Extended 3D Physics Capabilities with NCC (Non-axisymmetric Control Coil)

Jong-Kyu Park
For NCC working group and NSTX-U Research Team

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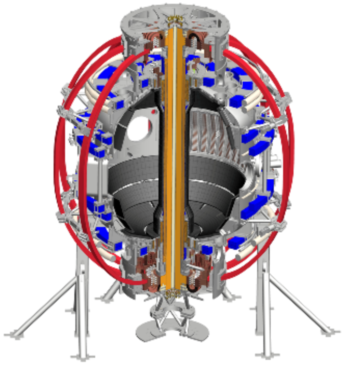
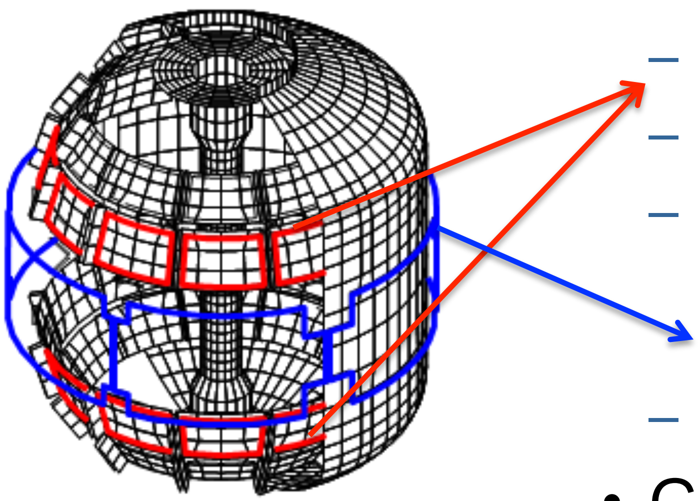
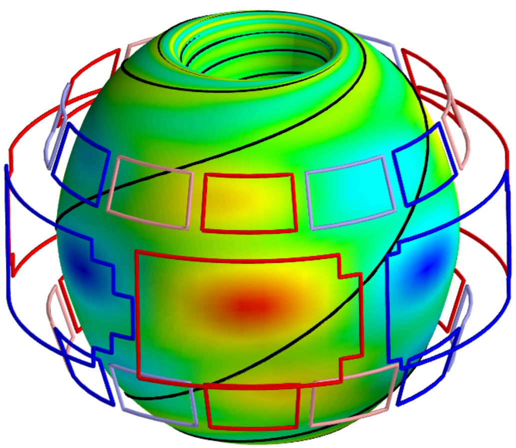


NCC is a set of 3D coils off the midplane, under physics studies and conceptual design

VALEN3D



IPEC – non-resonant n=3

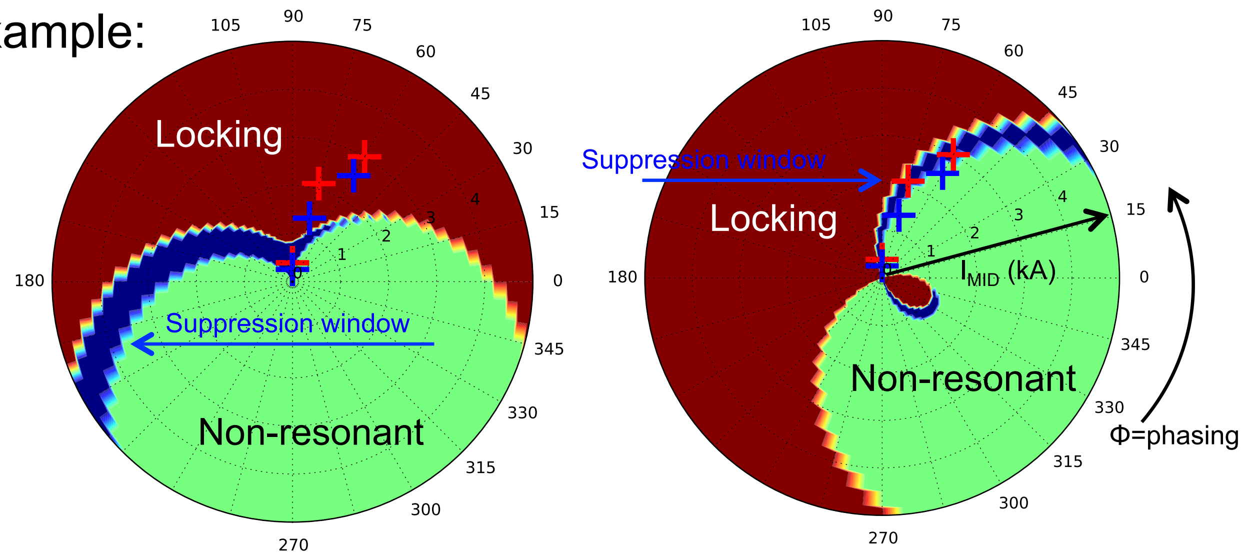


- NCC:
  - 2x12 off-midplane coils
  - Upper (NU) + Lower (NL) internal coil array
  - Practically 3 rows of internal coils as planned for ITER, if combined with existing (external) Midplane coil array
  - n=1-4 rotating capability with 6 SPAs
- Goal is to extend 3D capabilities on
  - Control of error field, magnetic braking (NTV), RWMs, ELMs, fast ion distributions, transport via rotation shear
- Physics studies still desired
  - To see if NCC can provide controllability, variability, flexibility, optimal fields w.r.t. known physics scaling and hypothesis

NSTX never achieved ELM suppression, but NCC + midplane will increase the probability of success (as shown in KSTAR)

- NSTX never achieved ELM suppression (ELM triggering instead) – questioning on RMP concept for ST or different operating regime
- 3 rows of internal coils can provide a way to access ELM suppression window by efficient edge-coupling as recently demonstrated in KSTAR

KSTAR n=1 example:
$I_{MID}<I_U=I_L=5kA$
$\phi=\phi_{UM}=\phi_{ML}$



(a) Vacuum superposition (b) With ideal response

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Empirical threshold (Locking "+", ELM suppression "+")

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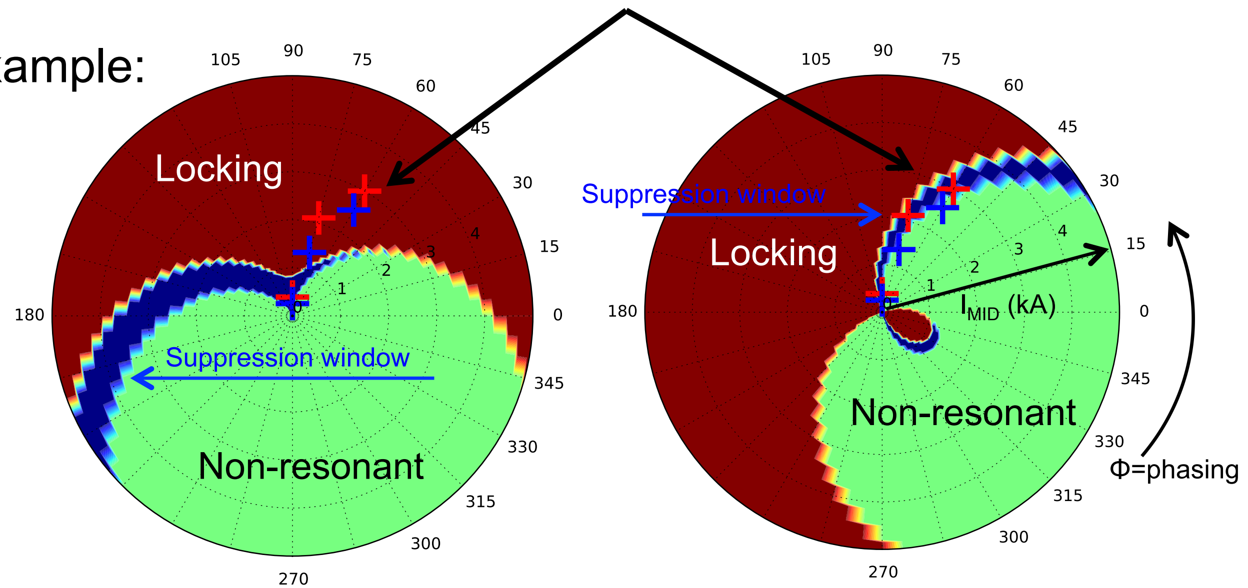

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Overview of physics studies

- IPEC+PENT: EF correction capability with minimized (or maximized) NTV, NTV with minimized resonant field – momentum vs. particle
- IPECOPT (IPEC+STELLOPT): Core NTV vs. Edge NTV
- VALEN3D : RWM control capability and optimized sensors
- MARSK: Response change by kinetic and rotational effects
- VMEC+COBRA: Ballooning instability in 3D geometry
- TRIP3D: Vacuum Island Overlap Width with NCC

Studies underway (Not all listed)

- GPEC: NTV optimization with self-consistent calculations
- M3D-C1: Single and two-fluid responses
- TRIP3DGPU with M3D-C1: Accurate field line integrations
- MARS-K: Advanced MHD spectroscopy

GPEC shows NCC can drive core-concentrated NTV while minimizing edge NTV, and vice versa

- GPEC gives self-consistent NTV torque matrix:

$$\tau_{NTV}(\psi) = \vec{\Phi}^{x\dagger} \cdot \overleftrightarrow{T}(\psi) \cdot \vec{\Phi}^{x}$$

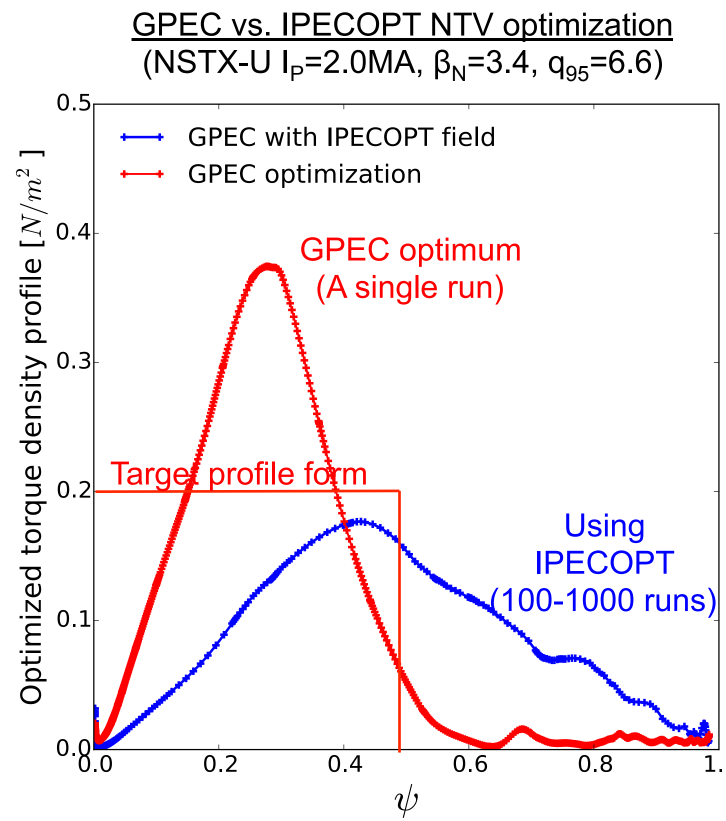
  – T is MxM matrix function (M: # of poloidal modes)

- Changing basis from $\mathbf{\Phi^x}$ to coil vector **C**:

$$\tau_{NTV}(\psi) = \vec{C}^{\dagger} \cdot \overleftrightarrow{T}_C(\psi) \cdot \vec{C}$$

  – NSTX-U NCC+MID: T_C is 3x3 for n=1-2 (for n=3, constrained 3x3)
  – KSTAR IVCC: T_C is 3x3 for n=1 (Studied for NTV)
  – ITER RMP+EF: T_C is 6x6 for n=1-2, 3x3 for n=3-4

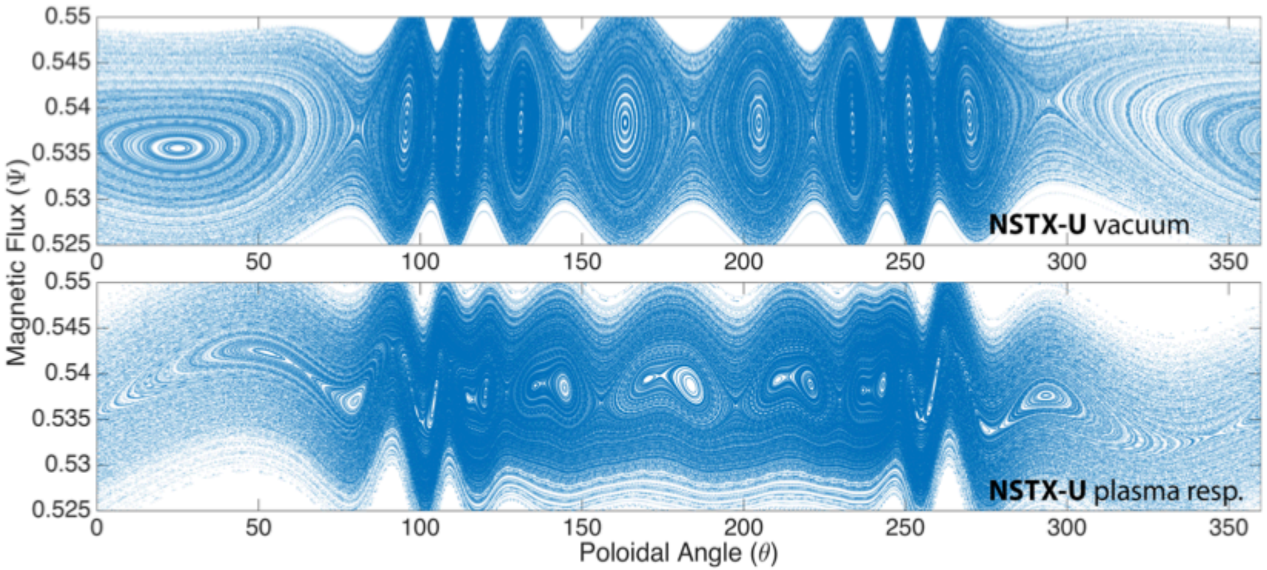
- Torque response matrix T contains all the information about self-consistent NTV torque that can be generated by external fields, or coils in a device



TRIP3DGPU will give accurate assessment of field line splitting with advanced 3D modeling

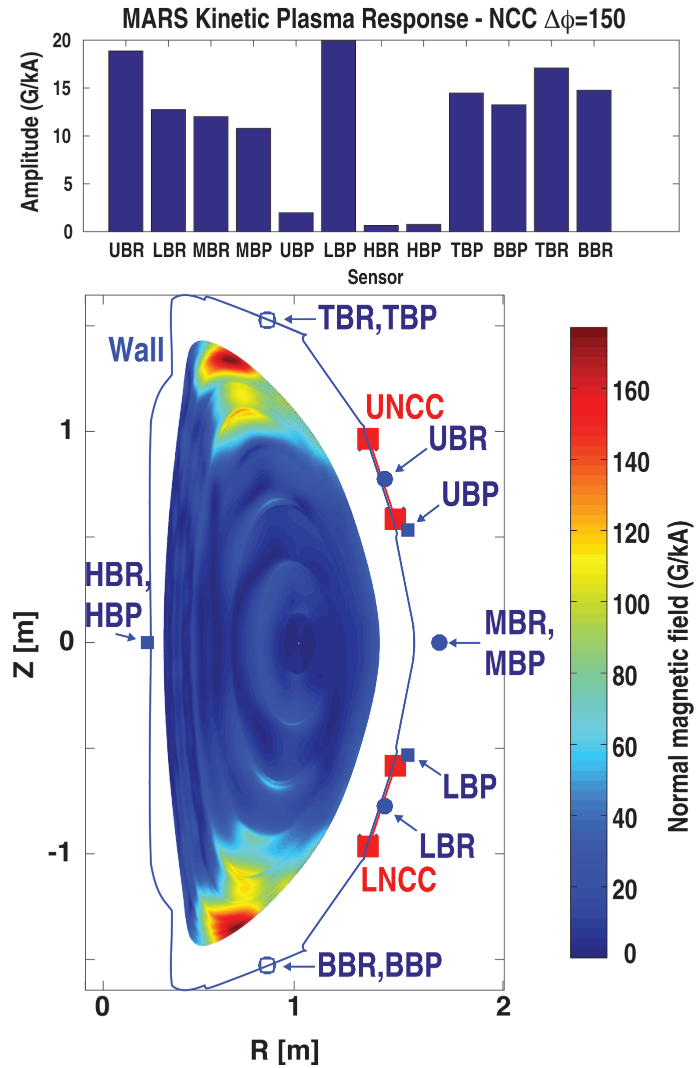
- PPPL-GA collaboration with TRIP3DGPU + M3D-C1 showed the importance of accurate equilibrium reconstruction in field line tracing
- Two competing effects in plasma response, “screening” of RMP islands and “kinking” of flux surfaces by NRMP
  - Compared to DIII-D, NSTX-U shows “less” screening and kinking, although still vacuum islands can be significantly affected by plasma response

In the courtesy of T. Evans



Advanced sensors and MHD spectroscopy will be important to address extended 3D capabilities by NCC

- PPPL-GA collaboration has been leading the design of advanced sensors, to better measure poloidal structure of 3D plasma response
- MARS-K applications showed good locations to install new sensors, and to effectively measure kinetic 3D response to NCC
- New sensors to control RWM with NCC have been also extensively studied with VALEN-3D



In the courtesy of M. Lanctot, E. Strait

Summary and Future work

- Studies showed that NCC can likely provide large figures of merit for error field correction, NTV rotation control, RMP ELM control, and RWM and PBM control
  - Coherency in the spectrum can be the best in the world by NCC+MID

- NCC+MID on NSTX-U provides both opportunity and challenge for new and advanced 3D numerical simulations, which can be validated in NSTX-U experiments in the future

- Still need to explore
  - If NCC can provide particle control, and RMP ELM suppression
  - If NCC can give better phase-space engineering for fast ions and heat flux splitting (with also advanced divertors)
  - If NCC can better control NTV and rotation shear to improve microturbulence
  - Optimal sensors to control RWM, to measure 3D response to NCC