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Quiescence of Magnetic Braking and Non-resonant Field Control in KSTAR

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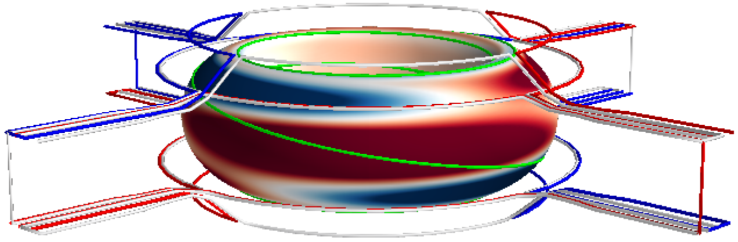
NFRI PPPL KSTAR

Motivation to quiescent magnetic braking

- 3D field in tokamaks can provide various utilities depending on field spectrum
- Resonant vs. Non-resonant Magnetic Perturbation (RMP vs. NRMP)
  - RMP can control ELMs by particle and heat transport
  - NRMP can modify rotation by momentum transport (NTV or magnetic braking)

- Reality is mixture, due to limited coils
  - Many poloidal modes, strongly coupled
- Excluding one for the other is important
  - To minimize unwanted effects
  - To isolate and understand mechanism



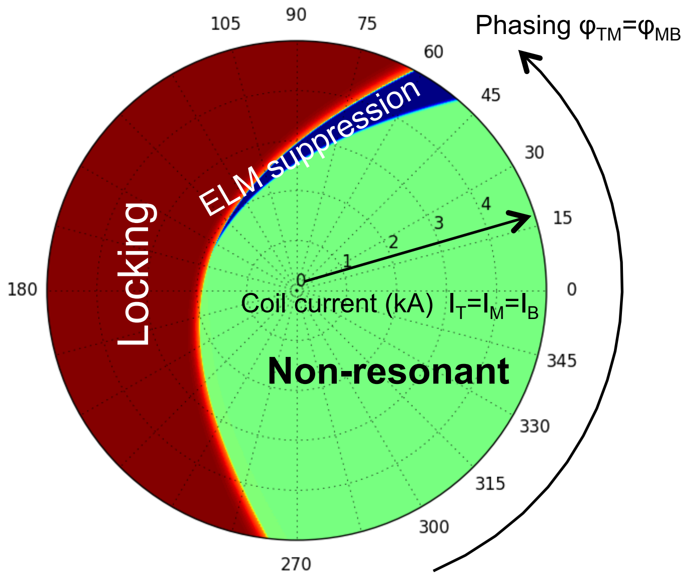
KSTAR IVCC -90p to #15433.08000

- <u>Quiescent magnetic braking – NRMP applications without RMP effects</u>, to control local rotation/shear without disturbing particle or heat transport channel

KSTAR provides great opportunity to nail down resonant effects in magnetic braking

- KSTAR IVCC consists of 3 rows of internal coils like ITER: Top, Middle, Bottom coils
- Spectral diversity for n=1 is greater than any other devices, enabling n=1 RMP ELM control
  - In magic window of coil configuration space
  - By isolating edge resonant coupling from core
- NRMP is even more diversified, giving great chance to study remnant RMP effects

Primary effects induced by KSTAR n=1 vs. (I,φ) – subset of coil configuration

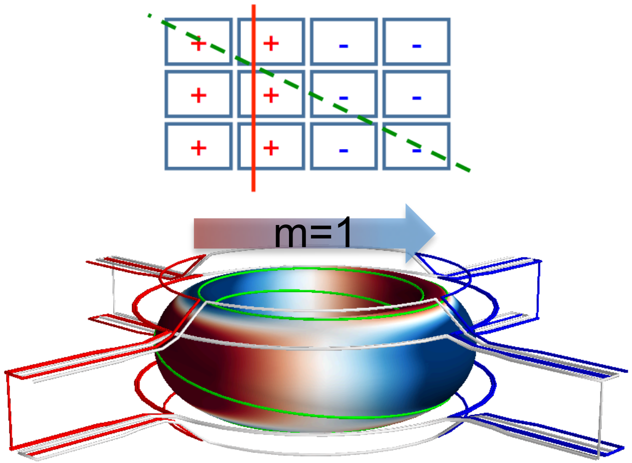


* This is n=1 study, but remnant RMP effects other than locking is also important for n>1

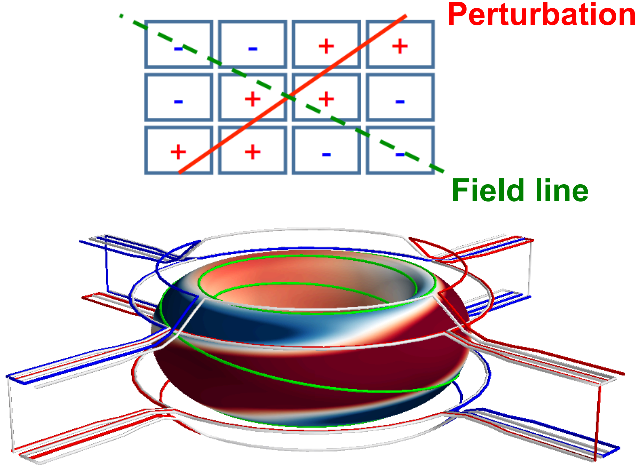
Geometrics for non-resonance

- Two most intuitive ways to generate non-resonant field:
  - Make long poloidal wavelength in perturbation : 0° phasing: m=1 dominant field
  - Place perturbation pattern across field lines : -90°(270°) phasing: RMP-orthogonal field
    - * Phasing: Toroidal phase shift from top to middle (identically from middle to bottom)

<u>0° phasing</u>



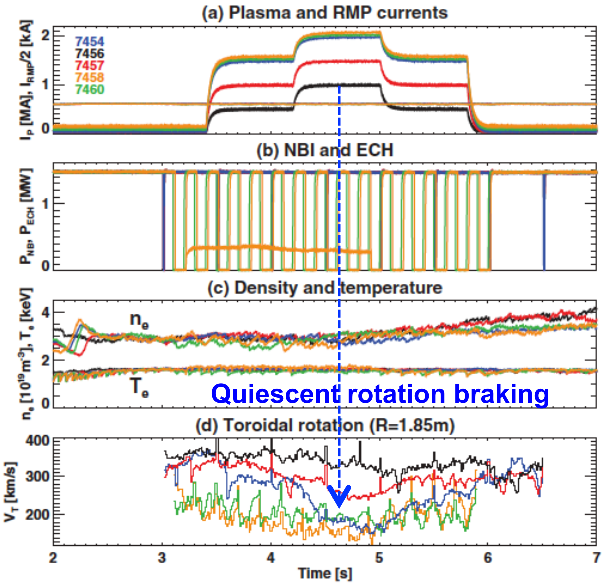
<u>-90° phasing</u>



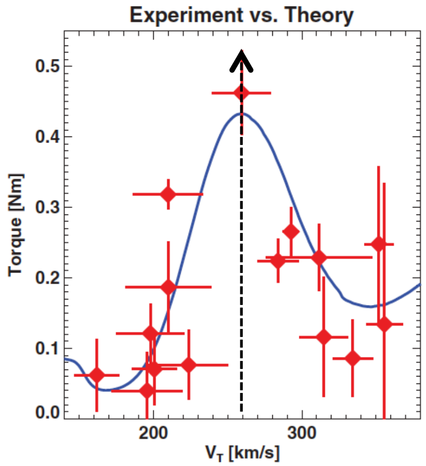
RMP-orthogonal field can be highly quiescent in magnetic braking as demonstrated in BH resonance studies

- RMP-orthogonal field (-90° phasing)
  - Unique in KSTAR as 3 rows of coils are needed
  - Successfully produced quiescent magnetic braking for low q_{95}≈4, weakly shaping (κ≈1.4)
  - Used to study 'pure' NTV effects and bounce-harmonic rotation resonance in NTV

J.-K. Park et al.,
PRL111, 095002 (2013)

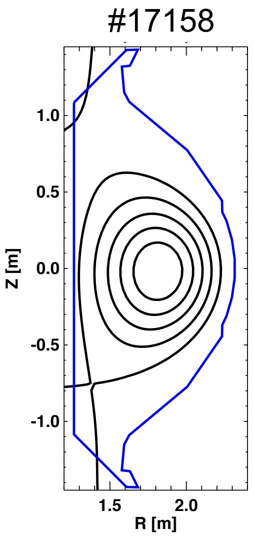


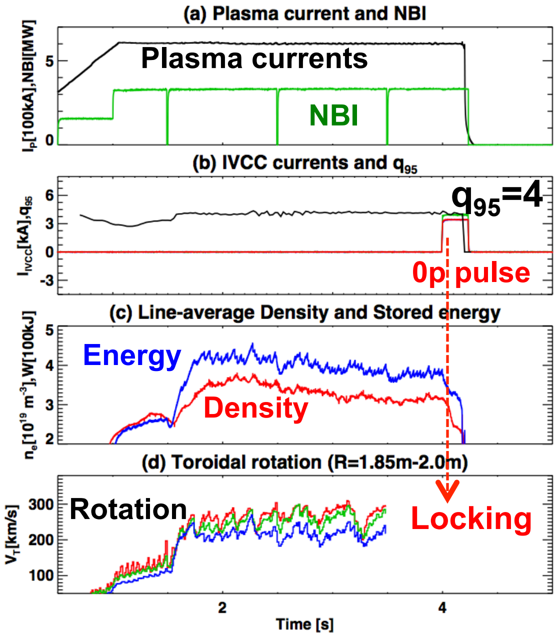
1st Bounce-Harmonic resonance
Shown in both

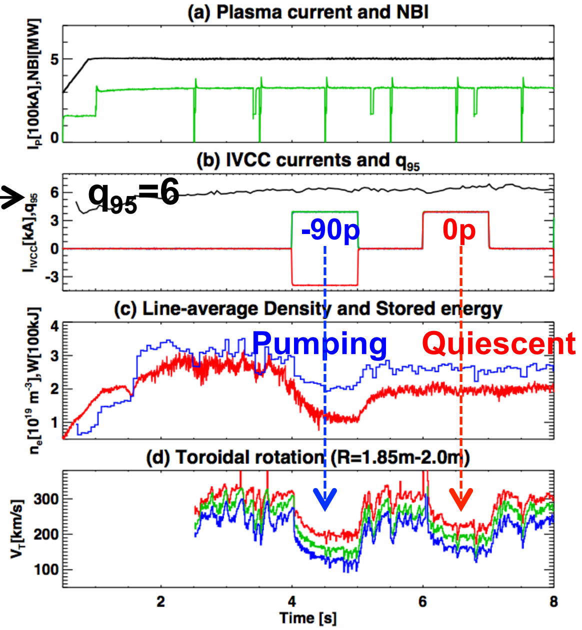


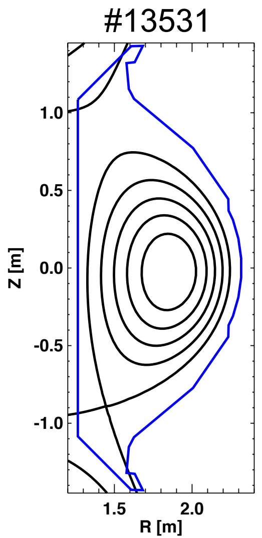
Further evidences show quiescence of magnetic braking requires fine matching between phasing and target

- Optimal phasing for quiescent braking varies sensitively (-90° vs. 0° issue)
  - -90° phasing → 0° phasing when q_{95}=4 → 6, and shaping becomes stronger



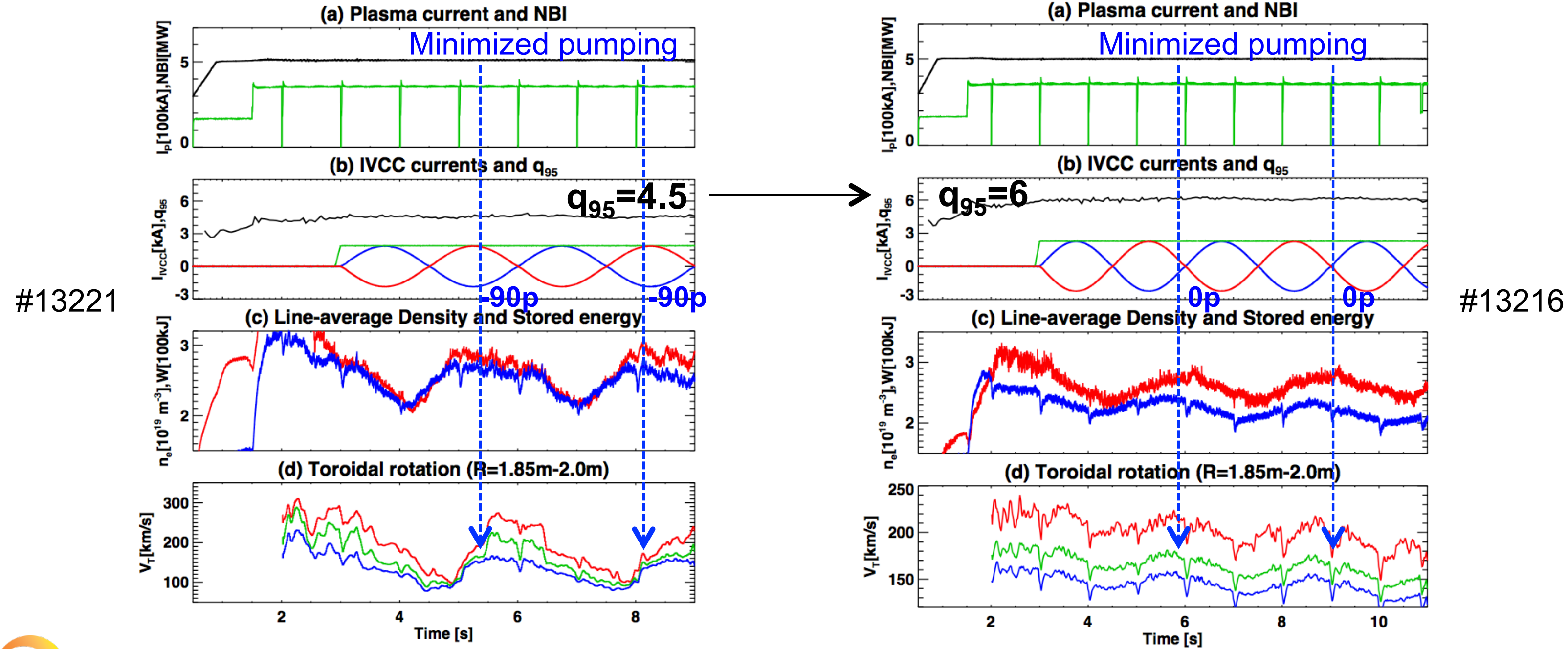






Similar trend found in continuous phasing scan

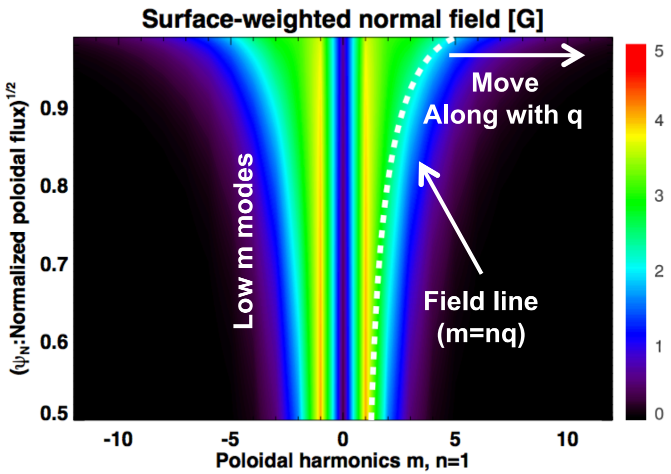
- Continuous phasing scan using 3 rows of coils also shows
  - -90° phasing → 0° phasing when q_{95}=4 → 6



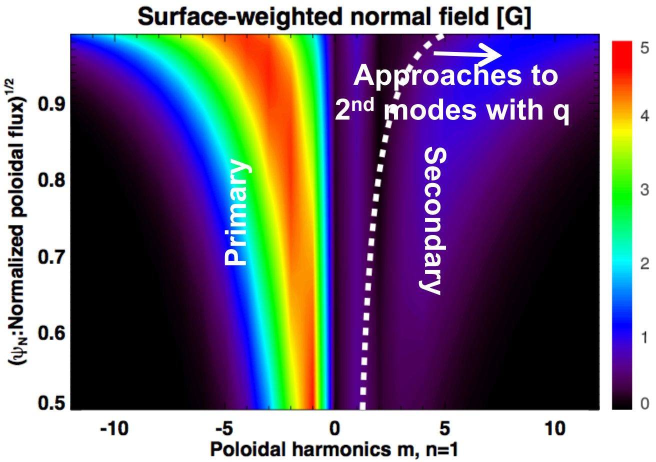
External kink coupling gives qualitative explanation, implying importance of small remnant RMP control for NRMP

- Resonant amplification is driven by well-known external kink coupling (m>nq)
- If q in the edge increases
  - Low m modes in 0° phasing move away from kink, becomes more non-resonant
  - m<0 modes in -90° phasing also move away, but small secondary m>0 modes approach

0° phasing

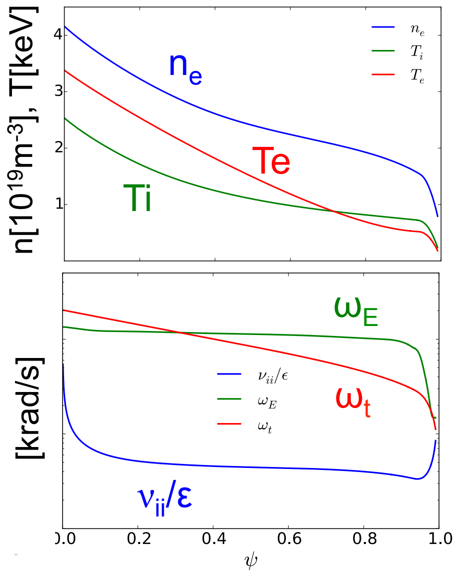


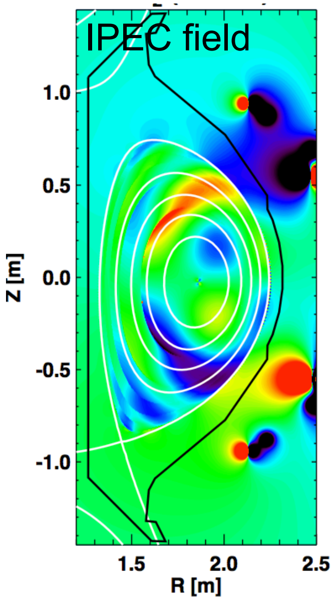
-90° phasing

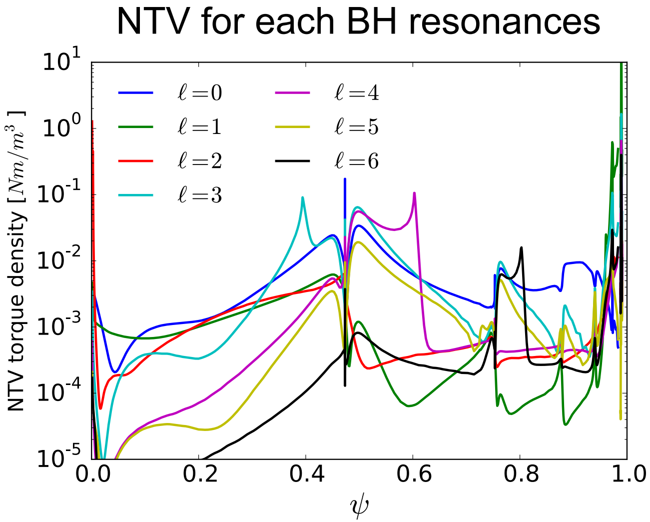


IPEC and PENTRC modeling used to evaluate resonant field and NTV, and figure of merit for quiescent NTV braking

- Figure-of-merit (FOM) for braking: Non-resonant vs. resonant torque $F_{QM} = \frac{T_{NTV}}{T_{j\times B}} \propto \frac{T_{NTV}}{\Sigma \delta B_{mn}^2}$
- IPEC-PENTRC is used for NTV simulation including bounce and transit resonant effects







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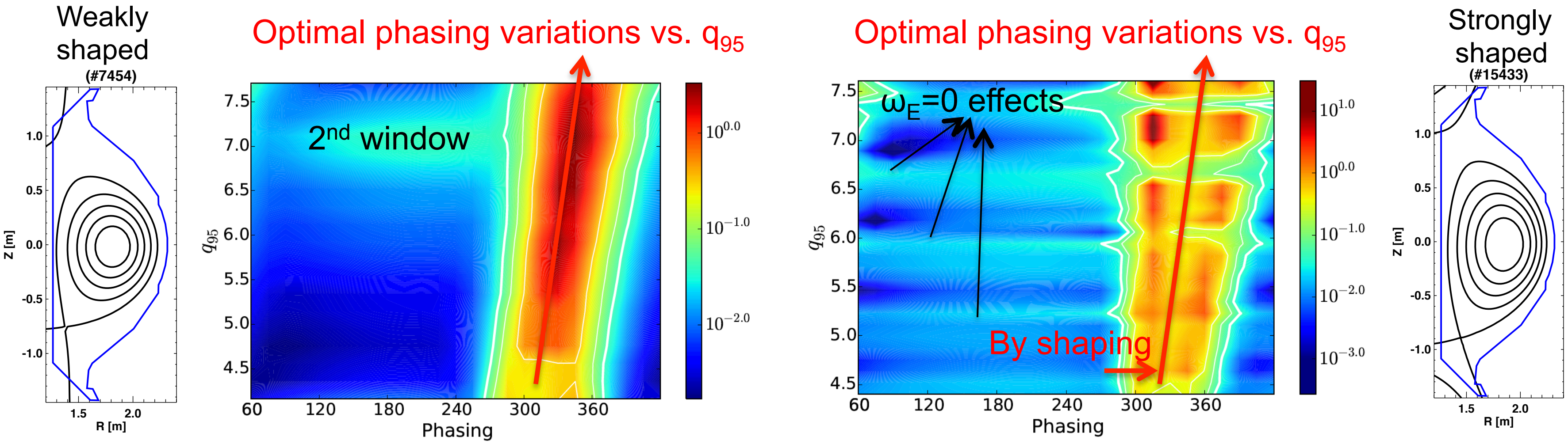
Modeled F_{QM} shows optimal phasing variations for quiescent braking consistent with observations

- Optimal F_{QM} moves to higher phasing (e. g. -90° → 0°) as q_{95} increases
- Optimal F_{QM} is also shifted to higher phasing when shaping increases
- F_{QM} model gives prediction consistent with observation
  - with new details, e.g. 2nd window for q_{95}>7.0, variation due to ω_E=0 at q surfaces



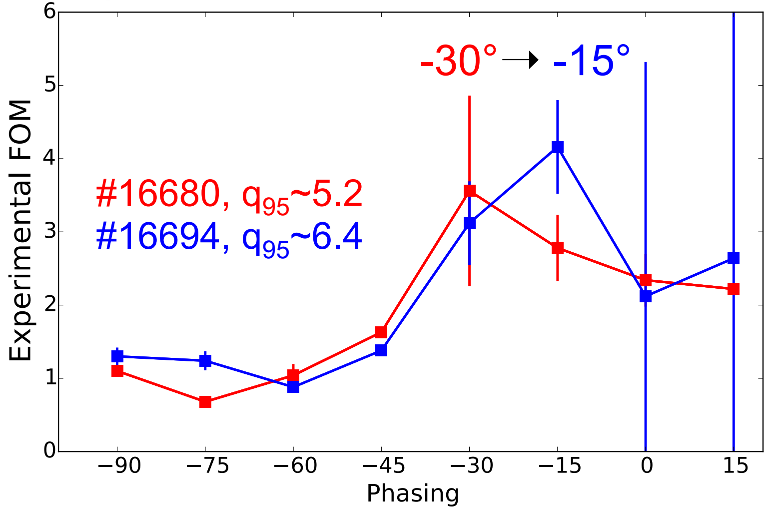
F_{QM} modeled by IPEC-PENTRC

Experimental validation for F_{QM} towards non-resonant field control for quiescent magnetic braking

- Empirically F_{QM} is about momentum vs. particle/heat level changes at the saturation level

$$F_{QM}^{Exp} = \frac{\Delta(nV)/nV}{\Delta(\Sigma nT)/\Sigma nT}$$

→ Empirical optimal phasing



- Modeled F_{QM} is however based on torque at the onset, which will drive rotation and energy degradation non-linearly

$$F_{QM}^{Exp} = \frac{\Delta(nV)/nV}{\Delta(\Sigma nT)/\Sigma nT} = \alpha\left(F_{QM}^{Model}\right)^{\beta}\ ?$$

- Quantitative comparisons with fine tuning for non-resonant coil configurations are important for physics validation and prediction for F_{QM}

Summary and Conclusion

- Versatile 3-rows of coils in KSTAR provide various n=1 NRMPs with fine tuning capability on field spectrum

- Optimal n=1 phasing for quiescent braking varies with q_{95} and shaping

- $F_{QM}=T_{NTV}/T_{JXB}$ modeling with IPEC-PENTRC explained empirical trends very well, including -90° vs 0° phasing issue, and predicted new details

- This study shows importance of remnant RMP control in NRMP applications, and modeled and validated F_{QM} can be used to predict quiescence in magnetic braking of rotation/shear