**Non-axisymmetric Control Coil (NCC) design and analysis for NSTX-U**

1. **ACTION ITEM**
	1. **Each TSG or together (MS, ASC, BP, T&T…) should set up, or propose, important important programmatic-level and/or physics questions and issues, which can be possibly resolved with NCC and thus can motivate NCC.**
	\* Please send these to jpark@pppl.gov, and cc to nstx\_tsg\_leaders@pppl.gov, jmenard@pppl.gov, mono@pppl.gov.
	\* Please attach the analysis plan, or short description, for the issue you propose.
	\* Examples are given in the following summary, as well as in comments from JEM, AHB, SAS, SPG.
	2. **Data, analysis, and presentation will be shared in** <http://nstx.pppl.gov/DragNDrop/Five_Year_Plans/2014_2018/design_studies/ncc/>
	\* Two coil geometries (primary and secondary options) will be in /coil/.
	\* Two (or one) representative NSTX-U geqdsk files will be in/geqdsk/.
	\* Other NSTX-U geqdsk files and TRANSP data will be in /kgeqdsk/.
	\* Each TSG can create their own area under /ncc/ and share the analysis results.
2. **SUMMARY OF QUESTIONS/ISSUES**
**\* These are not yet completed, but will be completed by combining TSG inputs and comments. See 3 for comments by JEM, SAS, TEE, AHB.**

	1. Programmatic-level questions (From JEM)
		1. What are the MHD thrusts/goals for the 5 year plan, and how do these thrusts motivate the implementation of the NCC coils? MS TSG will address this issue.
		2. Do we have a/the physics basis for explaining RMP ELM suppression? If not, what can NSTX-U add – both with and without NCC? BP TSG?
		3. How do recent and planned results from DIII-D, MAST, AUG, KSTAR impact the motivation/need for NCC in NSTX-U in support of ITER, FNSF, DEMO? What if anything makes NSTX-U + NCC unique? BP TSG?
	2. RWM active control (MS)
		1. What is the optimal set of 3D coils to achieve near-ideal n=1 wall limit pressure by RWM active control? VALEN3D can address this issue.
		2. What should be prepared to compensate 1-2 random coil failures in RWM active control? VALEN3D can illustrate examples.
		3. Are there any NSTX-U or FNSF/Demo-style equilibria where n > 1 RWMs could be a problem, for which having higher-n coil capability would be useful/essential for RWM control? VALEN3D for n>1?
	3. Error field correction and plasma response (MS)
		1. What is the importance of non-resonant field corrections when the resonant field is almost completely corrected? This is coupled to the issue below.
		2. Inversely, how can drive and control magnetic islands with non-resonant fields? IPEC can be used to address (i) and (ii).
		3. What is the importance of resonant and non-resonant error field corrections in fully non-inductive scenarios? IPEC+NTV can illustrate different plasma responses with fixed setting of correction.
	4. Rotation control by NTV braking (MS, ASC, T&T)
		1. What is the optimal set of 3D coils to achieve the sufficient level of the rotation (profile) control? IPEC+NTV can be used to produce a couple of very different torque profiles. Outputs should be studied with ASC to determine rotation profiles. Inputs are required from (4) and from T&T to illustrate the importance of the rotation control.
		- Can plasma rotation be increased with n > 1 toroidal propagation?
	5. RWM kinetic stabilization (MS)
		1. What are the optimal rotation profiles for RWM kinetic stabilization? MISK can address this issue.
		2. Can an optimized NCC field spectrum change edge fast ion profiles for RWM stability alteration? MISK can address this issue.
	6. ELM control (BP, MS)
		1. What is the field spectrum and strength required for ELM mitigation and ELM suppression, including very high-performance targets? TRIP3D can be used to illustrate the difference in the pitch-alignment, Chirikov overlap. IPEC can be added to show plasma response characteristics.
		2. What is the role of KAM ghost surfaces? TRIP3D field line loss can illustrate the uniqueness in NSTX.
		3. What is projected impact of lower nu\* in NSTX-U on RMP physics?
		4. What level of the temperature control can be achieved when the 3D fields can be flexibly rotated? Divertor IR analysis can address this issue.
	7. Simultaneous and integrated control for RWM/EF/NTV/ELM (MS, ASC, BP, T&T)
	- Can the proposed NCC achieve (1),(2),(3),(5) simultaneously?
	8. Perspective for ITER 3D coil capabilities
	- Is the integrated controllability largely changed in a fully non-inductive operation?

1. **COMMENTS
\* These comments will be incorporated into 2.**

From J. E. Menard

**Programmatic-level questions:**

1. What are the MHD thrusts/goals for the 5 year plan, and how do these thrusts motivate the implementation of the NCC coils?
2. Do we have a/the physics basis for explaining RMP ELM suppression? If not, what can NSTX-U add – both with and without NCC?
3. How do recent and planned results from DIII-D, MAST, AUG, KSTAR impact the motivation/need for NCC in NSTX-U in support of ITER, FNSF, Demo? What if anything makes NSTX-U + NCC unique?
	1. ASDEX will have 8 coils – won’t have smooth rotation of n=3. Also issues with not getting ELM mitigation at low collisionality?
	2. MAST results show n=4-6 better for ELM reduction/mitigation than for n=3.
	\*But MAST-U may not have this capability due to PF coil/NBI interferences

**Physics/Technical questions:**

1. Are there any NSTX-U or FNSF/Demo-style equilibria where n > 1 RWMs could be a problem, for which having higher-n coil capability would be useful/essential for RWM control?
	1. Get info from Stefan’s stability analysis of NSTX-U scenarios using TRANSP?
2. How much flexibility in rotation/rotation profile control (and therefore possible RWM/NTM control) do NCC coils provide relative to mid-plane only?
	1. Better ability to damp rotation to low value (using n=2 or 3 NTV) and do RWM feedback control using n=1, etc?
	2. Ability to vary local rotation shear to impact NTM stability?
	3. Impact on pedestal transport through rotation shear (in addition to RMP)?
	4. Reduce the resonant damping relative to non-resonant to better avoid locked modes while damping the flow?
	5. Ability to go to high-n for physics validation studies of plasma equilibrium and transport response vs. n
3. How much flexibility/capability in RMP does the NCC coil set provide relative to mid-plane only?
	1. See Evans results – ACTION: need to get NSTX-U equilibria with q-scan to T. Evans
	2. See also results from JK Park
	3. Should even consider getting Todd to write or at least review the NSTX-U 5 year plan text covering the NCC RMP physics
	4. What is projected impact of lower nu\* in NSTX-U on RMP physics?
	5. For ITER – pump-out of density drops pressure and stabilizes ELMs – so need to find way of getting density up. What causes pumpout? How to optimize to keep pressure high while still suppressing ELMs

**Additional comments:**

1. No demonstration yet from any machine of RMP ELM control in (nearly) fully non-inductive and high beta (i.e. above no-wall limit) scenarios as needed for ITER AT, advanced FNSF, or Demo
2. Demonstration of ability get CD from all co-NBI AND ability to control rotation with NTV and NBI (for example to stably access very low rotation) could be unique in the world – especially relevant to Demo
	1. Todd: Possible to get ELM suppression on DIII-D in hybrid scenarios in a few instances, and with expanded mode spectrum from new coils could probably do better.

From S. A. Sabbagh (Motivation for NCC)

* 1. RWM physics, and control using n = 1, n > 1
	2. DEFC with greater field correction capability
	3. ELM mitigation (n ≤ 6)
	4. NTV physics, and vφ control (with n ≤ 6)
		1. Strong, precise, controllable NTV effect observed in NSTX

\*Routine open-loop vφ profile alteration is not routinely performed on other devices

* + 1. Increase vφ via n > 1 toroidal propagation
	1. Model-based RWM state space controller
		1. Multi-mode RWM control and DEFC with observer.
		2. NCC can provide quantitative evaluation of the importance of multi-mode spectrum (n and m) for RWM control and DEFC
		\*Spectrum will gain helicity – important to expand research
		\*n > 1 mode spectrum observed but importance of control / dynamic correction never tested
		3. Physics and control of “nonrigid” mode evolution.
		4. RWM state-space controller allows far greater flexibility of global mode stabilization physics studies with these coils, with a relatively simple control software upgrade
		5. RWM state space control of ITER-similar coil set
	2. Simultaneous use of actuators sharing multiple control roles
		1. Unique physics coupling in control systems (key for ITER)
		\*e.g. RWM, TM stability depends on vφ,q,n,T profiles; vφ control will depend on NTV (vφ,q,n,T profiles) – NCC may improve such control
		2. Control model testing that utilizes NCC in coupled systems
		\*For vφ control, βN control, RWM control, DEFC, RWM passive stability
	3. Control physics of partial coil coverage; “failed coil” control physics and tests
	4. The NCC is best justified by defining how NSTX-U can uniquely investigate the associated physics, for example:
		1. Unique operation in non-inductively driven plasmas
		\*This major operational regime for NSTX-U, which may require greater control, provides a unique lab to test NCC advanced stability physics
		2. Unique high beta ST operational space
		\*Perform advanced stability control using NCC in operating space where disruptivity is not maximized at the highest βN, or βN/li.

From T. E. Evans (Motivation for NCC)

* 1. In high δ, κ DN plasmas, n=6 fields from the NCC could produce a wider edge stochastic layer than n=3 I-coil fields in DIII-D
		1. Over a wider range in q95 (i.e., 5.3 ≤ q95 ≤ 12.8)
	2. Combined n=6 and EF/RWM n=3 field line loss fractions could exceed those due combined n=3 I-coil and n=1 C-coil fields in DIII-D
	3. NSTX-U may be the only machine that could rotate n=3 perturbations smoothly to smooth out heat flux to the divertor.
	4. Can explore the stochastic transport physics of the Chirkov parameter getting larger and larger above unity.
	5. Can explore the physics of transport barriers that prevent the inner stochastic field lines from getting out and hitting the wall.
	6. ELM mitigation techniques typically cause density pumpout, but is this really necessary? Can we manipulate the shape of the pedestal profiles?

From A. H. Boozer (Motivation for NCC for plasma response in general)

The extreme sensitivity of toroidal plasmas to externally produced non-axisymmetric magnetic fields implies that at least an empirical understanding of the effects, both good and ill, is required. The value of proposed sets of non-axisymmetric control coils (NCC) is determined by how well they provide that understanding.

Two types of effects are of importance: (1) resonant effects, which means driving islands, and (2) neoclassical toroidal viscosity effects, which means affecting the variation of the magnetic field strength along the magnetic field lines. Both effects can be assessed by IPEC for an arbitrary spatial distribution of the normal component of the externally produced magnetic field at the location of the unperturbed plasma surface. All possible external magnetic perturbations can be represented by considering the linear effect of all Fourier modes of the normal component of the externally produced magnetic field, which in effect is what IPEC does. Standard optimization techniques can then be used to determine which external magnetic distributions (the linear combinations of the Fourier modes) are most important for producing physics effects. The value of proposed sets of non-axisymmetric control coils is then be easily determined by the extent to which they can efficiently and independently drive the important external field distributions.

An NCC set would provide important empirical knowledge if it were capable of producing perturbations that:

* 1. Have little effect on plasma performance as well as those to which the performance is highly sensitive.

	External magnetic perturbations can be ordered by the plasma sensitivity to them. The number and type of perturbations to which the plasma has sensitivity must be understood for both error field control and for the use of NCC to control plasma properties.
	2. Produce NTV effects with no resonant effects.

	The magnetic field strength can be perturbed with non-resonant magnetic fields, but whether one can produce large NTV effects without driving islands is obscure. This is important for both plasma control for understanding error field effects.
	3. Drive islands while producing minimal NTV effects.

	It is not possible to drive islands with no NTV effects, but it is important to understand how NTV effects can be minimized. Whether resonant or NTV effects are of primary importance in specific control issues, such as ELM's, requires empirical studies.
	4. Affect the plasma edge but not the core.

	One would like to affect various annular regions of the plasma differently with external magnetic perturbations. The extent to which this can be done has not been seriously explored by codes such as IPEC but is expected to be limited. The edge is a special case because one can use magnetic fields that have such a high wavenumber that they cannot penetrate into the core. Unfortunately, the coils for high wavenumber perturbations must be very close to the plasma, which makes their fusion relevance obscure. It is important to determine whether the edge can be affected without degrading the core plasma using lower wavenumber perturbations.
1. **OTHERS**
Design Considerations

	1. Vacuum feedthroughs
	2. Power supplies
	3. Cooling
	4. Impact on disruption loads
	5. Mounting