NSTX-U 5 Year Plan for Non-axisymmetric Control Coil (NCC) Applications

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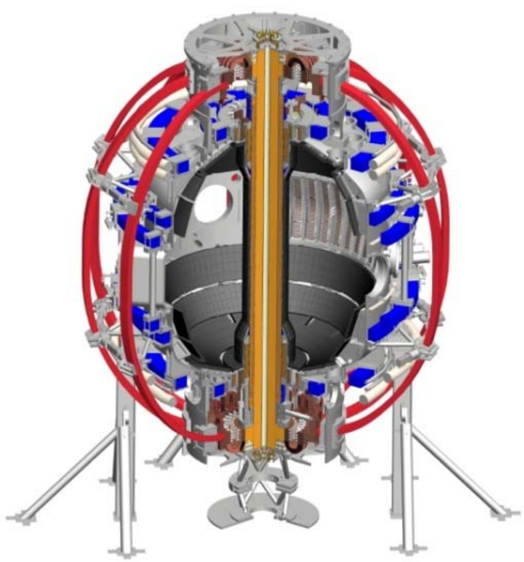

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Motivation

- The use of 3D fields to control error fields, RWMs, momentum (rotation), and particle/heat transport is essential to meet NSTX-U programmatic/TSG goals and support ITER
  - Access reduced ν^* and high-β combined with ability to vary q, rotation
  - Error fields: To control LMs and TMs at low collsionality
  - Rotation: To improve micro-to-macro stability
  - Particle/heat: To modify pedestal, edge stability, divertor flux
  - RWMs: To achieve high-β advanced operation with active control

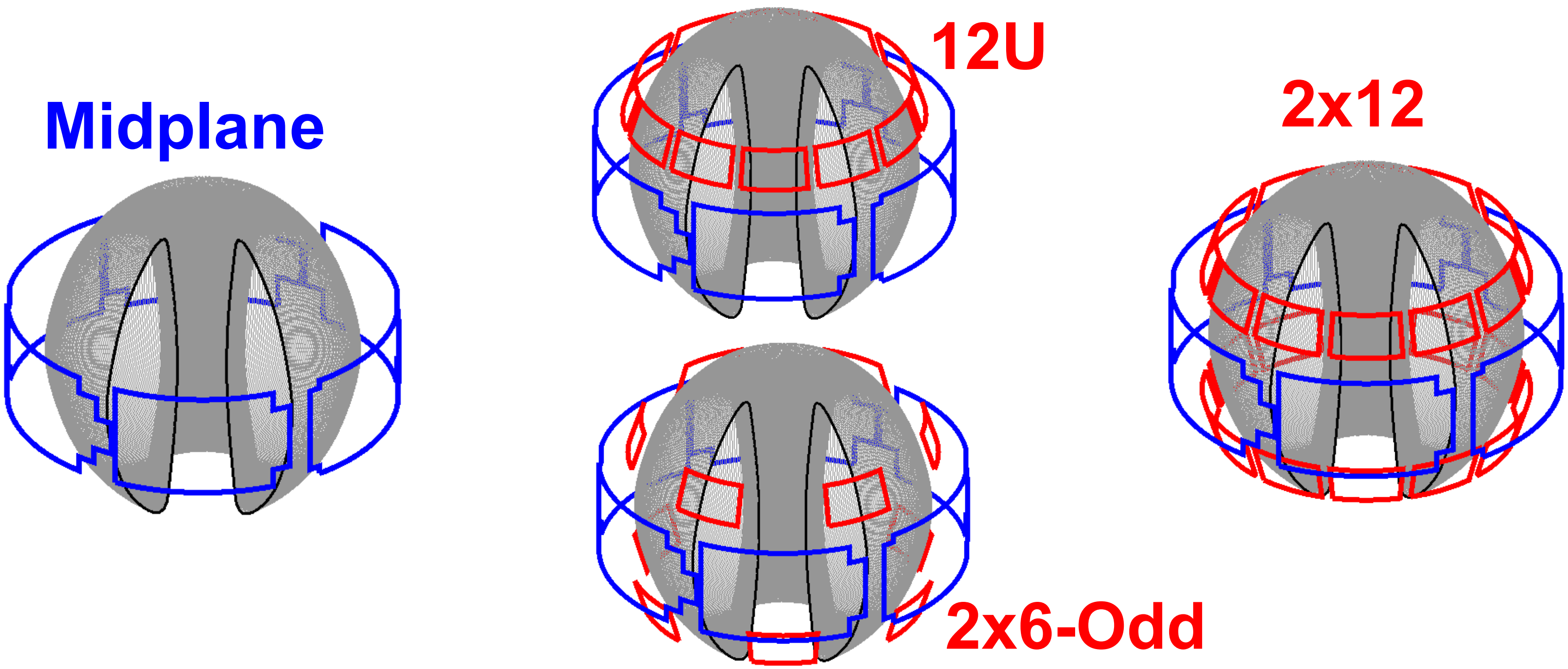
- Proposed non-axisymmetric control coils (NCC), if combined with present RWM/EFC, will be a unique and powerful 3D tool for future STs as well as tokamaks

Outline

- Proposed NCC geometry for NSTX-U
  - Partial and full choices for NCC
- Comparison of partial/full NCCs using Figures-Of-Merit
  - Error field control
  - Rotation control
  - RMP for ELM control
  - RWM active control
- Summary
  - Coil performance comparison table
- Future plan for analysis

A range of off-midplane NCC coil configurations is being assessed for potential physics capabilities

- NCC proposal: Use two off-midplane rows of 12 coils toroidally
  - To produce rich poloidal spectra for n=1 – 6
  - To rotate n=1 – 4
  - Poloidal positions of 2x12 coils have been selected based on initial studies
- Partial NCCs are also under active investigation
  - Anticipate possible staged installation to the full 2x12
  - 3 best options are presented here and compared with existing midplane coils



Figures-Of-Merit for EF/NTV/RMP/RWM have been analyzed with partial/full NCCs for NSTX-U

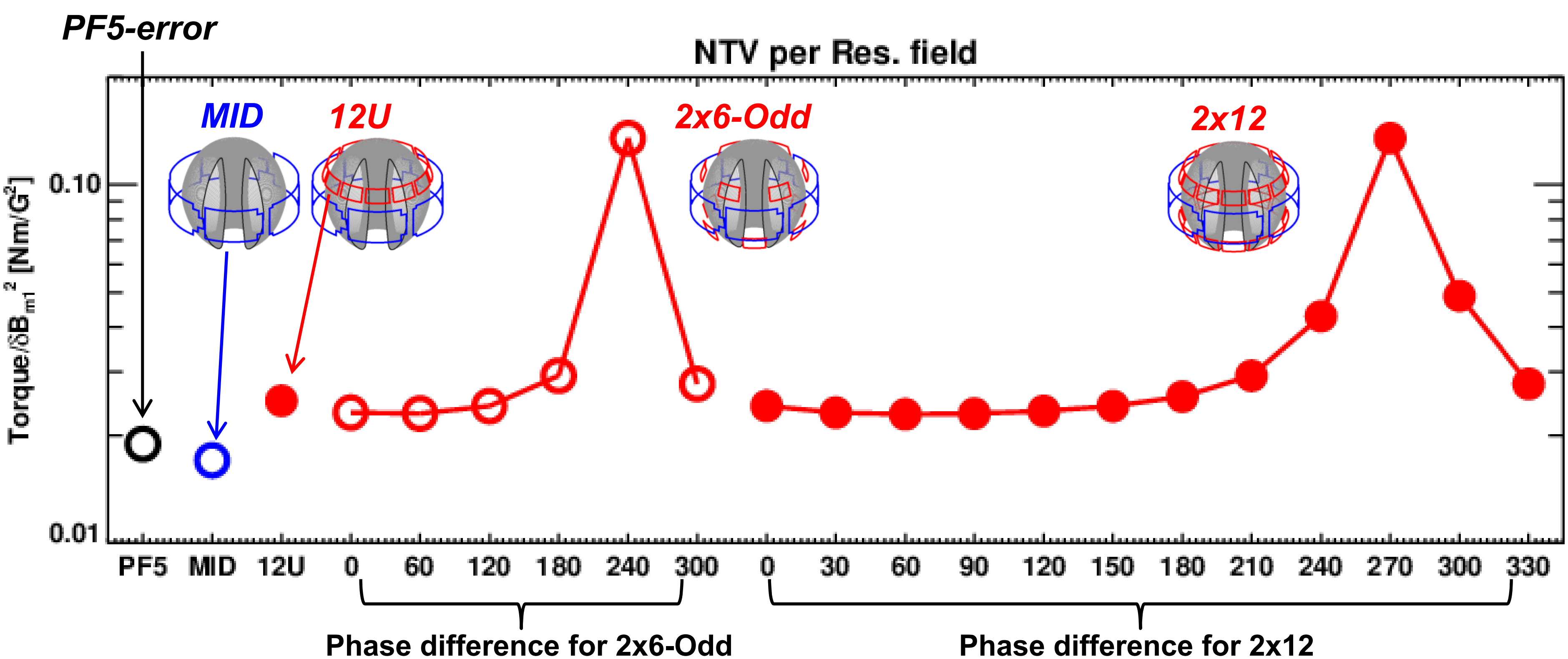
- Various combinations of targets and coils have been investigated
  - NSTX-U target plasmas: TRANSP
  - Stability analysis: DCON
  - 3D equilibrium analysis: VAC3D and IPEC
  - NTV analysis: Combined NTV
  - RWM analysis: VALEN3D

- Figures-Of-Merit defined for each physics element
  - **Error field control: NTV per resonant field**
    Quantifies selectivity of non-resonant vs. resonant field
  - **Rotation control: Core NTV per Total NTV**
    Quantifies controllability of rotation by NTV braking
  - **RMP for ELM control: NTV per Chirikov**
    Quantifies edge particle/heat control without affecting core
  - **RWM active control: β Gain**
    Quantifies high-β advanced operation

Selectivity of n=1 non-resonant field vs. resonant field can be greatly enhanced with partial NCCs

- Figure of Merit for error field control: NTV per resonant field
  - High FOM is good for the field application without locking or tearing excitation
  - Variability of FOM can be advantageous for error field physics study
- FOM can be largely enhanced with 2x6-Odd, comparable to 2x12

$$F_{N-R} \equiv \frac{T_{NTV}}{\sum_{\psi_N < 0.85} \delta B_{mn}^2}$$



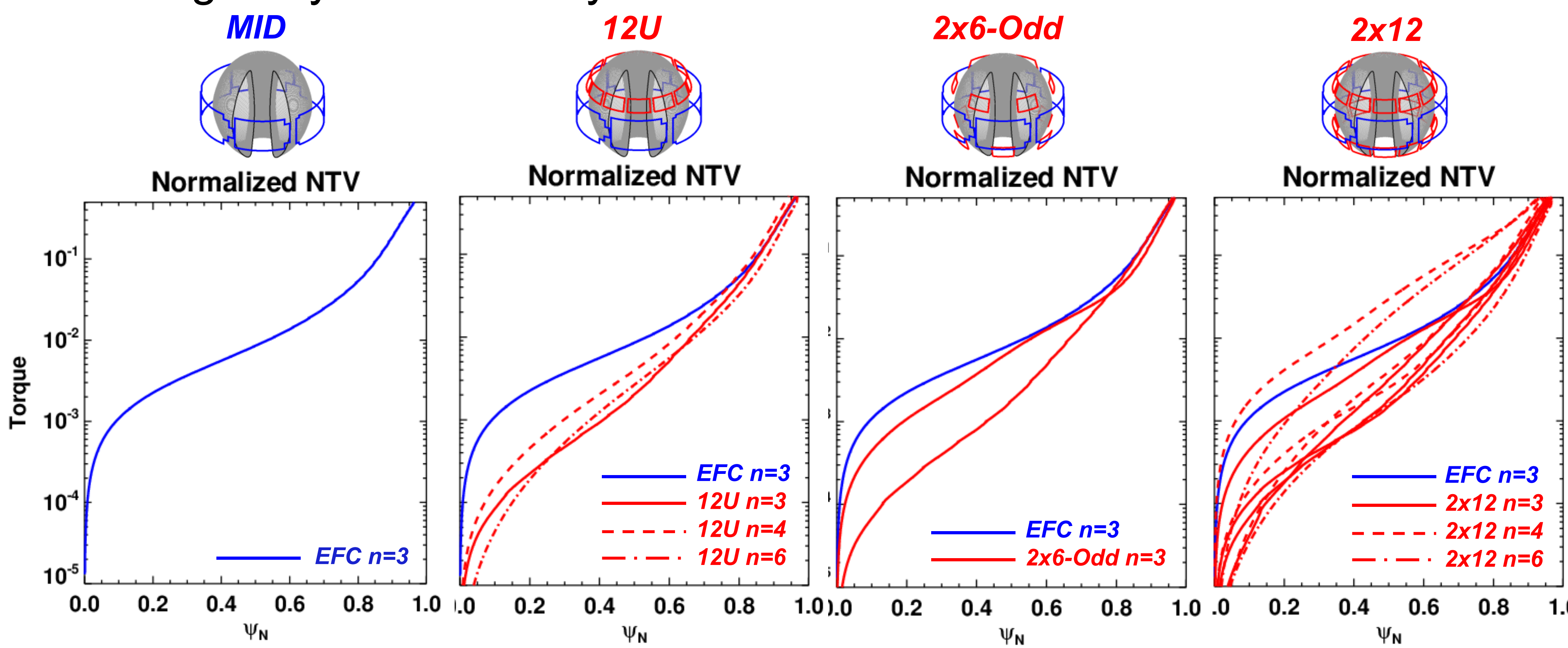
** Combinations of EFC to NCC are not shown here*

Controllability of rotation by NTV braking can be enhanced slightly by 2x6, and largely by 2x12

- Figure of Merit for rotation control: Core to total NTV
  - Variability of FOM is good for rotation profile and rotation shear control

$$F_{N-N} \equiv \frac{T_{NTV}(\psi_N < 0.5)}{T_{NTV}(\psi_N < 1)}$$

- Variability of core NTV braking can be slightly enhanced by 2x6-Odd, but will be greatly increased by 2x12

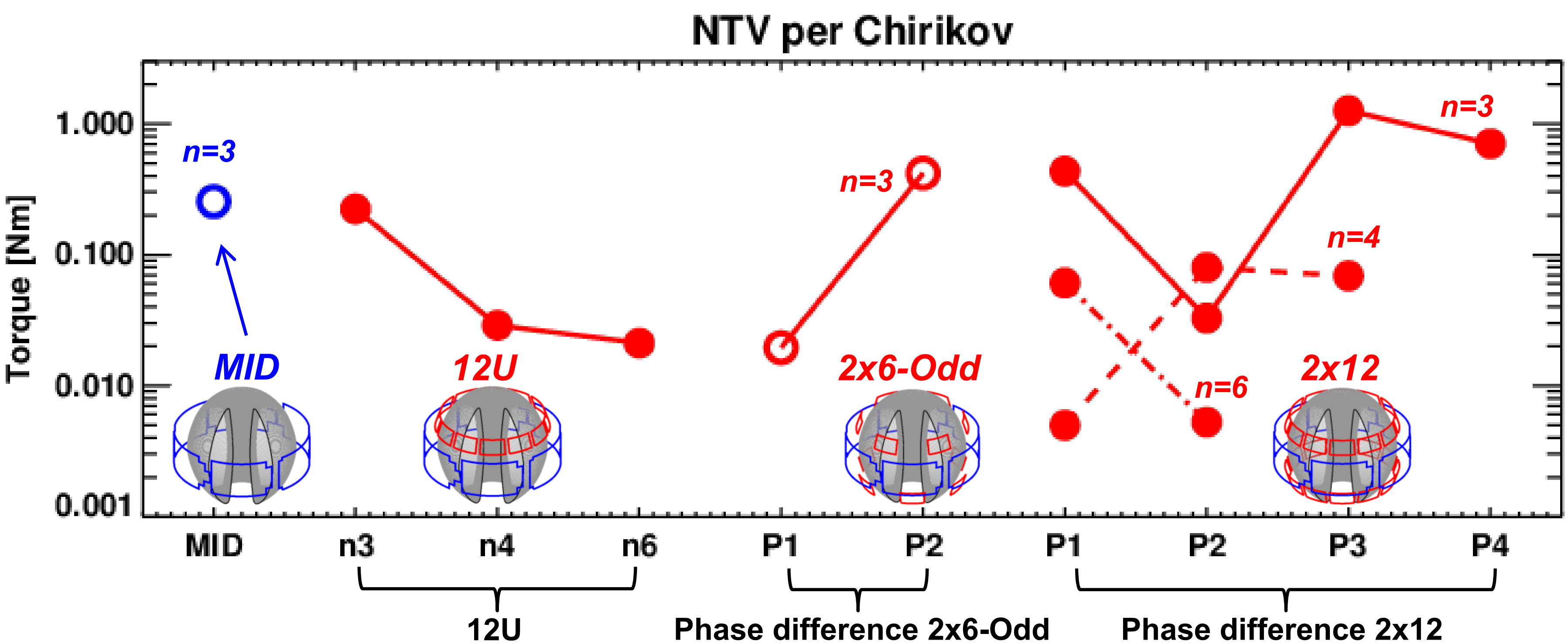


*** Same line types are used when only phases between upper and lower coils are different***

*** Combinations of EFC to NCC are not shown here***

RMP characteristics can be improved by 1x12 or 2x6, and even more refined by 2x12

- Figure of Merit for RMP: NTV when Chirikov=1 is achieved $F_{N-C} \equiv \frac{T_{NTV}}{\left(C_{vacuum,\psi_N=0.85}\right)^4}$
  - Low FOM is good since it is important to access Chirikov=1 without driving 3D neoclassical transport
  - Variability of FOM can be advantageous for RMP physics study
- NTV can be reduced by 1x12 or 2x6, and can be even be decreased by up to an order of magnitude by n=4 and n=6 in 2x12

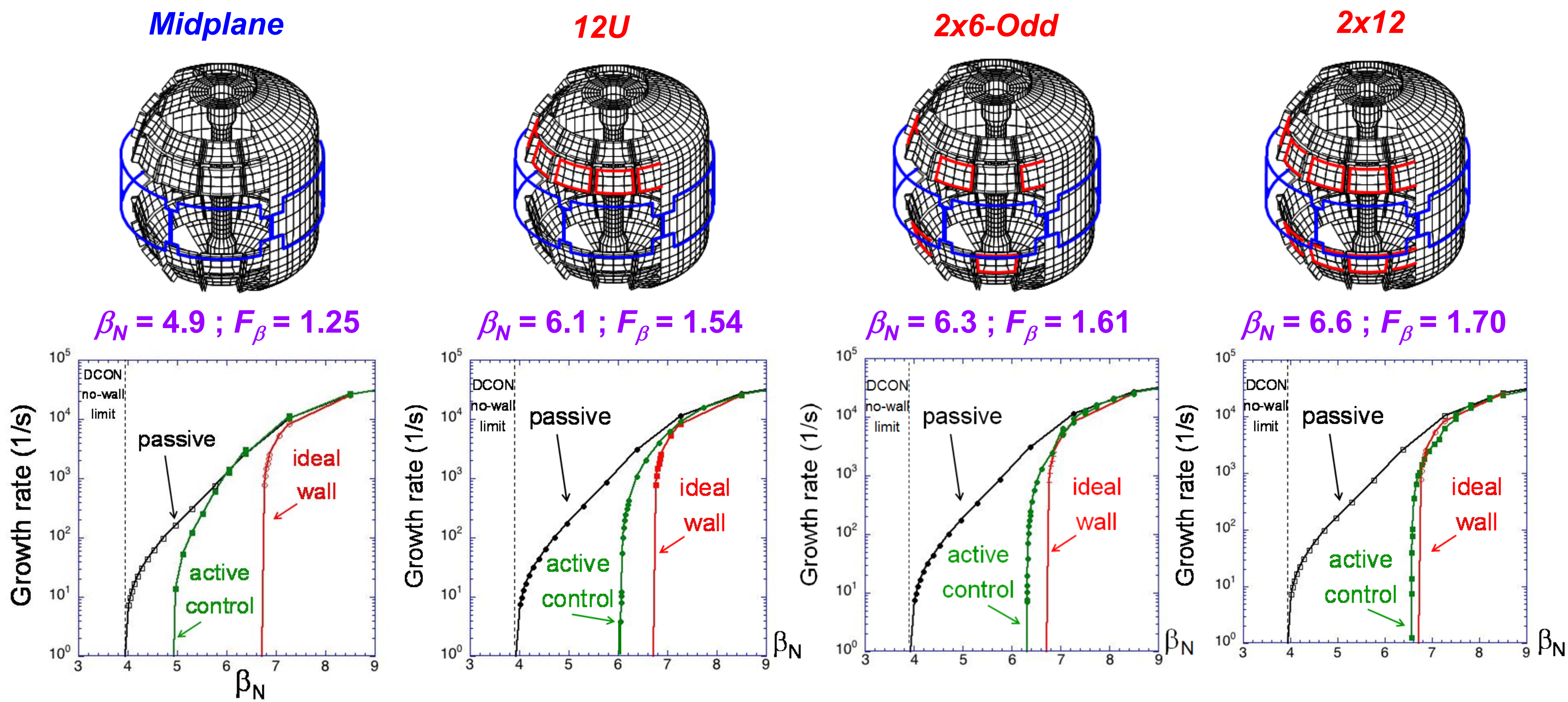


** Combinations of EFC to NCC are not shown here*

RWM control capability increases and physics studies are expanded as NCC coils are added

- Figure of Merit for RWM control: β gain over marginal stability
  - High FOM is good for sustained high-β operation
- RWM control performance increases as NCC coils are added
  - Full 2x12 option: very close to the ideal-wall limit

$$F_\beta \equiv \frac{\beta_{active}}{\beta_{no-wall}}$$



Summary of analysis

- Figures-Of-Merit analyses indicate 2x6-Odd is more favorable than 12U for error field, rotation control, RMP, RWM control
  - 12U can provide high-n rotating capability, but poloidal spectrum is too limited to give good FOM

Figures of Merit	Favorable values	MID	12U	2x6-Odd	2x12
EF (n=1) $F_{N-R} \equiv \dfrac{T_{NTV}}{\sum_{\psi_N<0.85} \delta B_{mn}^2}$	High F_{N-R}	0.017	0.025	0.13	0.13
	Wide ΔF_{N-R}	1.00	1.00	5.65	5.65
NTV (n≥3) $F_{N-N} \equiv \dfrac{T_{NTV}(\psi_N < 0.5)}{T_{NTV}(\psi_N < 1)}$	Wide ΔF_{N-N}	1.00	2.00	3.97	19.6
RMP (n≥3) $F_{N-C} \equiv \dfrac{T_{NTV}}{\left(C_{vacuum,\psi_N=0.85}\right)^4}$	Small F_{N-C}	0.25	0.021	0.019	0.005
	Wide ΔF_{N-C}	1.00	10.5	22.1	252
RWM (n=1) $F_\beta \equiv \dfrac{\beta_{active}}{\beta_{no-wall}}$	High F_β	1.25	1.54	1.61	1.70

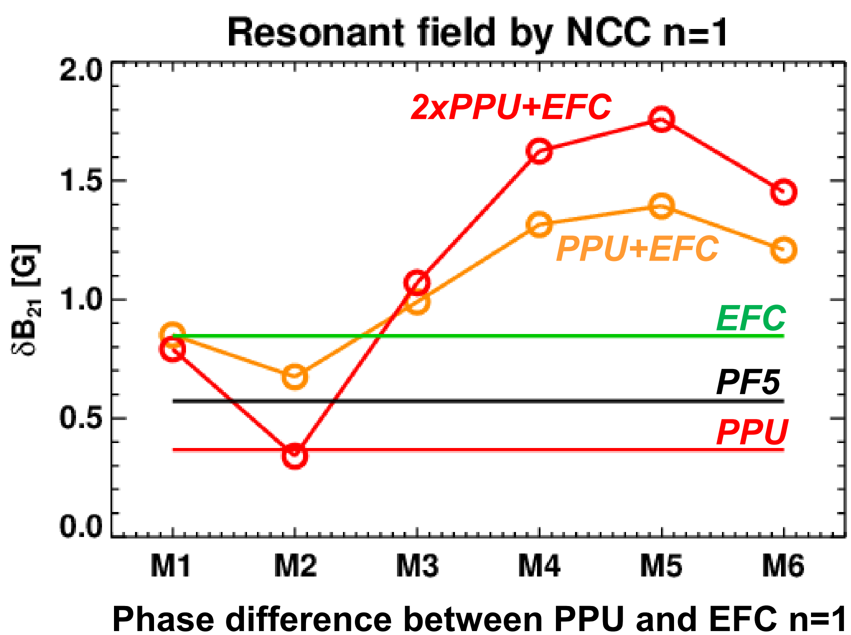
Future analysis plans

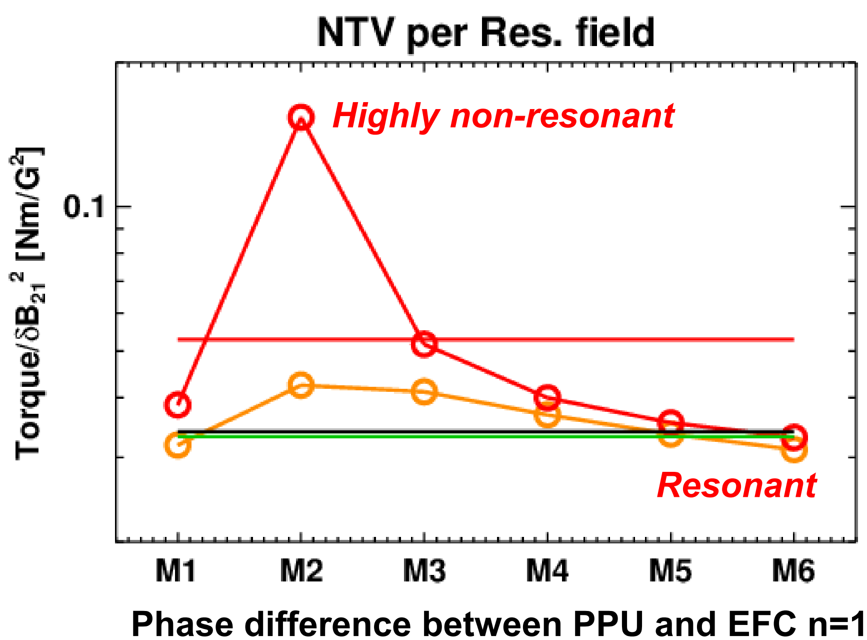
- Additional configurations will be investigated
  - Combined coil configurations between NCCs and EFC, including different Ampere-turn ratios, and with constraint of only 6 independent power supplies
  - Target plasmas with different q_{min} and q-shear
  - VALEN3D calculations of conceptual design of optimized sensors for RMP control
- Important coil configurations will be identified based on FOM and coupled with varied collisionality and rotation
  - Present IPEC-NTV calculations will be performed
  - NTVTOK, MISK, MARS-K calculations will be added
- Advanced computations will be performed for selected coil configurations, target plasmas, kinetic profiles
  - POCA will be used for selected cases
  - FORTEC3D or XGC0 can be tested for a few limited cases

Back up

1x6 array can provide large selectivity of non-resonant to resonant field

- 1x6 PPU array produces comparable resonant field per currents with very different non-resonant field contents
- "Non-resonant field selectivity", defined by NTV torque per $(dB_{21})^2$, can be varied by an order of magnitude if PPU and EFC currents are optimized
  - This capability is essential to understand "non-resonant error field" effects on locking and tearing in tokamaks including ITER **MS** **ITPA WG9**

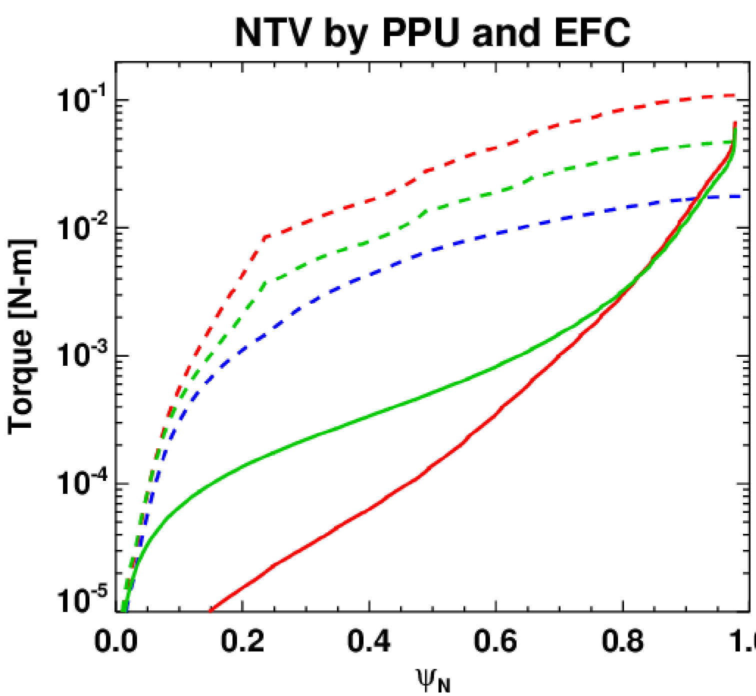




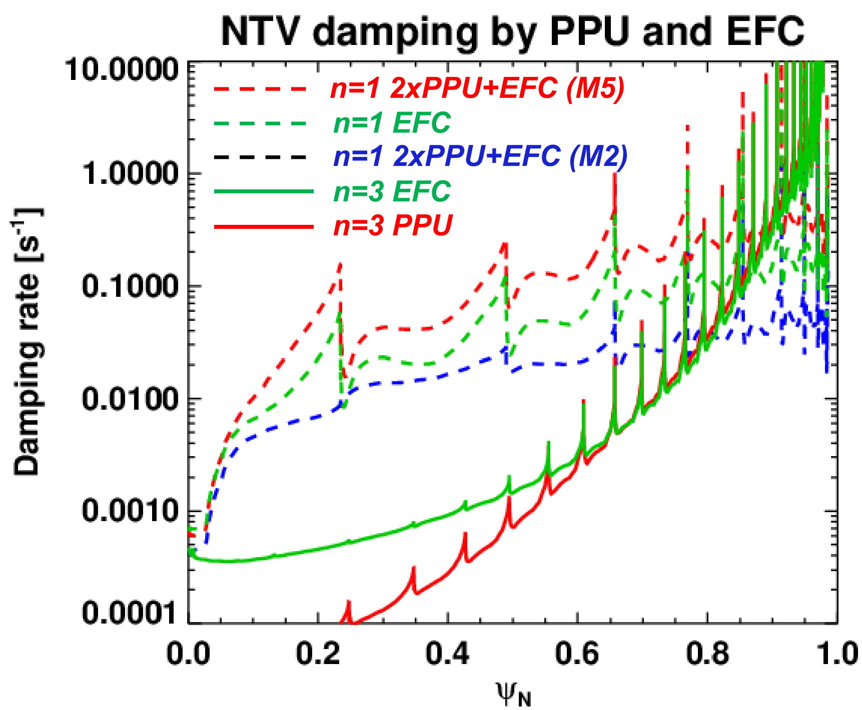
**PPU currents per EFC (1kAt is the base) should be further optimized (Likely more than 2)*

Local rotation control will be possible to large extents if n=1 and n=3 PPU+EFC are utilized

- 1x6 PPU, when combined with EFC, can produce spatially very different NTV braking profiles
- Local control of rotation and rotation shear will be possible to large extents if combined with off-axis NBI beams
  - This capability is essential to achieve advance control of macroscopic to microscope instabilities **MS, TT, EP**



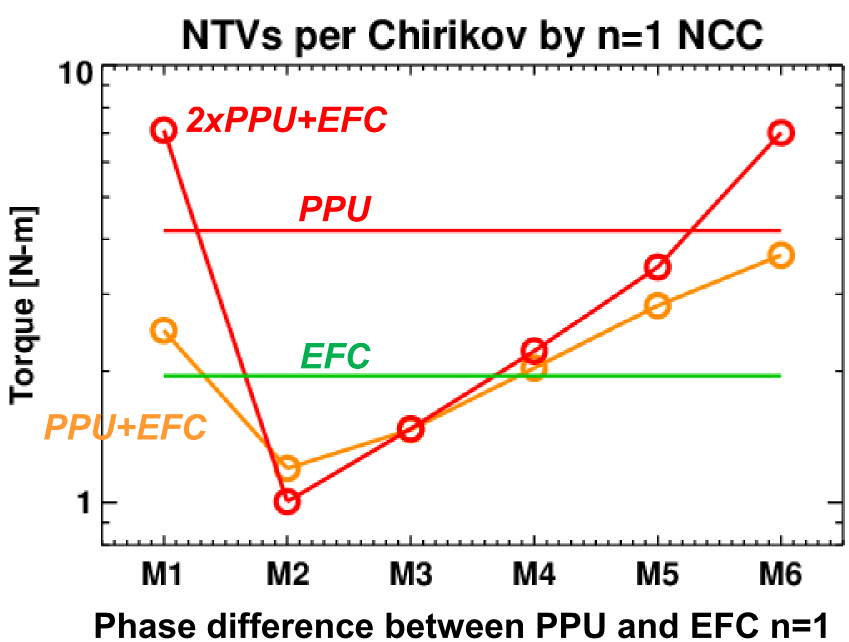
**Note torque profile is the integrated torque from the core*

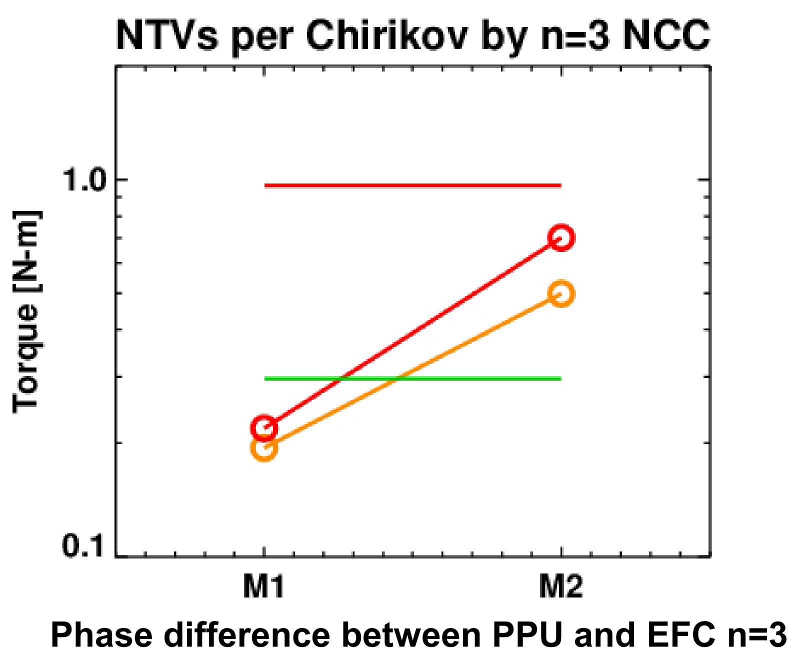


**Note damping profiles assume NTV alone, but should be combined with NBI and momentum diffusion model*

PPU can increase figure of merits for RMP, which can be tested against ELM triggering capability

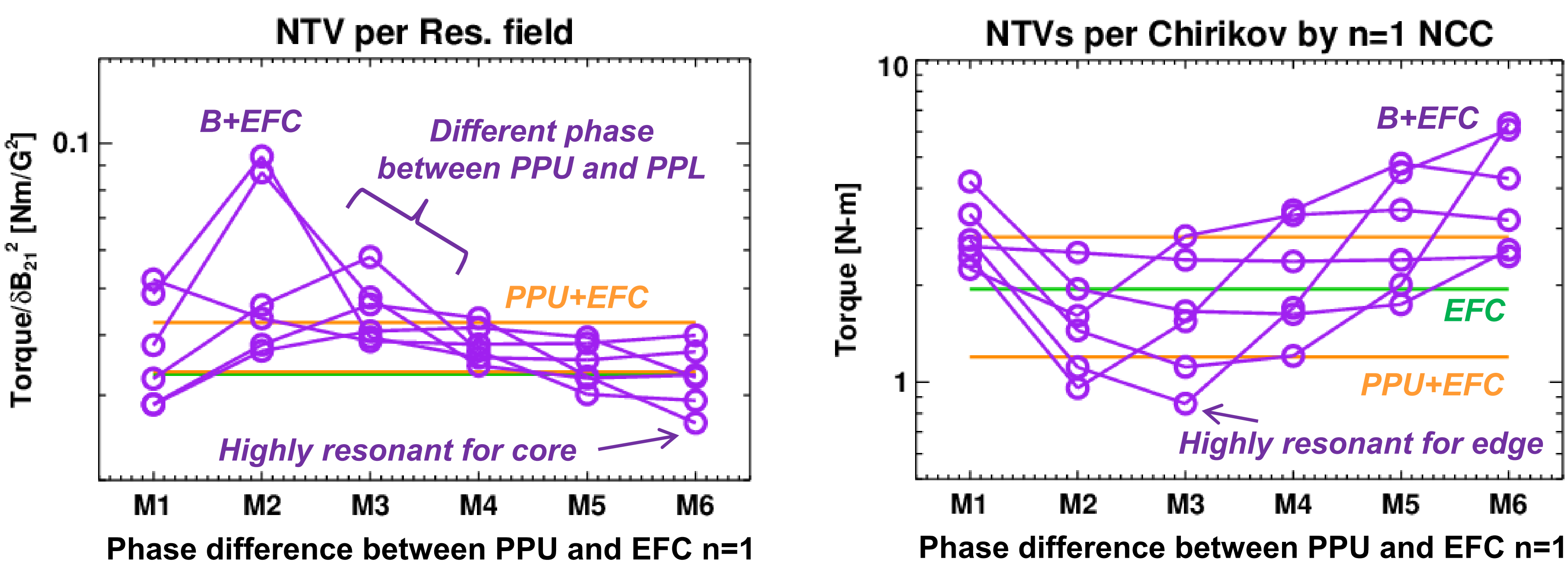
- 1x6 PPU, when combined with EFC, can meet Chirikov overlap criteria with various NTV braking characteristics
  - Figure of merit can be defined by NTV when Chirikov overlap parameter = 1
- Wide range of figure of merit can be produced when PPU is optimized with EFC, and can be tested for ELM modification
  - n=1 can give 1~10, and n=3 can give 0.1~1.0 Nm per Chirikov
  - ELM triggering vs. suppression threshold can be studied **BP**





Another 6-array can largely extend n=1 and n=3 field selectivity, rotation controllability, FOMs

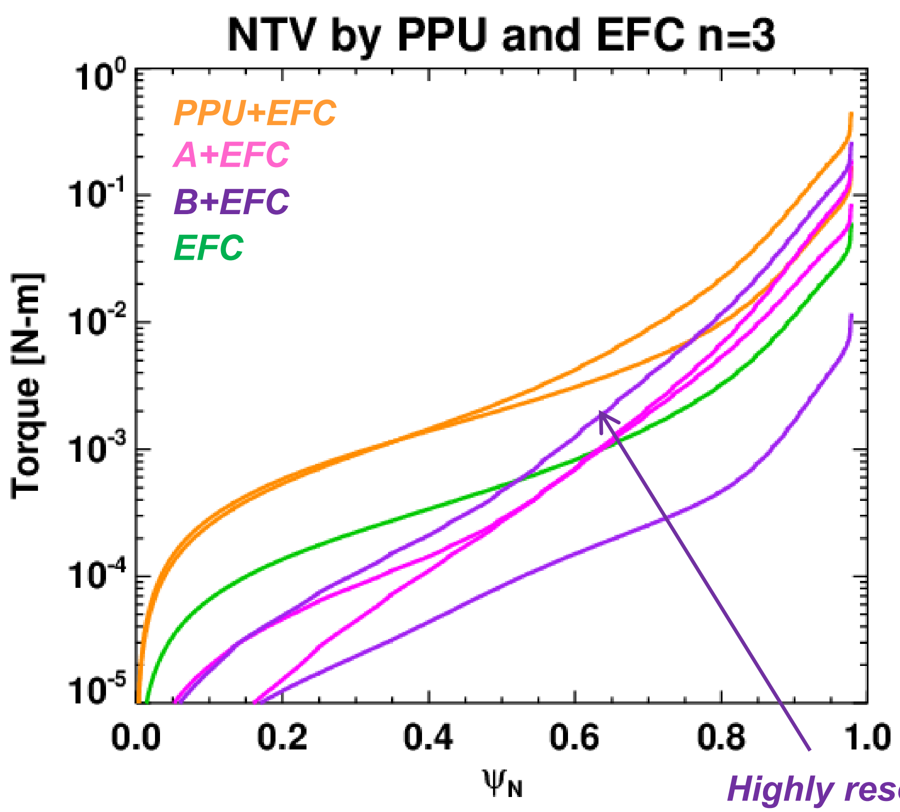
- Another 6-array can largely extend "non-resonant" and "resonant field selectivity" by changing alignment between fields to resonant helical pitch
- RMP figure of merit can be also further increased or decreased
  - **Particularly 2x6 is essential to decrease torque/dB_{21}^2, and thus increase "resonant field selectivity", and also to decrease torque per Chirikov**
- Optimized currents are expected to greatly improve n=1 capability *MS, BP*

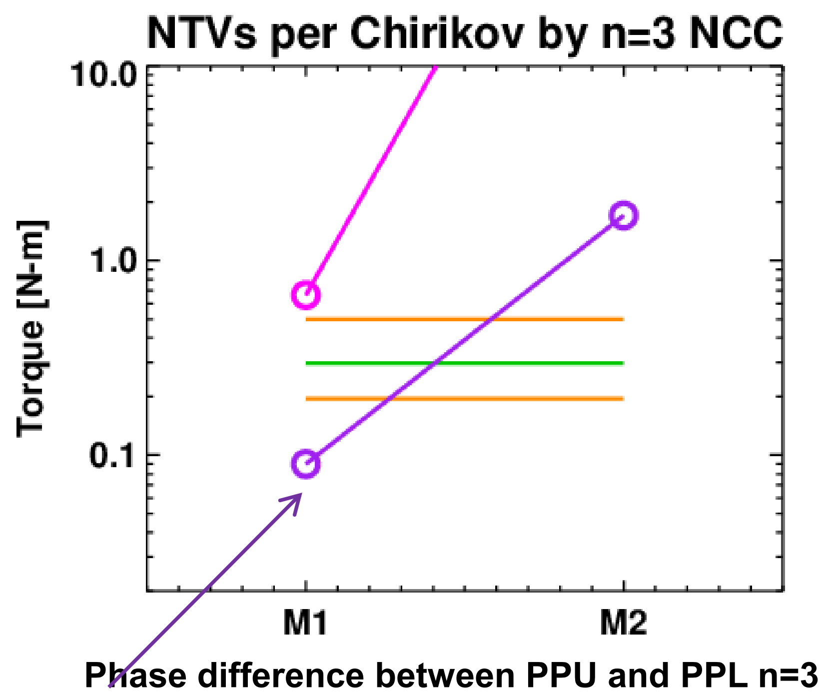


**All coils are in the same currents (1kAt is the base) and ratio is not optimized*

2x6 array, if optimized (B#), NTV braking controllability and RMP FOM variability can be largely enhanced

- 2x6 array can increase NTV braking controllability when option B# is used and EFC is nulled or optimized **MS, TT, EP**
- Option B is also effective to produce good RMP, by decreasing NTV per Chirikov **BP**



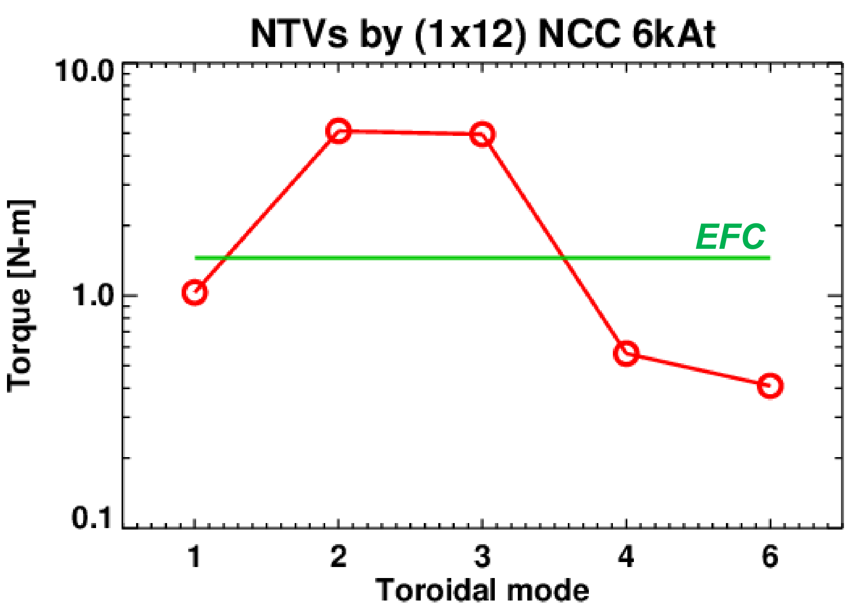


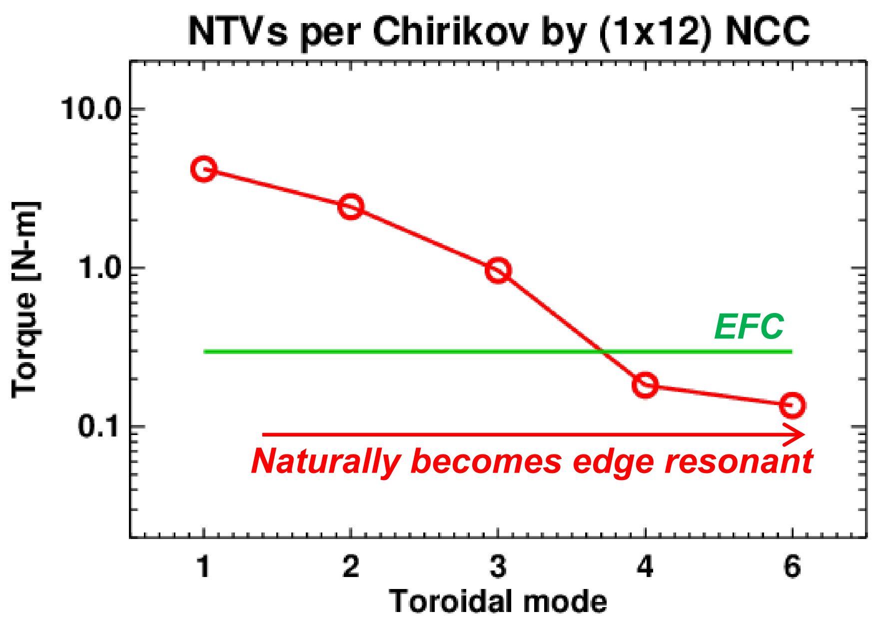
Highly resonant with edge

**Note torque density profile for n≥3 is always peaked in the edge for these examples, which means that rotation profile will be primarily scaled down by momentum diffusion, but other q-profile equilibrium can be different*

1x12 array NCC will be important to explore n≥3 spectral variations and rotation capability

- 1x12 upper array alone can enhance rotation controllability and RMP characteristics using natural attenuation of high toroidal harmonics
- ITER aims n≥3, and 12 toroidal array will allow detailed n≥3 physics studies with 3D diagnostics by field rotation
- Preliminary studies for full NCC with 2x12 (without combined with EFC) showed an-order-of-magnitude variation in rotation and RMP FOM can be easily produced **MS, TT, EP, BP**





Full NCC can provide high-β advanced operation near ideal-wall limit by active RWM control

- Full NCC, if combined with idealized sensors, will allow high-β advanced operation even near ideal-wall limit by active RWM control **MS, ASC**
  - Idealized sensors: RWM control up to $\beta/\beta_{no\text{-}wall} = 1.70$ ~ ideal wall limit
  - Present sensors: lower performance, but can be optimized with state-space controller