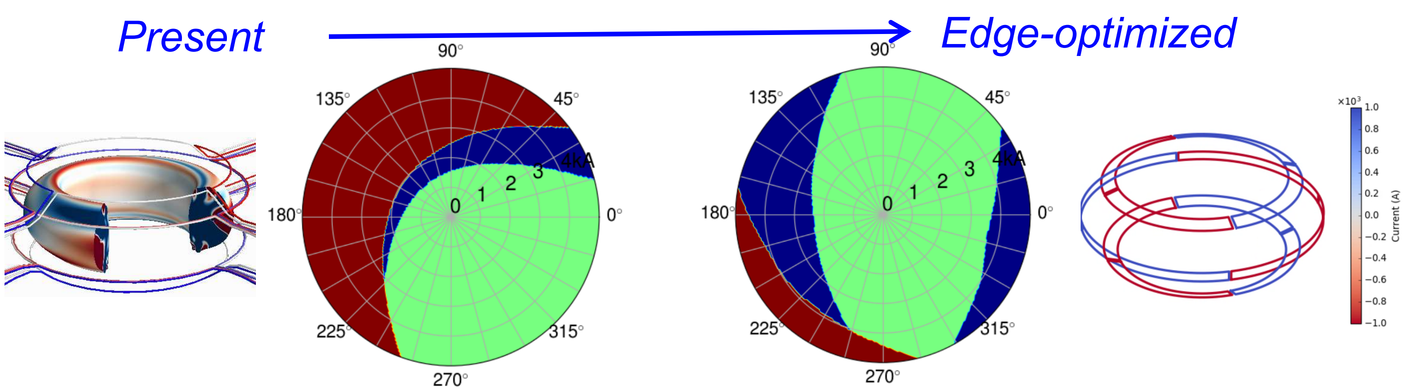
Based on 2017 spectrum



Significant structure at top and bottom



[S. M. Yang, APS]



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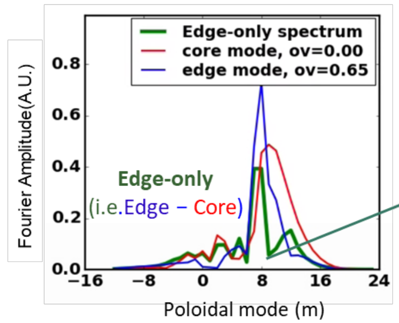
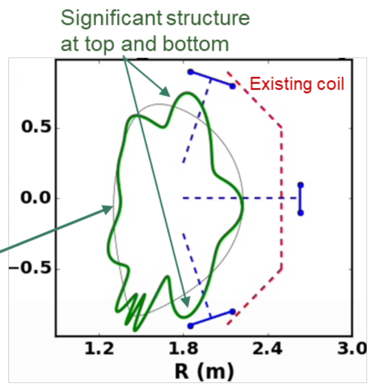
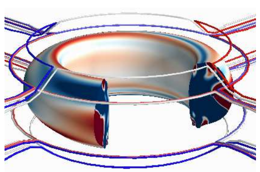


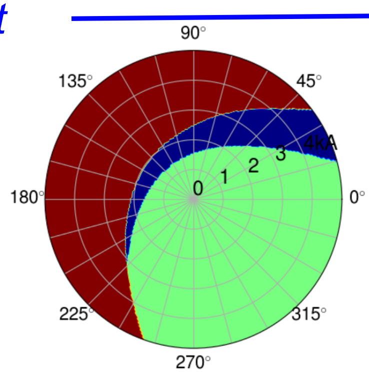


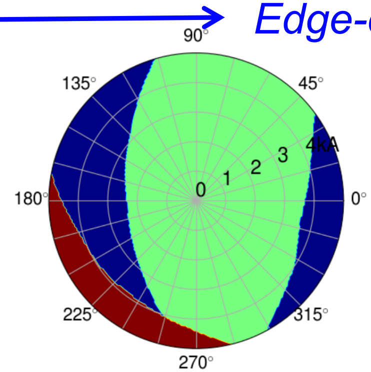
[S. M. Yang, APS]

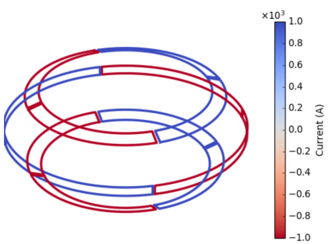
Present → *Edge-optimized* → *Even more*

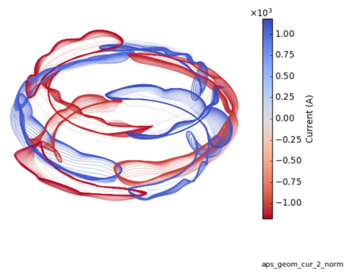
[C. Zhu, FOCUS]











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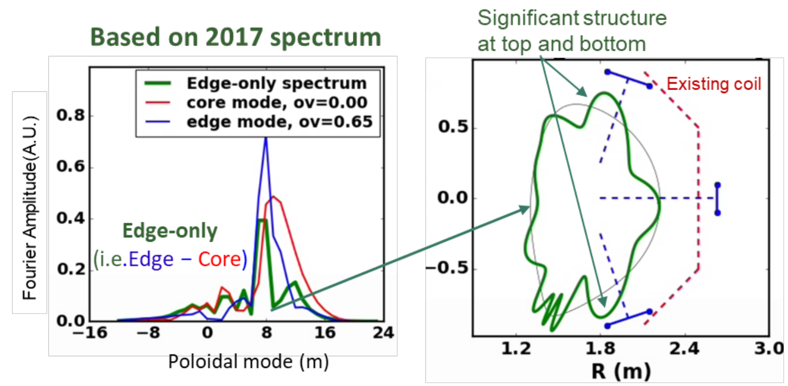
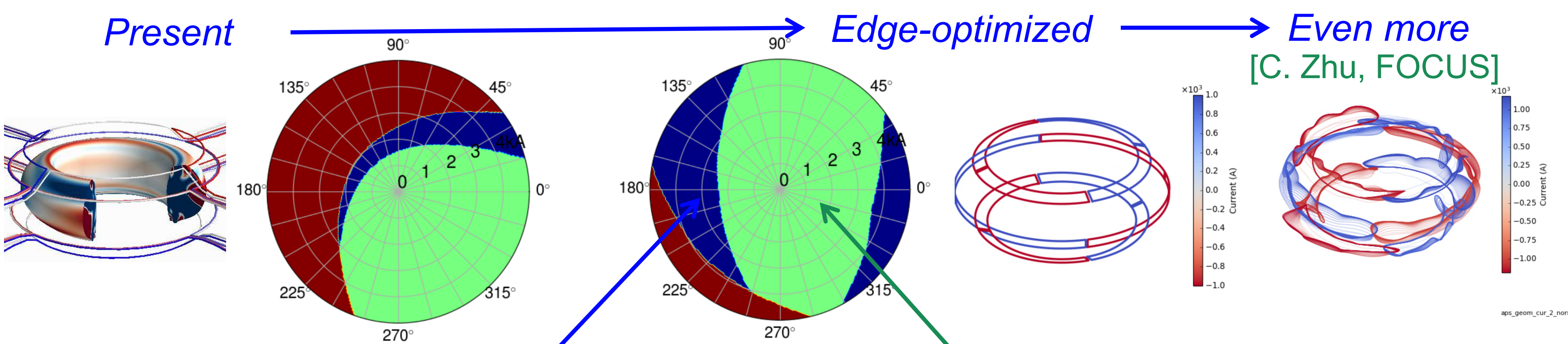


[S. M. Yang, APS]



Confinement, heat flux optimization, and control in improved windows

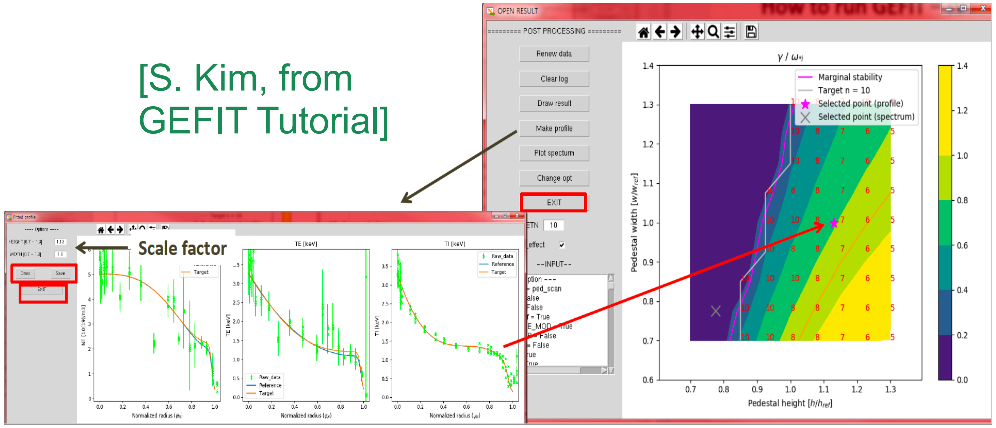
NRMP/QSMP optimization

- Predicted windows will be the basis of transport and heat flux optimization, and RT adaptive control

Kinetic EFIT and 3D optimization workflow has also been under development for KSTAR analysis

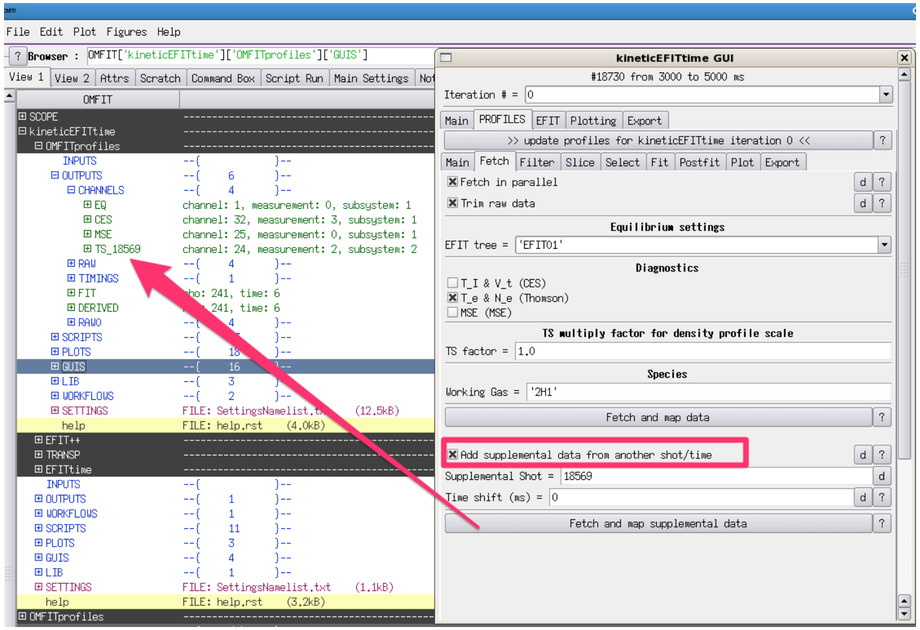
- GEFIT (SNU-NFRI) adapted (by S. M. Yang) for KSTAR kinetic EFITs
  - Edge stability (ELITE, EPED) and profile contingencies considered
  - Collaboration will be continued with Y. S. Na (sabbatical)

[S. Kim, from GEFIT Tutorial]



- OMFIT (by N. Logan, J. S. Kang) has been also implemented for KSTAR
  - Several modules (OMFITProfiles, KineticEFITTIme, GPEC) are already available
  - 3D coil optimizers can be added as in PPPL and GA OMFIT version

[N. Logan]



Question about non-resonant (either error or applied) field will be addressed with GPEC applications

- GPEC solves perturbed equilibrium consistent with neoclassical effects due to small non-axisymmetric fields

$$\underbrace{\vec{j}_0\times\vec{\nabla}\times(\vec{\xi}\times\vec{B}_0)+\vec{\nabla}\times\vec{\nabla}\times(\vec{\xi}\times\vec{B}_0)\times\vec{B}_0+\vec{\nabla}(\vec{\xi}\cdot\vec{\nabla}p)}_{\text{Ideal MHD force}}=\underbrace{\vec{\nabla}\cdot((\delta p_{\parallel}-\delta p_{\perp})\hat{b}\hat{b}+\delta p_{\perp}\vec{I}}_{\text{Drift-kinetic force}}$$

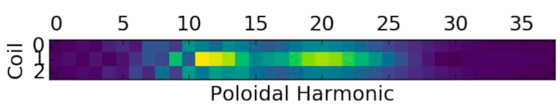
Ideal MHD force

Drift-kinetic force
which also gives NTV in 2nd order

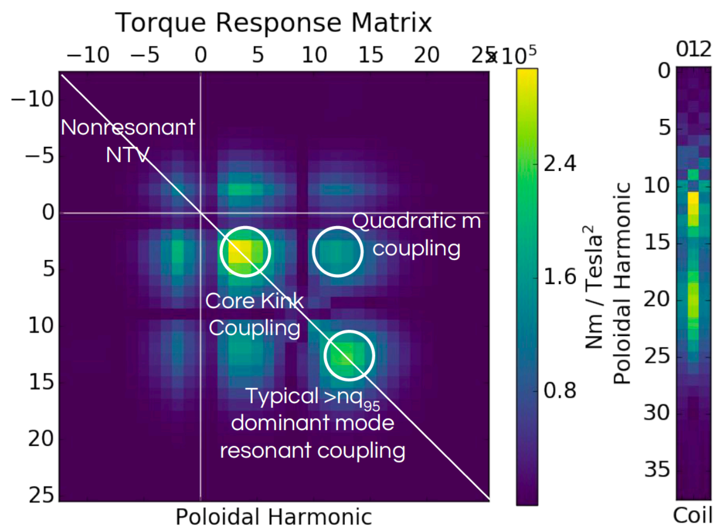
- Key product by this self-consistent formulation is torque response matrix

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

[Park, POP (2017)]
[Logan, APS (2018)]



All possible NTV torque due to 3D fields on the boundary in a KSTAR target plasma →



Extreme-case study for torque matrix is strong non-resonant field without discernible effect : QSMP

- All possible NTV torque that KSTAR can drive using their 3 coils (per target equilibrium, kinetic profiles, and also toroidal mode number n):

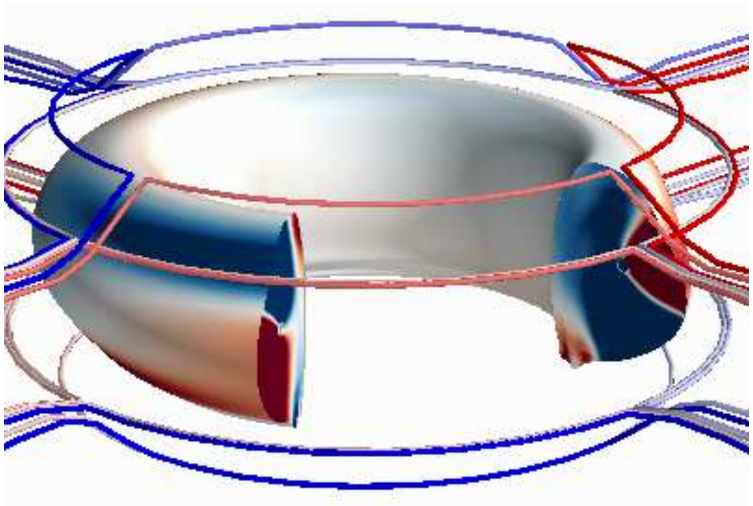
$$\tau_{\varphi}(\psi) = \Phi^{+} \cdot \boldsymbol{T}(\psi) \cdot \Phi = I^{+} \cdot M^{+} \cdot \boldsymbol{T}(\psi) \cdot M \cdot I = I^{+} \cdot \boldsymbol{T_c}(\psi) \cdot I$$

**I: Complex vector representing KSTAR coil currents and phases*

$$= \begin{pmatrix} I_U e^{-i\phi_U} & I_L e^{-i\phi_L} & I_C e^{-i\phi_C} \end{pmatrix} \cdot \begin{pmatrix} T_{UU}(\psi) & T_{UL}(\psi) & T_{UC}(\psi) \\ T_{LU}(\psi) & T_{LL}(\psi) & T_{LC}(\psi) \\ T_{CU}(\psi) & T_{CL}(\psi) & T_{CC}(\psi) \end{pmatrix} \cdot \begin{pmatrix} I_U e^{i\phi_U} \\ I_L e^{i\phi_L} \\ I_C e^{i\phi_C} \end{pmatrix}$$

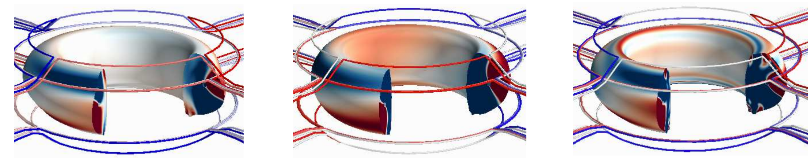
- Eigenvector with minimum eigenvalue is the coil setting that creates minimum torque, and minimum |dB| : one as close as possible to quasi-symmetric variations in 3D tokamaks

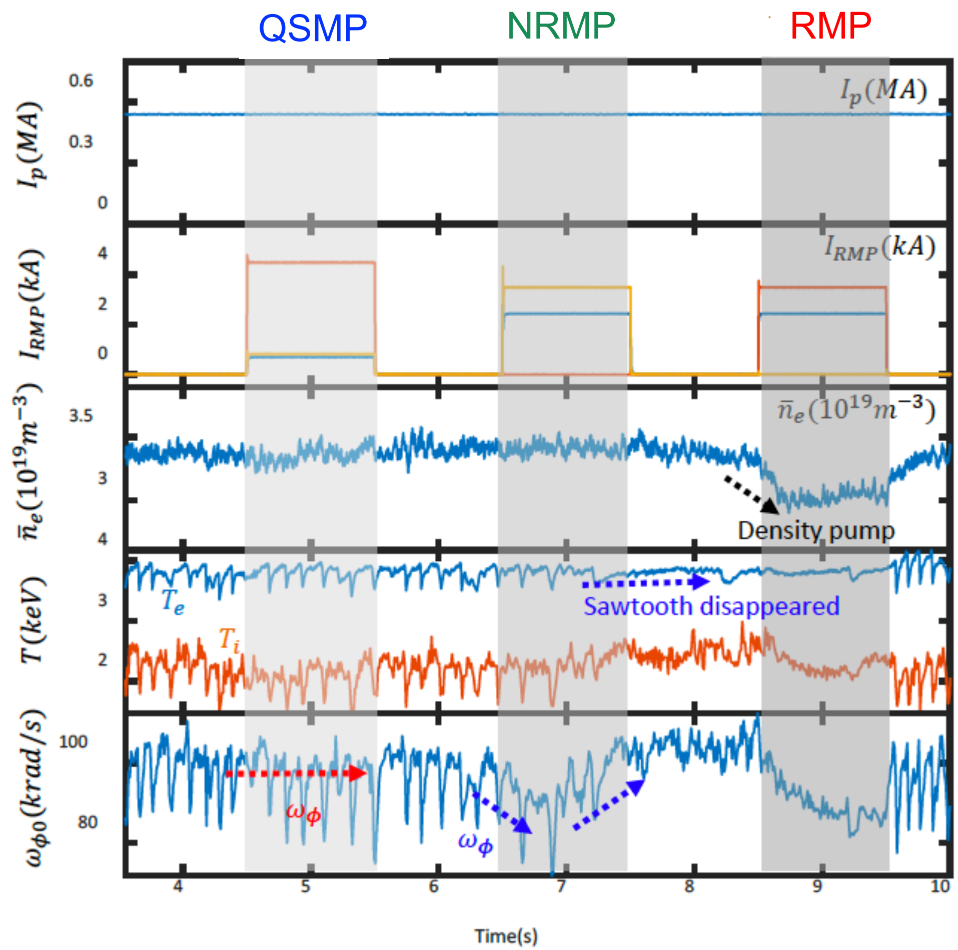
- QSMP is the ideal residual of resonant and non-resonant EFC



QSMP has been contrasted against NRMP and RMP

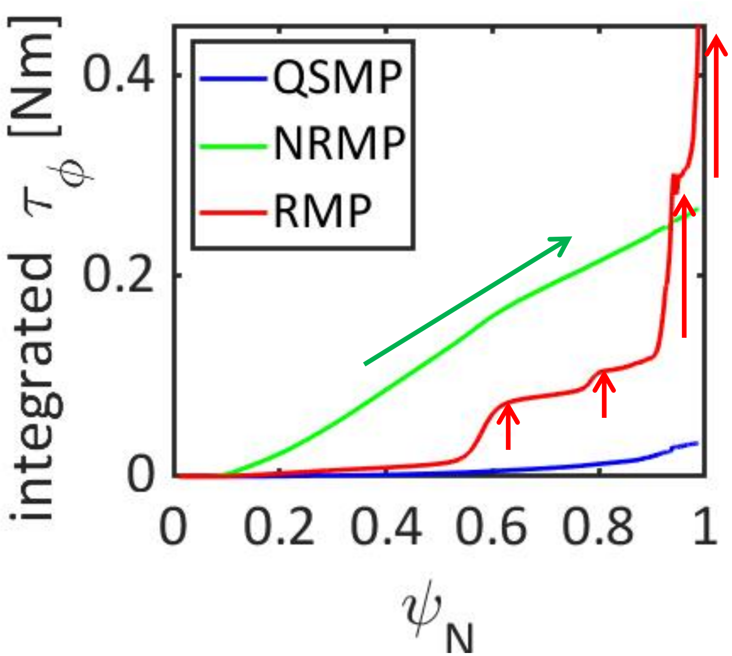
- IPEC/GPEC (in OMFIT) has been used to configure the coils and make n=1 QSMP, NRMP, RMP, as tested by S. M. Yang
- RMP generates strong density pumping, confinement degradation, and rotational damping
- NRMP induces only rotational damping
- QSMP did not generate any meaningful effects

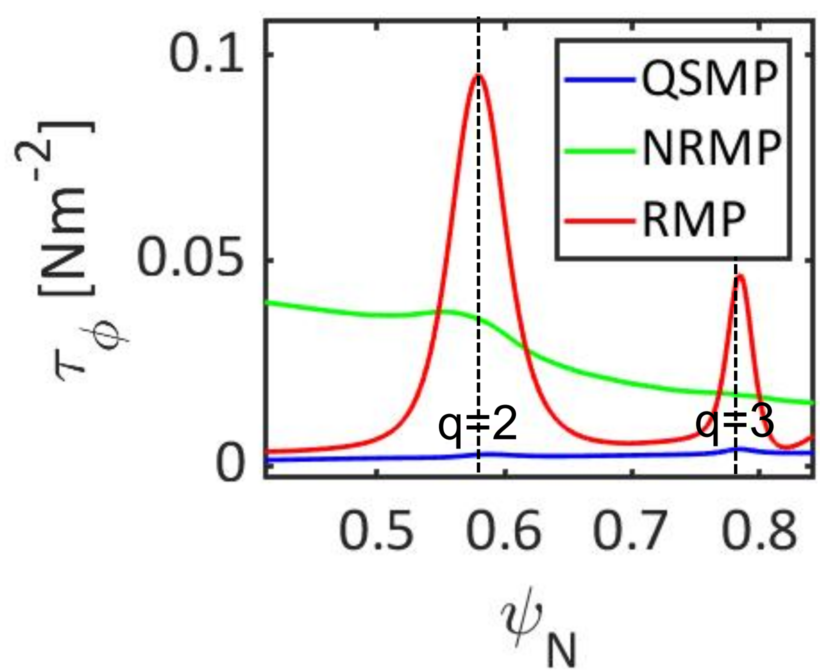




NRMP optimization requires local resonant torque reduction and QSMP requires global reduction as predicted

- NRMP and QSMP optimization shows expected reduction of resonant and non-resonant torque
  - NRMP & RMP : Similar torque in total, consistent with experiments
  - However, RMP gives torque only near resonant layers, although NRMP gives torque globally
  - Both torques are minimized in QSMP, as seen in experiments

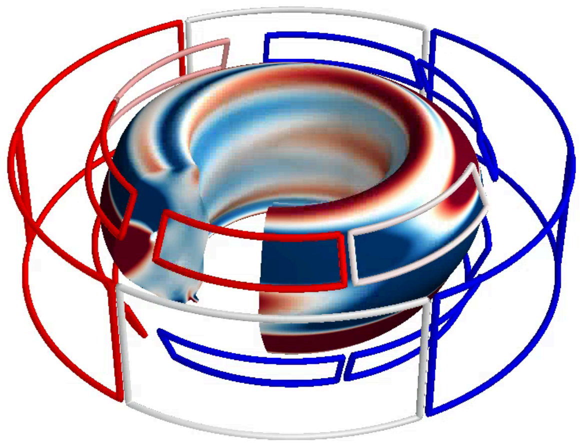


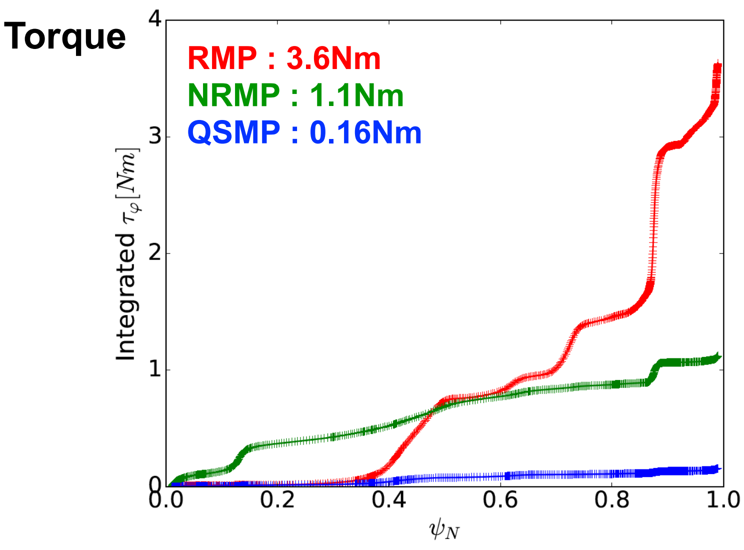


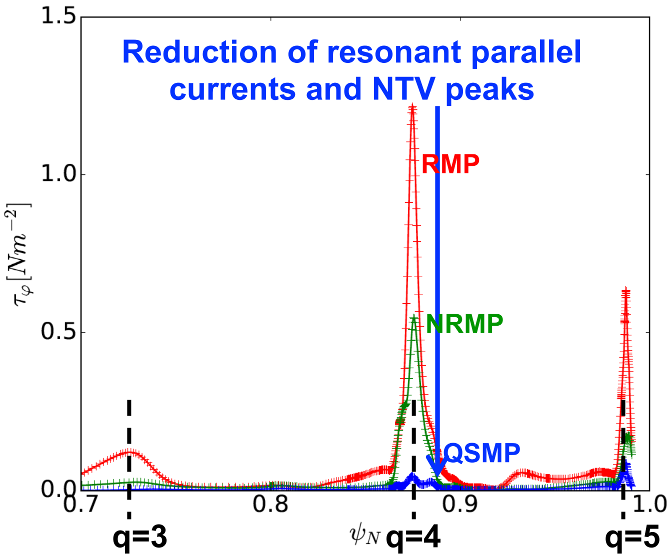
QSMP in DIII-D also did not induce any discernible effects in every channel inspected so far

- QSMP vs. NRMP and RMP has also been successfully tested in DIII-D using I+C coils
  - Robustly shows no effect, even in highly sensitive target such as high β_N (>3.0) or through L-H transition

[J.-K. Park, APS (2018)]







Summary

- New international research project on RMP has been successfully initiated in KSTAR from 2019
  - Based on recent progress made by PPPL-KSTAR collaboration
  - [Task1] Improved understanding on shape effects (by Y. M. Jeon's talk)
  - [Task2] Initial BT scaling obtained and power scaling will also be tested
  - [Task3-4] ECEI and IR data obtained for future analysis
  - [Task5] Successful implementation and test of RT RMP controller, relay feedback MHD spectroscopy, and fast jog control
  - [Task6] Developed 3D coil optimizing workflow, resulting in improved 3D coils for RMP (and NRMP)
- NRMP studies also continued, successfully testing QSMP predicted by GPEC in KSTAR (and DIII-D)
  - Demonstrating no effects by 3D fields despite substantial deformation