The study of non-axisymmetric control (NCC) coil applications in NSTX-U

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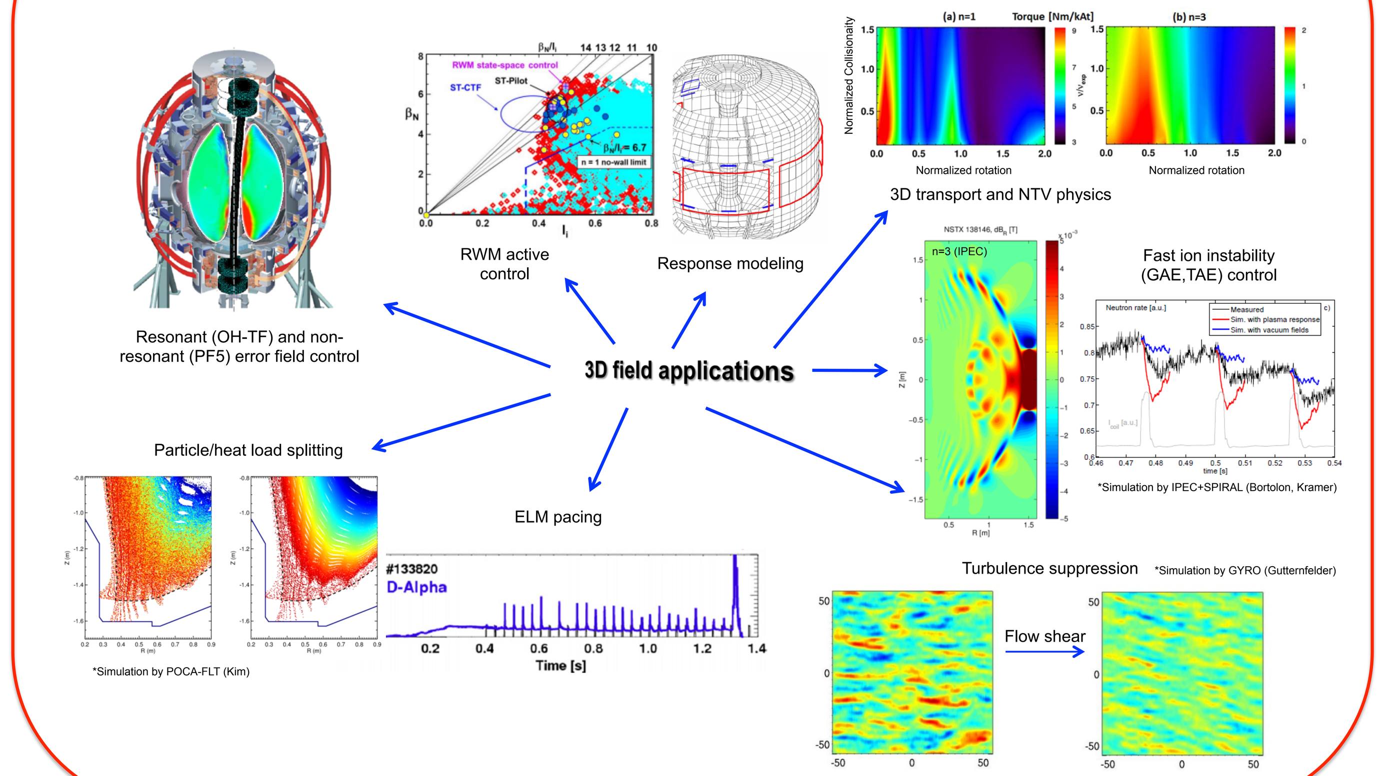
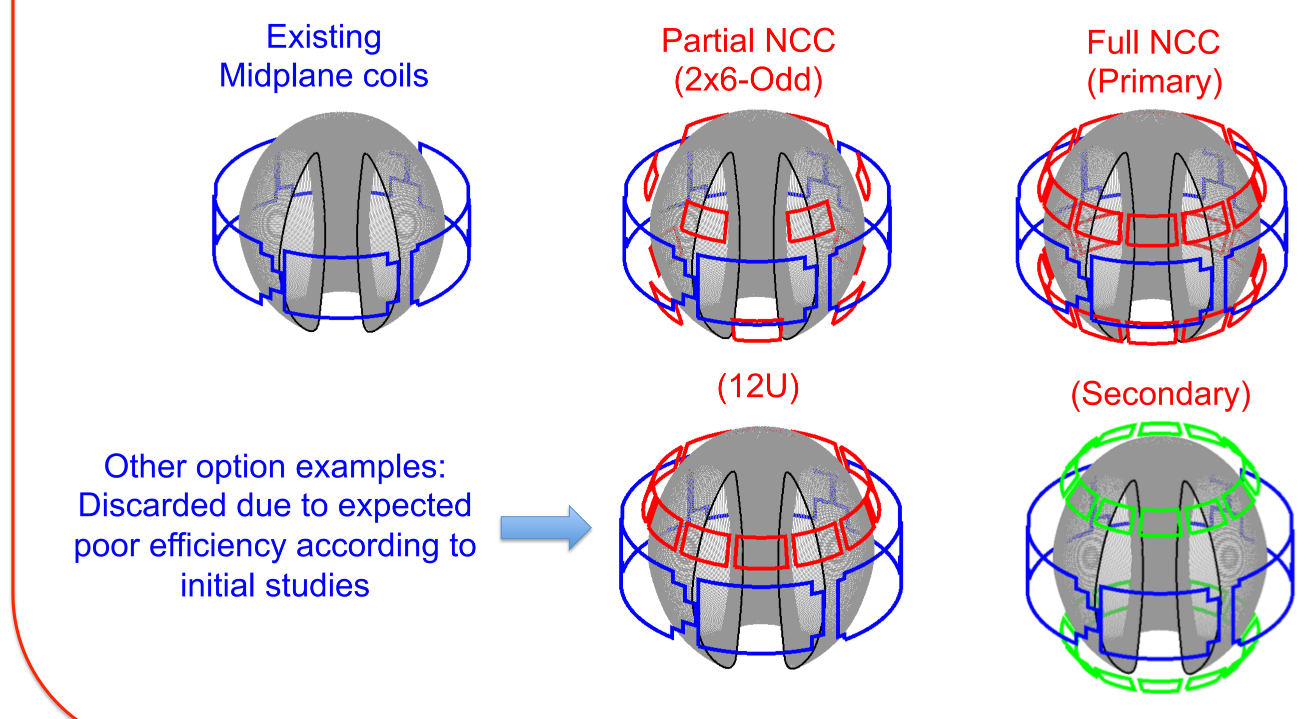
Motivation

- Expanded 3D field capability is essential to meet NSTX-U programmatic and topical science group goals and support ITER



Proposed NCC Geometry

- A range of off-midplane NCC coil configurations is being assessed
- Full NCC : 24 coils, presently considered as 2 off-midplane rows of 12 coils toroidally
- Partial NCC : 12 coils, presently considered as 2 off-midplane rows of 6 coils toroidally



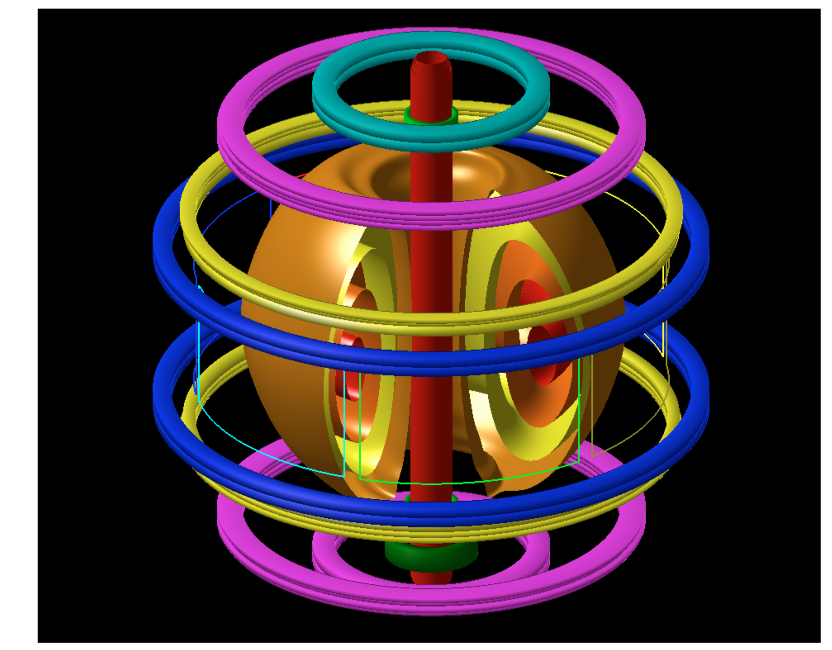
Summary of Physics Analysis with Quantified Table

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

Figures of Merit		Favorable values	MID	12U	2x6-Odd	2x12
EF (n=1)	$F_{N-R} \equiv \frac{T_{NTV}}{\sum_{\psi_N<0.85} \delta B_{mn}^2}$	High F_{N-R}	0.017	0.025	0.13	0.13
RWM (n=1)	$F_\beta \equiv \frac{\beta_{active}}{\beta_{no-wall}}$	High F_β	1.25	1.54	1.61	1.70
NTV (n≥3)	$\Delta\left(F_{N-N} \equiv \frac{T_{NTV}(\psi_N<0.5)}{T_{NTV}(\psi_N<1)}\right)$	Wide ΔF_{N-N}	1.00	2.00	3.97	19.6
RMP (n≥3)	$F_{N-C} \equiv \frac{(C_{vacuum,\psi_N=0.85})^4}{T_{NTV}}$	High F_{N-C}	3.92	41.3	51.3	201
		Wide ΔF_{N-C}	1.00	10.5	22.1	252

Future Analysis Plan

STELLOPT to optimize NCC in NSTX-U



- IPEC-PENT will provide resonant and non-resonant field penetration and NTV profiles
- STELLOPT will use IPEC-PENT outputs to study the BEST FIELD configuration for target physical quantities, such as resonant field at the rational surfaces and NTV in the core
- Then STELLOPT will also investigate the BEST COIL configuration to couple to the best field configuration

M3D-C1 and TRIP3D to optimize RMP characteristics

- M3D-C1 is being used to verify ELM suppression criteria for RMP including plasma response
- Then the new RMP criteria and conditions will be studied using M3D-C1 for NCC configuration

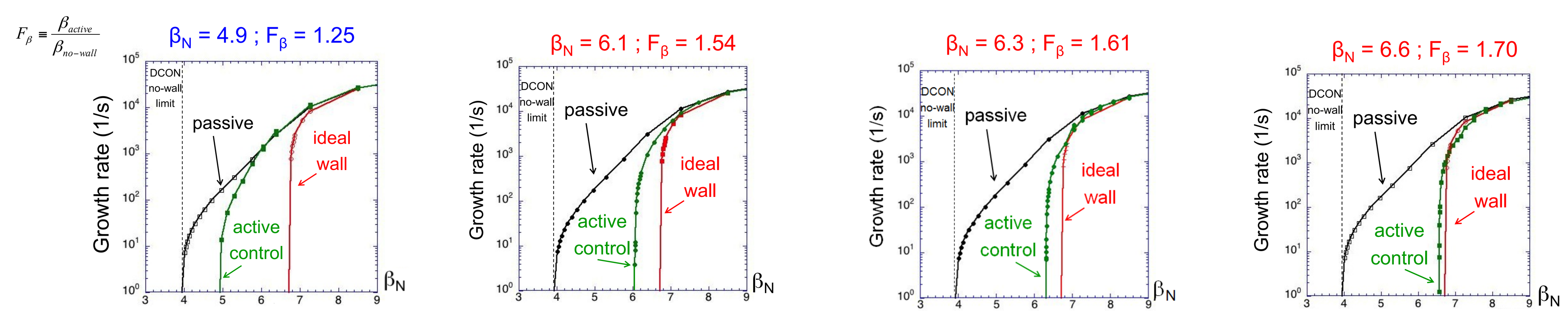
Optimization of coils and power supplies with all tools

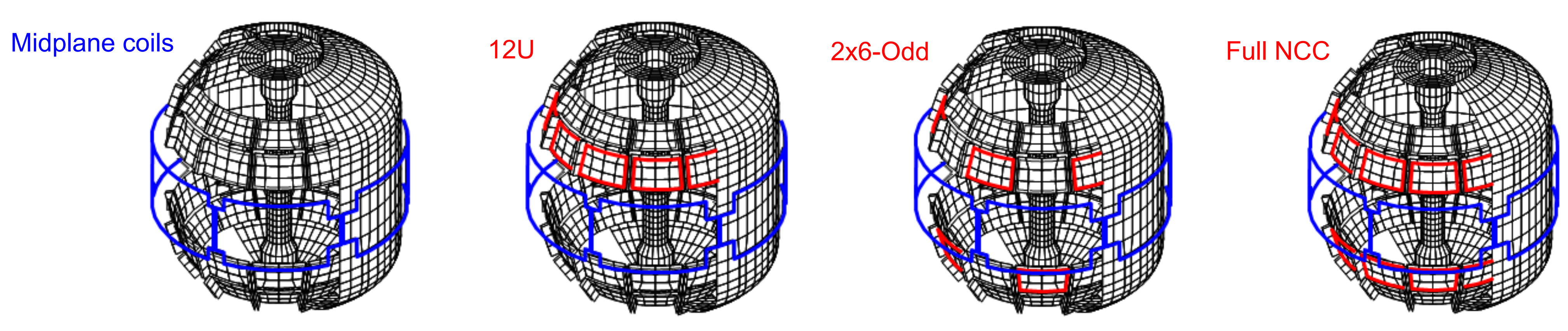
- Combined NCC and midplane, including different Ampere-trun ratios and with constraint of only 6 independent power supplies
- Explore more target plasmas with different q-profiles
- IPEC-PENT, MISK, MARSK-Q, TRIP3D-GPU, NTVTOK, POCA, M3D-C1, STELLOPT will be used to quantify error field, NTV, RWM, RMP characteristics

Physics Analysis for RWM, Error Field, NTV, RMP, 3D Stability

RWM

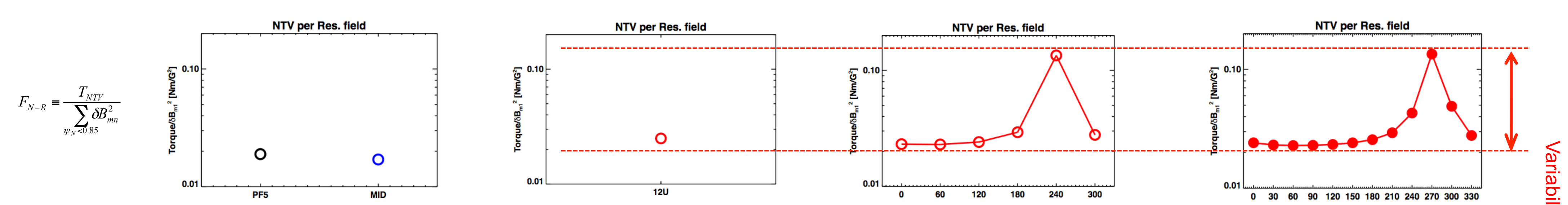
- VALEN3D analysis shows RWM control performance increases as NCC coils are added
- NSTX-U can operate very close to the ideal wall-limit when full NCC is used with optimized sensors





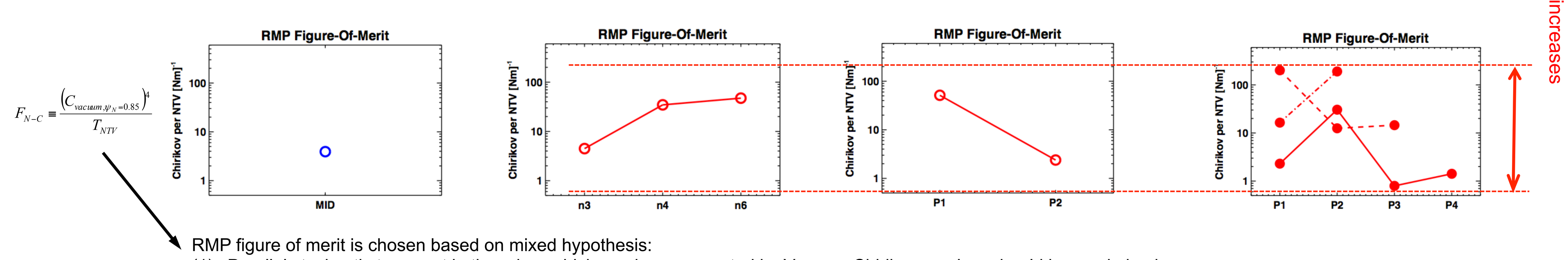
EF

- IPEC and RLAR analysis show that 2x6-Odd partial NCC and 2x12 full NCC can provide range of non-resonant field control while minimizing n=1 resonant error field, which is a critical issue for tokamaks



RMP

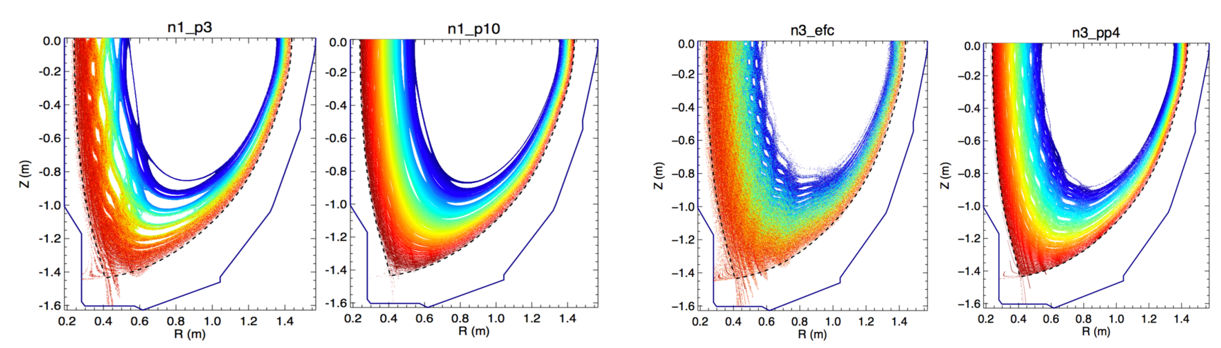
- NTV at fixed Chirikov can be varied by 1 order of magnitude with partial NCCs, 2 order of magnitude with full NCC



RMP figure of merit is chosen based on mixed hypothesis:
(1) Parallel stochastic transport in the edge, which can be represented by Vacuum Chirikov overlap, should be maximized
(2) Perpendicular neoclassical transport in the core, which can be represented by NTV, should be minimized

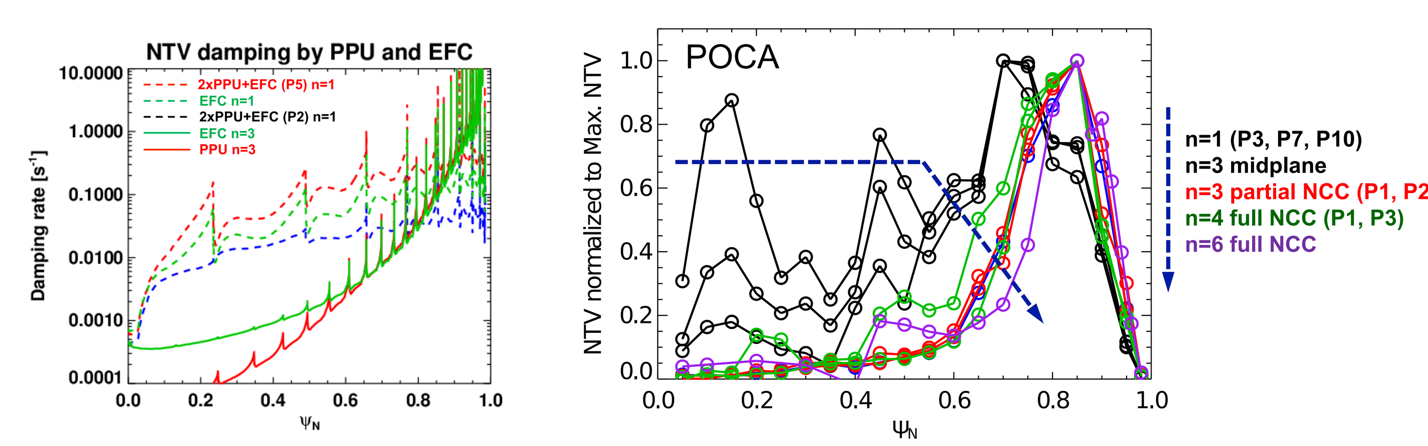
Heat flux splitting

- POCA-FLT analysis shows full NCC can produce either highly resonant or highly non-resonant strike point splitting using n=1 or n=3



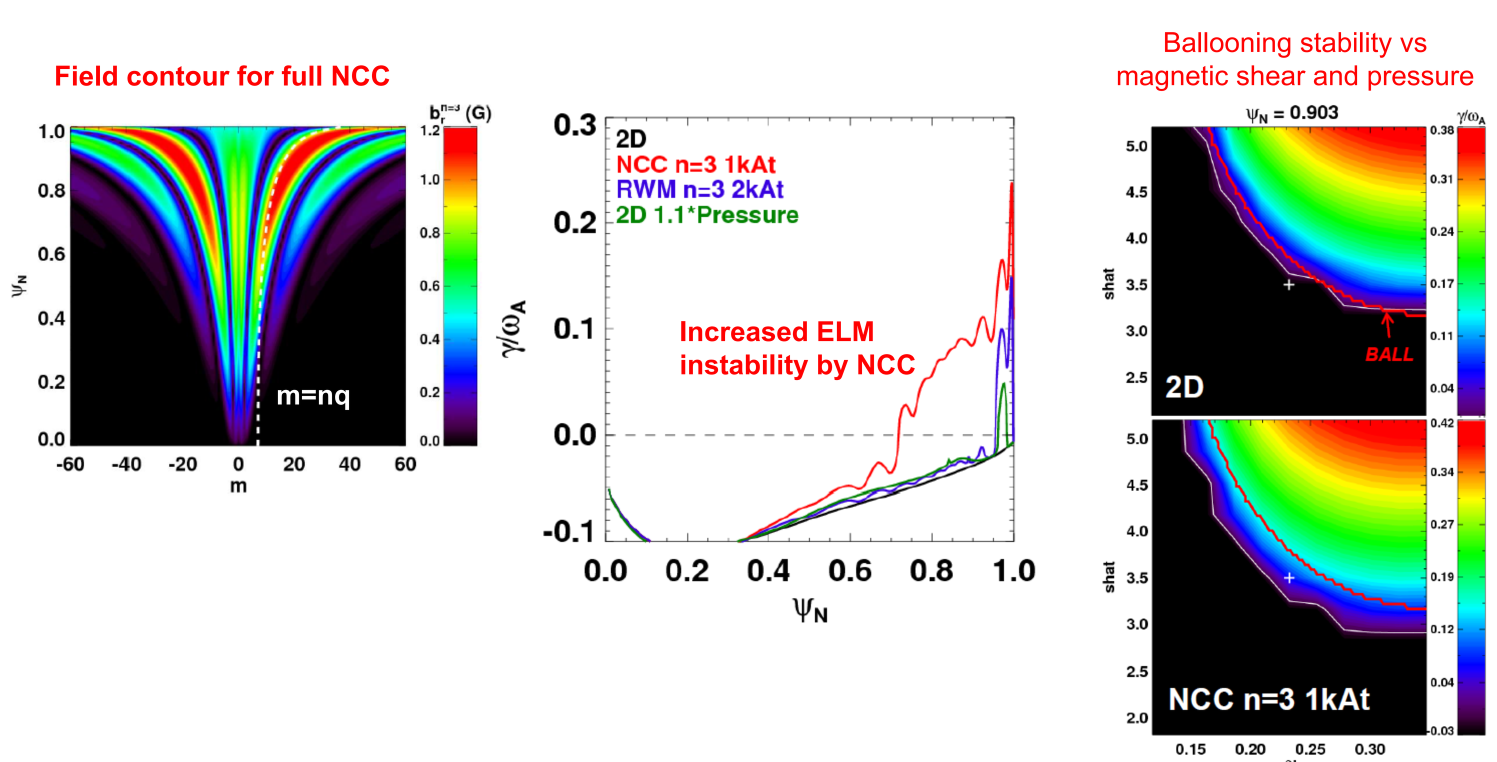
NTV

- NTV analysis including POCA particle simulations shows that full NCC can enhance variability of core-to-edge torque and rotational damping profiles



3D stability

- VMEC+COBRA analysis shows full NCC can possibly increase the ELM triggering and pacing capability by broadening ballooning unstable region



Appendix for numerical codes

- IPEC: Ideal perturbed equilibrium code
  J.-K. Park, A. H. Boozer and A. H. Glasser, Phys. Plasmas ***14*** *(2007) 052110*
- RLAR: Combined NTV calculator with reduced large aspect ratio approximation
  J.-K. Park, A. H. Boozer and J. E. Menard, Phys. Rev. Lett. ***102*** *(2009) 065002*
- PENT: Combined NTV code without geometric simplification
  N. Logan, J.-K. Park, K. Kim et al., Submitted to Phys. Plasmas (2013)
- VALEN3D: 3D electromagnetic code for RWM
  J.M. Bialek Allen H. Boozer, M. E. Mauel and G. A. Navratil, Phys. Plasmas ***8*** *(2001) 2170*
- POCA: Particle simulation code for 3D neoclassical transport (FLT: Field line tracing module)
  K. Kim, J.-K. Park, G. Kramer and A. H. Boozer, Phys. Plasmas ***19*** *(2012) 082503*
- VMEC: 3D ideal equilibrium code for stellarators
  S. P. Hirshman and D. K. Lee, Comput. Phys. Comm. ***39*** *(1986) 143*
- COBRA: 3D ballooning stability code (BALL: 2D ballooning stability code)
  R. Sanchez, S. P. Hirshman, J. C. Whitson and A. S. Ware, J. Comput. Physics ***161*** *(2000) 576*
- STELLOPT: Stellarator optimizer
  D. A. Spong, S. P. Hirshman, L. A. Berry et al., Nucl. Fusion ***41*** *(2001) 711*
- TRIP3D-GPU: Fast field line tracing code
  T. E. Evans, R. A. Moyer, P. R. Thomas et al., Phys. Rev. Lett. ***92*** *(2004) 235003*
- M3D-C1: 3D non-linear two-fluid code
  N.M. Ferraro, S. C. Jardin and P. B. Snyder, Phys. Plasmas ***17*** *(2010) 102508*
- MISK: Perturbative kinetic stability code
  J.W. Berkery, S. A. Sabbagh, R. Betti et al., Phys. Rev. Lett. ***104*** *(2010) 035003*
- NTVTOK: NTV code connecting regimes with pitch-angle collisional operator
  Y. Sun, Y. Liang, K.C. Shaing, et al., Nucl. Fusion ***51*** *(2011) 053015*
- MARSK: Kinetic stability code
  Y.Q. Liu, M. S. Chu, I. T. Chapman and T. C. Hender,, Phys. Plasmas ***15*** *(2008) 112503*
- MARSQ: Quasi-linear kinetic stability code
  Y. Q. Liu, A. Kirk and Y. Sun, Phys. Plasmas ***20*** *(2013) 042503*
- SPIRAL: Full particle orbit following code
  G. J. Kramer, R. V. Budny, A. Bortolon et al., Plasma Phys. Control. Fusion ***55*** *(2013) 025013*
- GYRO: Non-linear tokamak microturbulence code package
  J. Candy and R. E. Waltz, J. Comput. Phys. ***186*** *(2003) 454*