NSTX-U

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

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for the NSTX Research Team

NSTX-U 5 Year Plan Review
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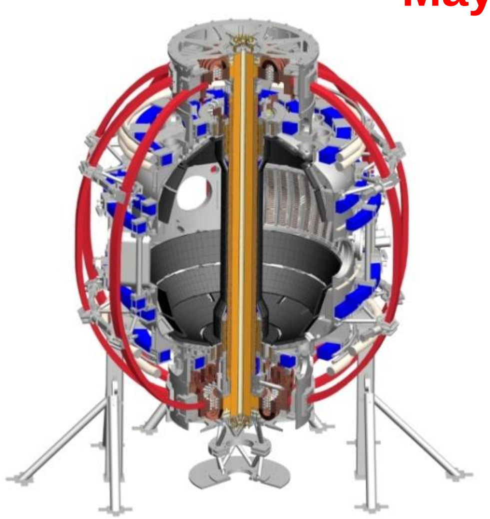

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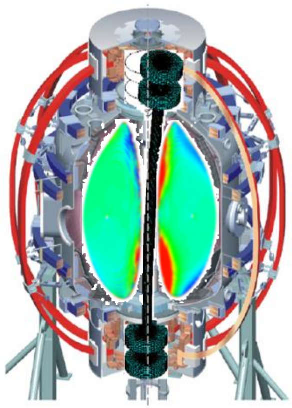
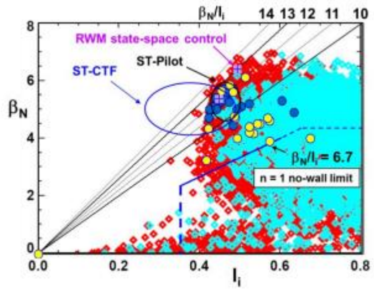
Motivation: Expanded 3D field capability on NSTX-U is essential to meet NSTX-U programmatic/TSG goals, and support ITER

- Expanded 3D field capability needed to control error fields, RWMs, momentum (rotation), particle/heat transport, ELM control, etc.

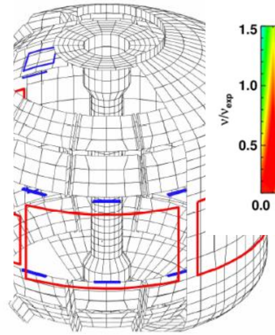
3D field applications



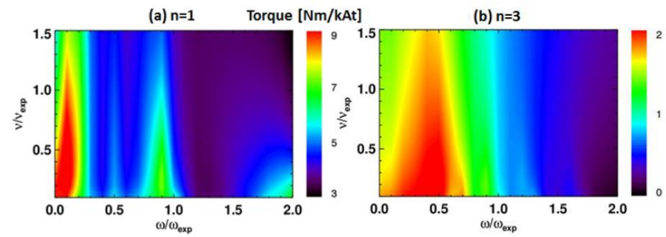
Resonant (OH-TF) and non-resonant (PF5) error field control



RWM active control

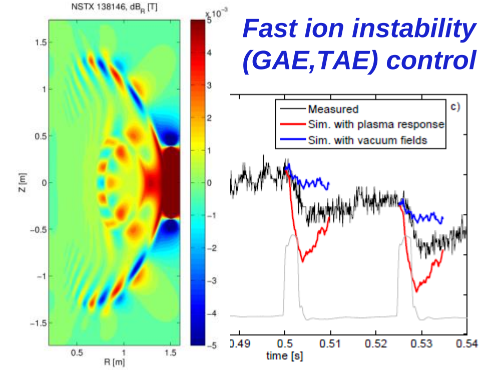


Response modeling

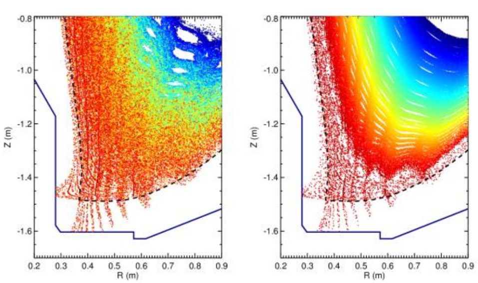


3D transport and NTV physics

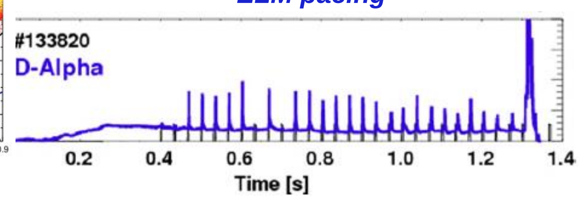
Fast ion instability (GAE,TAE) control



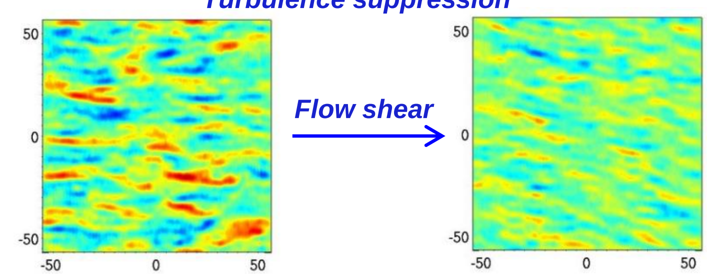
Particle/heat load splitting



ELM pacing



Turbulence suppression



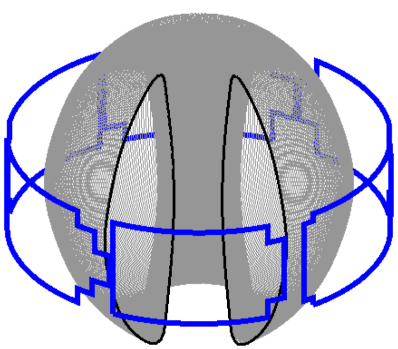
Outline

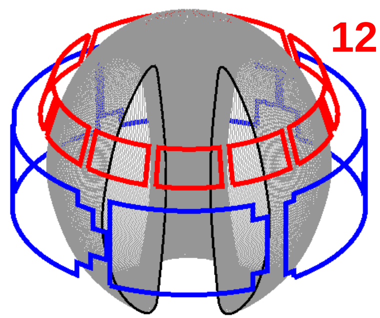
- Proposed NCC geometry for NSTX-U
  - Partial and full choices for NCC
- Physics analysis and NCC applications
  - Resonant and non-resonant error field control
  - RWM active control
  - Rotation control via NTV
  - RMP characteristics for stochastic and neoclassical transport
  - RMP characteristics for 3D stability
- 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 wide poloidal spectrum to vary resonant vs. non-resonant coupling
  - To rotate n=1 – 4 fields to diagnose plasma response such as heat flux spreading in divertor
  - 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 will be discussed and compared with existing midplane coils

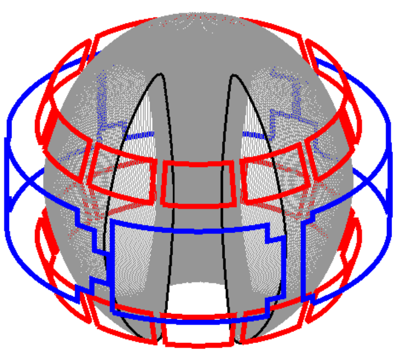
Existing Midplane coils



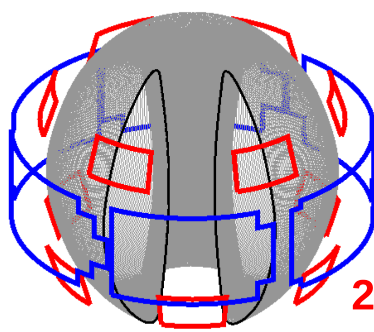


12U

NCC Options



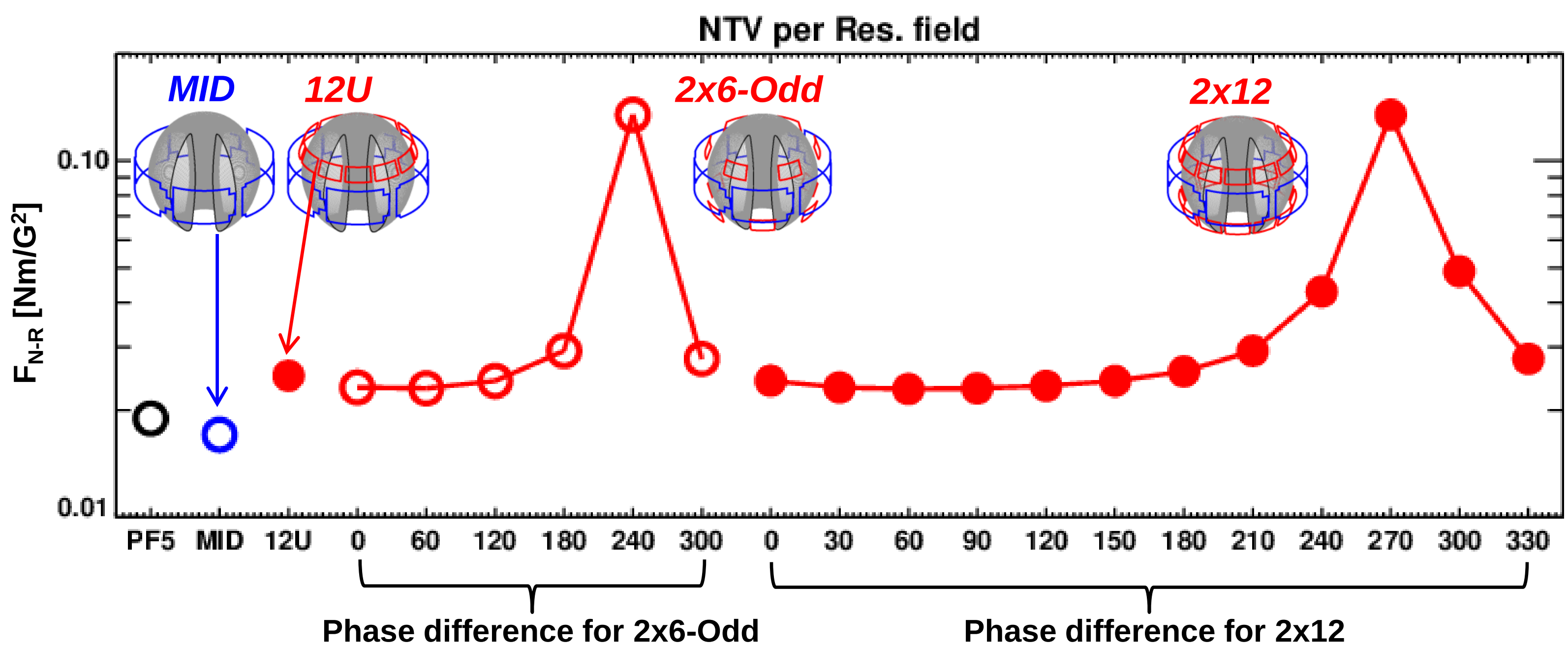
2x12



2x6-Odd

Wide variation of n=1 non-resonant vs. resonant field made possible by NCC

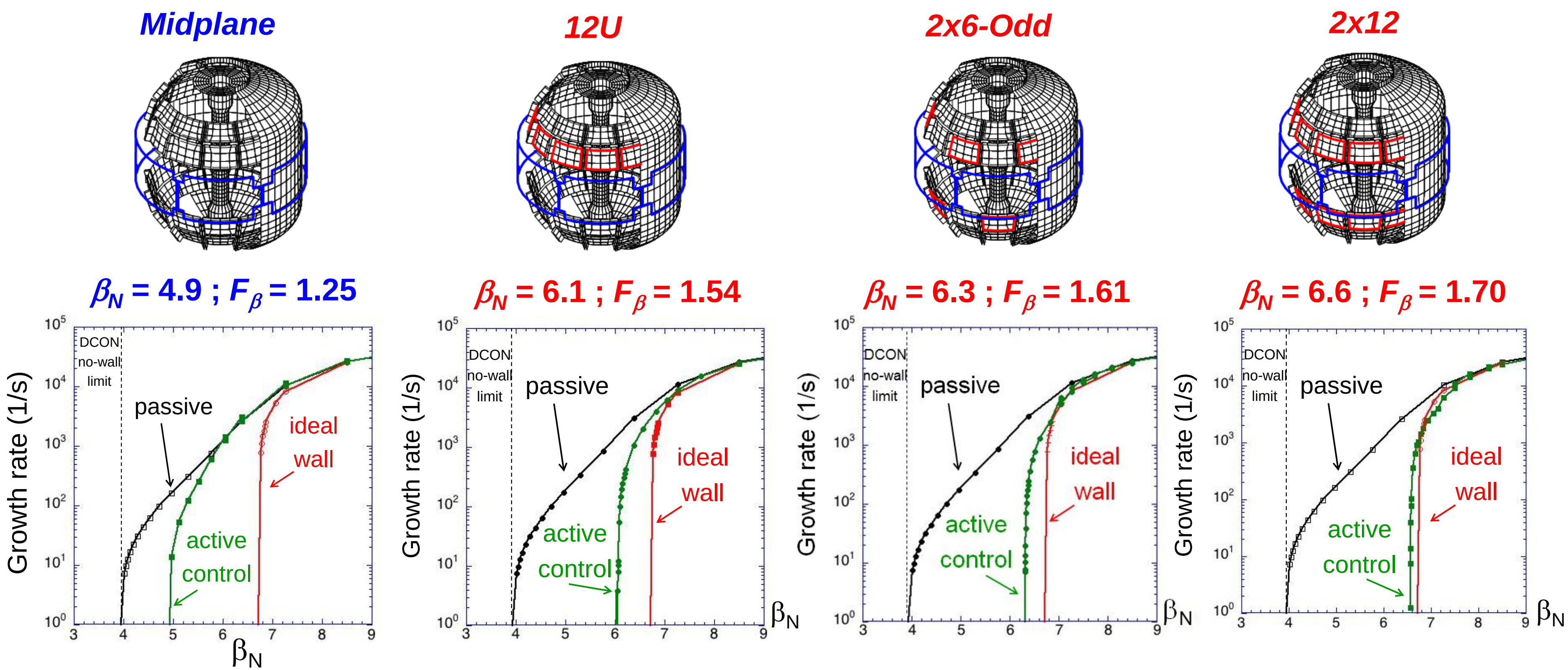
- IPEC and combined NTV analysis show that 2x6-Odd partial NCC and 2x12 full NCC can provide range of non-resonant error field control while minimizing n=1 resonant error field, which is a critical issue for tokamaks
- Non-resonant field physics can be quantified by NTV, via $F_{N-R} \equiv \dfrac{T_{NTV}}{\sum_{\psi_N<0.85} \delta B_{mn}^2}$
  - High F_{N-R} as well as its variability are important



*** Combinations of midplane coils with NCC are partially tested and shown in backup slides***

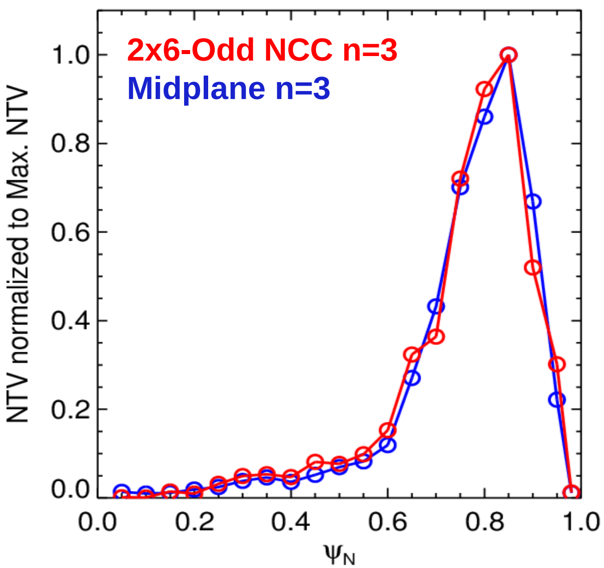
RWM control capability increases and physics studies are expanded with NCC

- VALEN3D analysis shows RWM control performance increases as NCC coils are added
  - **Can operate very close to the ideal-wall limit with full 2x12 NCC**
  - Can be quantified by β-gain $F_\beta \equiv \frac{\beta_{active}}{\beta_{no-wall}}$

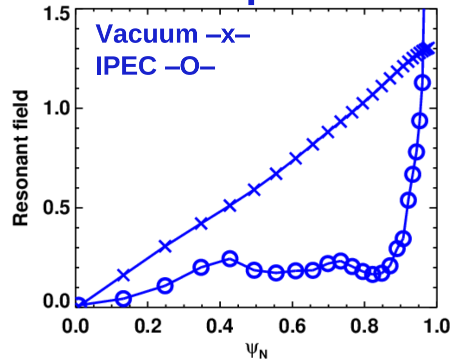


NCCs greatly expand possible resonant field profiles for similar n=3 NTV braking – will aid understanding of RMP

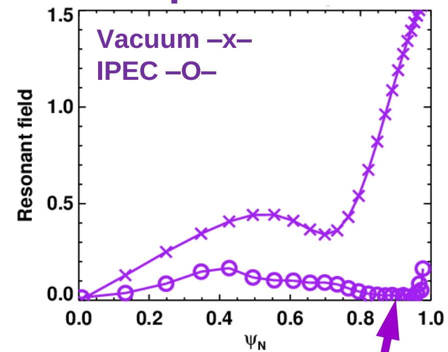
NTV torque profiles by POCA



Midplane

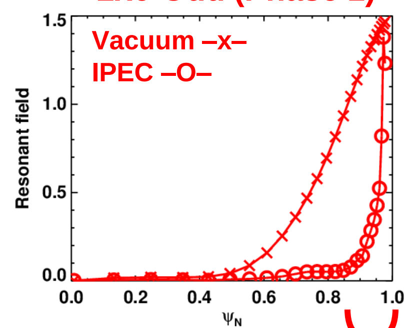


Midplane + NCC

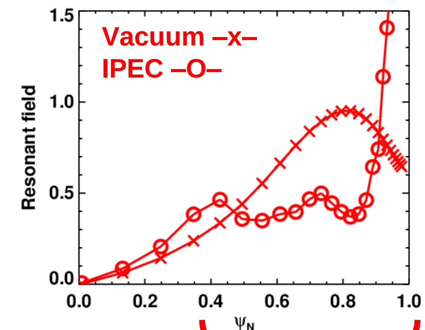


Addition of NCC can minimize edge resonant field

2x6-Odd (Phase 1)



2x6-Odd (Phase 2)

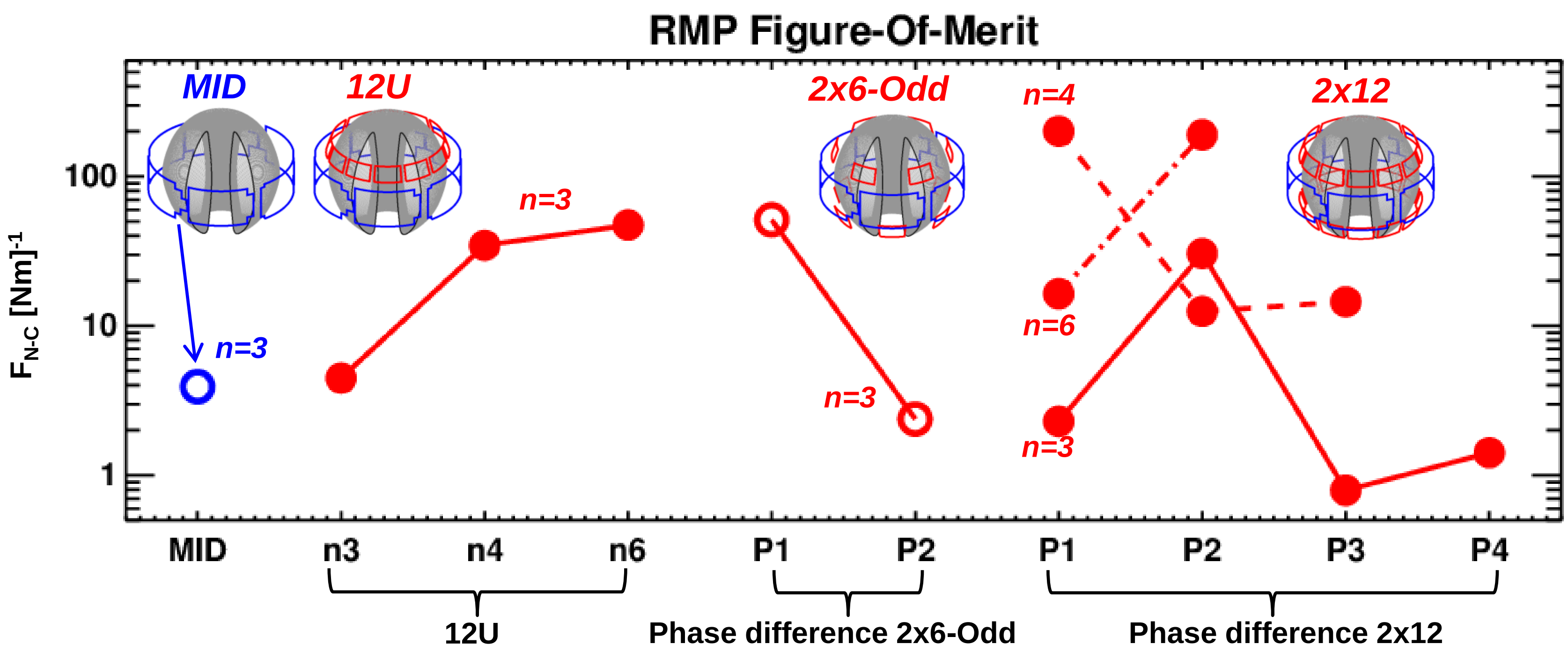


Phase of NCC can control resonant profile width

- Full NCC can further enhance variability of NTV across radius to control rotation and shear, and thus microscopic-to-macroscopic instabilities (backup slides)

NTV at fixed Chirikov can be varied by 1 order of magnitude with partial NCC, 2 orders of magnitude with full NCC

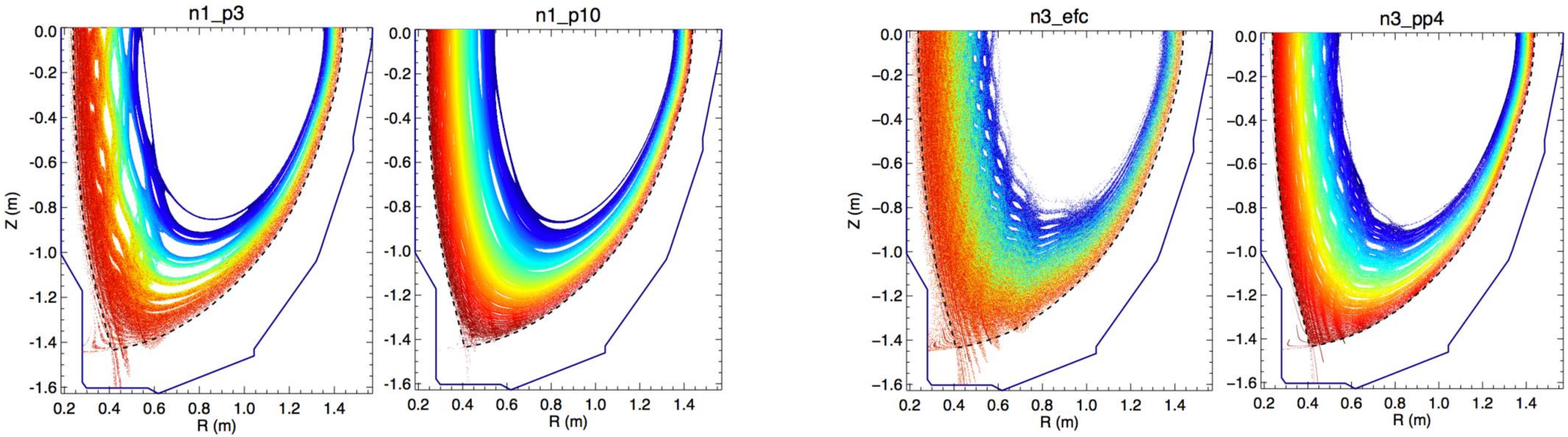
- Empirical RMP characteristics: Chirikov overlap and pitch-alignment
  - Chirikov overlap implies dominant stochastic transport in the edge
  - Good pitch-alignment implies small non-resonant fields, which are related to small neoclassical 3D transport (NTV) in the core
  - These mixed hypothesis can be quantified by $F_{N-C} \equiv \frac{\left(C_{vacuum,\psi_N=0.85}\right)^4}{T_{NTV}}$



Field line tracing calculations show vacuum stochastic layers can be substantially modified by NCC

- POCA-FLT simulations for NCCs show important modifications of vacuum stochastic layers for both n=1 and n=3

Resonant n=1 | **Less resonant n=1** | **Midplane n=3** | **Less resonant n=3 using NCC**

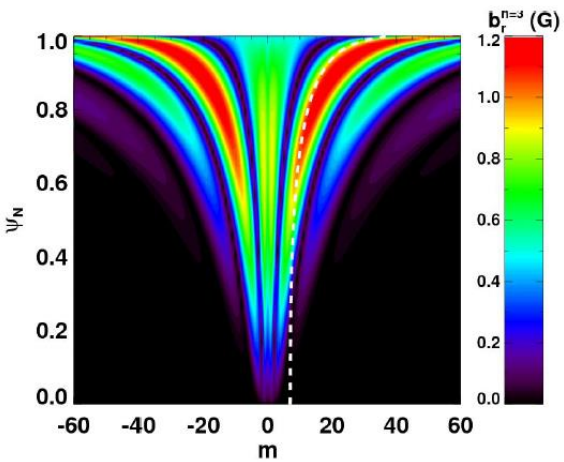


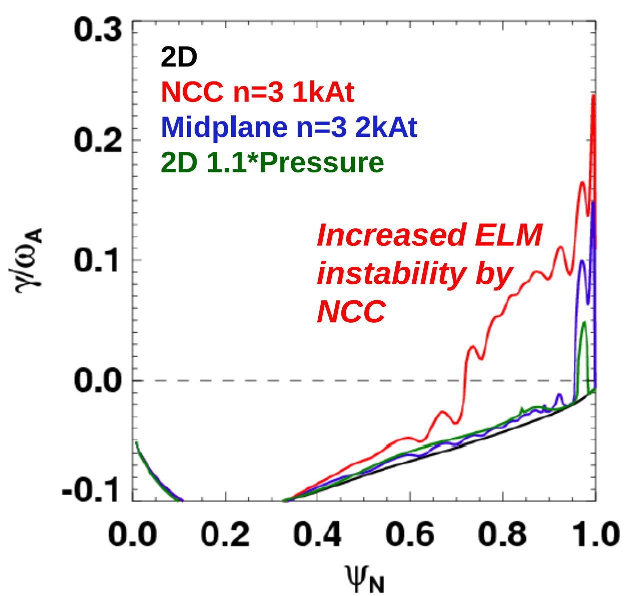
- Although the vacuum hypothesis may not be precise even in the edge, these predictions can be tested in NSTX-U for ELM control and compared with divertor diagnostics for particle and heat splitting

Stability analysis using stellarator tools indicates 3D equilibrium effects are important for pedestal ballooning instability

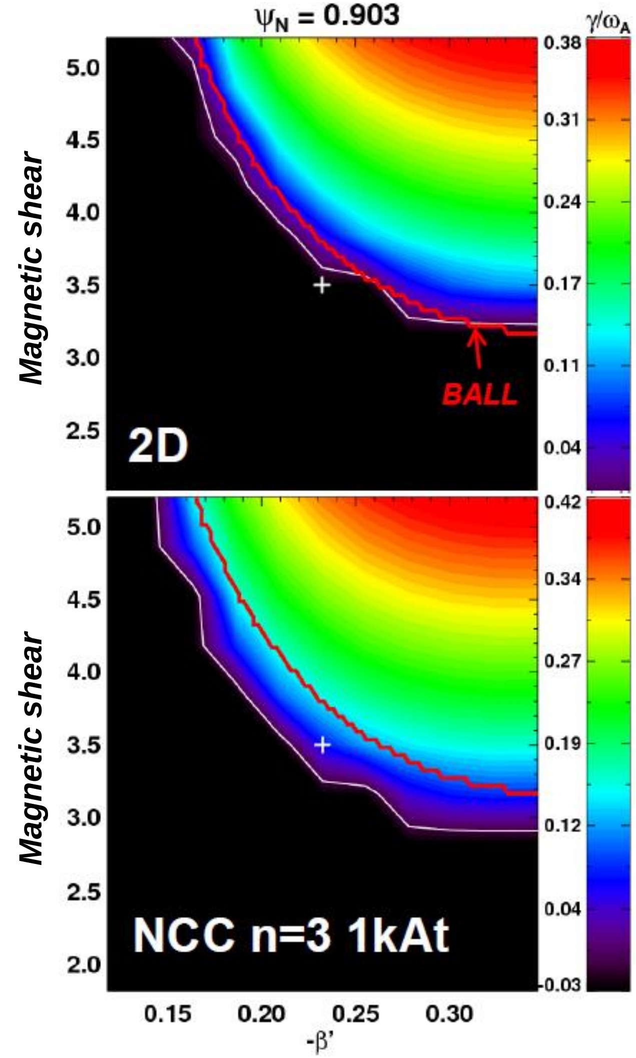
- Midplane coil applications in NSTX showed strong ELM triggering and pacing
- VMEC+COBRA analysis for NSTX-U shows NCCs may significantly increase this capability
  - NCCs can broaden ballooning unstable region by ~30% compared to midplane coils or 2D (benchmarked with BALL)

Full NCC n=3 (Up-down symmetric)





<u>ISOLVER+VMEC+COBRA</u>



Summary of initial analysis

- For partial NCCs, 2x6-Odd is more favorable than 12U for error field, RWM control, rotation control, and RMP characteristics
  - 12U can provide high-n rotating capability, but poloidal spectrum is limited
- Full NCC greatly expands capability for NTV and RMP physics and control
- Quantified FOM table:

Figures of Merit	Favorable values	MID	12U	2x6-Odd	2x12
EF (n=1)	**High $F_{N\text{-}R}$**	**0.017**	**0.025**	**0.13**	**0.13**
RWM (n=1)	**High F_{β}**	**1.25**	**1.54**	**1.61**	**1.70**
NTV (n≥3)	**Wide $\Delta F_{N\text{-}N}$**	**1.00**	**2.00**	**3.97**	**19.6**
RMP (n≥3)	**High $F_{N\text{-}C}$**	**3.92**	**41.3**	**51.3**	**201**
	Wide $\Delta F_{N\text{-}C}$	**1.00**	**10.5**	**22.1**	**252**

**** Figures of merit for NTV is defined and illustrated in backup slides***

Analysis plans for upcoming year

- Additional configurations will be investigated
  - Combine NCC and midplane, including different Ampere-turn ratios, and with constraint of only 6 independent power supplies
  - Various target plasmas with different q_{min} and q-shear

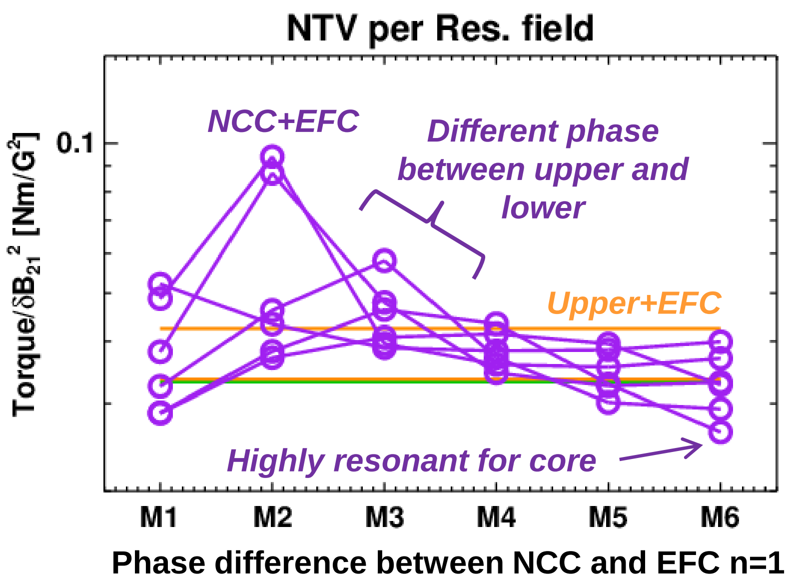
- Important coil configurations will be identified using FOMs, with varied collisionality and rotation
  - IPEC-NTV, MISK, MARSK, MARSQ, NTVTOK, VALEN3D, TRIP3D will be used to quantify error field, NTV, RWM, RMP characteristics
  - SVD methods with FOM matrices, with and without coil constraints, will also be performed to assess fundamental advantages of NCCs in NSTX-U

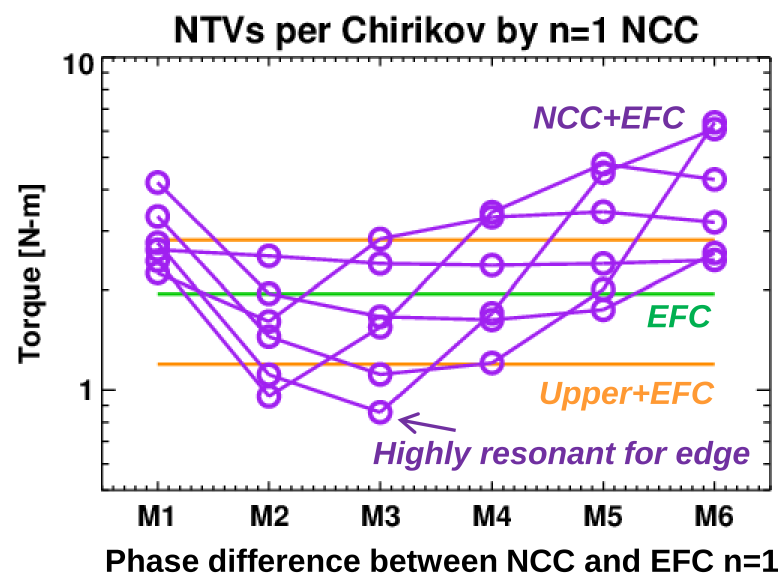
- Advanced computations will be performed for selected coil configurations, target plasmas, kinetic profiles
  - POCA, FORTEC3D, and XGC0 will be used for selected cases

Backup

Partial NCCs combined with midplane coils can greatly extend selectivity of n=1 resonant vs. non-resonant field

- Partial NCCs, if combined with midplane coils, can greatly extend “non-resonant” and “resonant field selectivity” by changing alignment between fields to resonant helical pitch
- RMP FOM 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 further improve n=1 capability





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

Controllability of rotation by NTV braking can be enhanced by 2x12, and also by mixed n's

- Semi-analytic calculations show that full NCC can greatly enhance variability of NTV across radius, which is essential to control rotation profiles and shear, and therefore microscopic-to-macroscopic instabilities
  - NTV variability for core to edge can be defined as $\Delta\left(F_{N-N} \equiv \frac{T_{NTV}(\psi_N < 0.5)}{T_{NTV}(\psi_N < 1)}\right)$
- n=1 non-resonant error fields, if successfully utilized, can further increase NTV profile control