Present status and plans for Non-axisymmetric Control Coil (NCC) design

J.-K. Park,

J. W. Berkery, A. H. Boozer,
J. M. Bialek, S. A. Sabbagh, J. M. Canik, K. Kim,
R. Maingi, T. E. Evans, S. P. Gerhardt, J. E. Menard
*for the NSTX Research Team*

(From NSTX-U 5 Year Plan Review)
Theory – NSTX-U Joint Meeting for MS
LSB B233, PPPL
October 1, 2013

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC
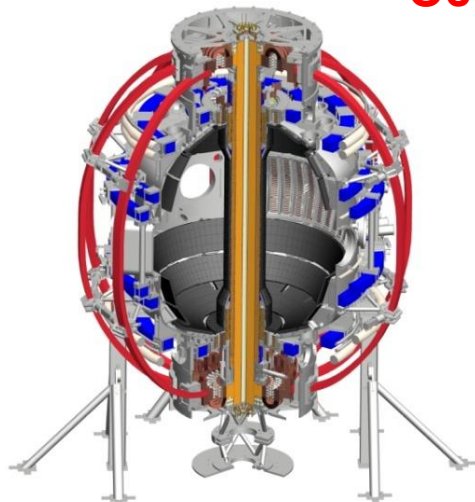
Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Present NCC proposal for NSTX-U 5yr plan

- 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
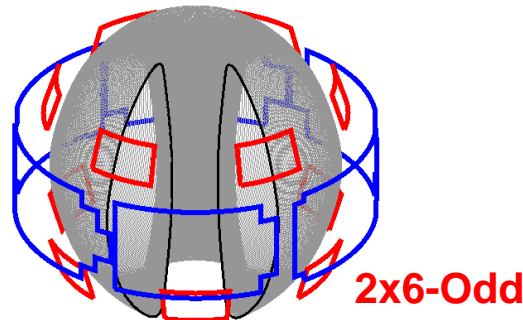
Existing Midplane coils

NCC Options

12U
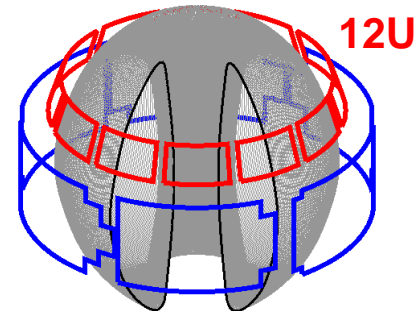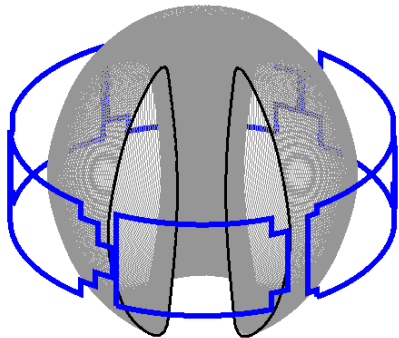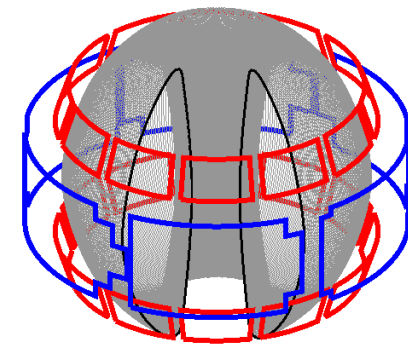
2x6-Odd

2x12

Summary of analysis done

- Locking, RWM, NTV, Chirikov have been analyzed by IPEC, IPEC-RLAR, POCA, VALEN-3D with "possible" Figures of Merit (FOM)

- Present conclusion: 2x6-Odd for partial NCC. Full NCC will have greater benefits for RWM and RMP studies

Figures of Merit	Favorable values	MID	12U	2x6-Odd	2x12
EF (n=1): Non-resonant field / resonant field	High F_{N-R}	0.017	0.025	0.13	0.13
RWM (n=1) : β gain	High F_{β}	1.25	1.54	1.61	1.70
NTV (n≥3) : Variability of core to edge NTV	Wide ΔF_{N-N}	1.00	2.00	3.97	19.6
RMP (n≥3) : Chirikov / NTV, and its variability	High F_{N-C}	3.92	41.3	51.3	201
	Wide ΔF_{N-C}	1.00	10.5	22.1	252

Example 1: RWM control capability increases and physics studies are expanded with NCC
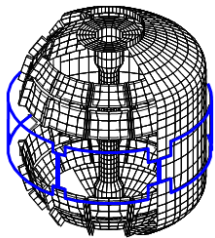
- VALEN3D analysis shows RWM control performance increases as NCC coils are added

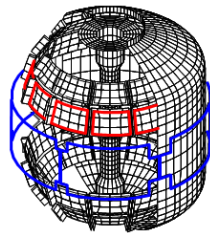 - **Can operate very close to the ideal-wall limit with full 2x12 NCC**

  - Can be quantified by β-gain $F_\beta \equiv \dfrac{\beta_{active}}{\beta_{no-wall}}$
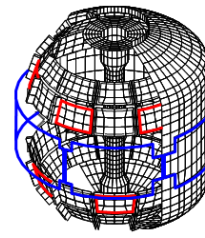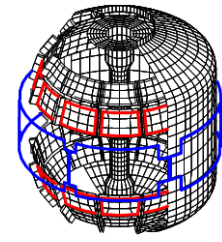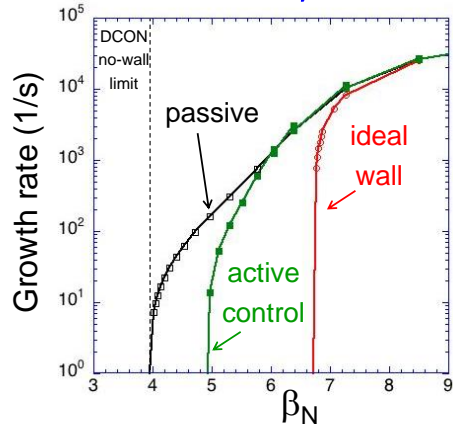
J. Bialek, S. Sabbagh

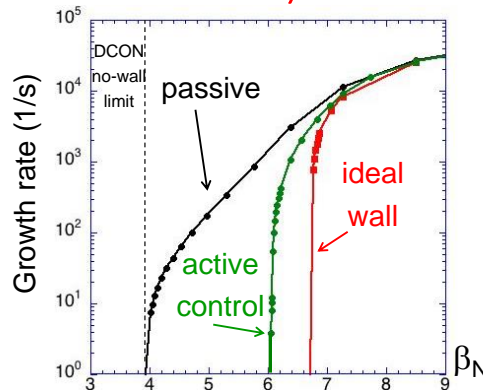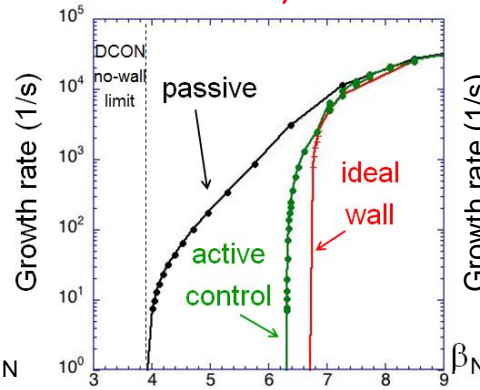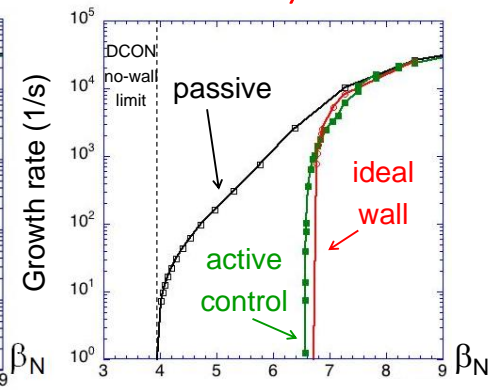| *Midplane*	*12U*	*2x6-Odd*	*2x12*
β_N = 4.9 ; F_β = 1.25	β_N = 6.1 ; F_β = 1.54	β_N = 6.3 ; F_β = 1.61	β_N = 6.6 ; F_β = 1.70

Example 2: 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 $F_{N-C} \equiv \dfrac{\left(C_{vacuum, \psi_N = 0.85}\right)^4}{T_{NTV}}$

RMP Figure-Of-Merit
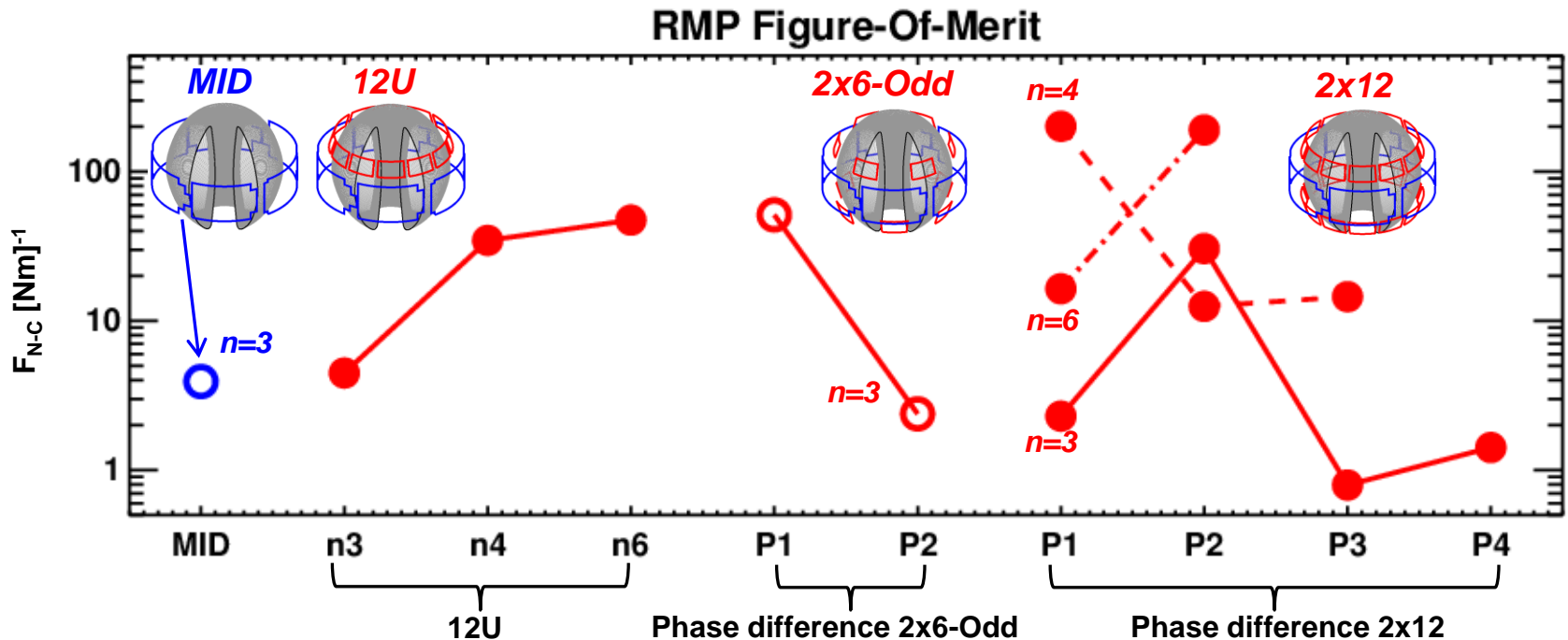
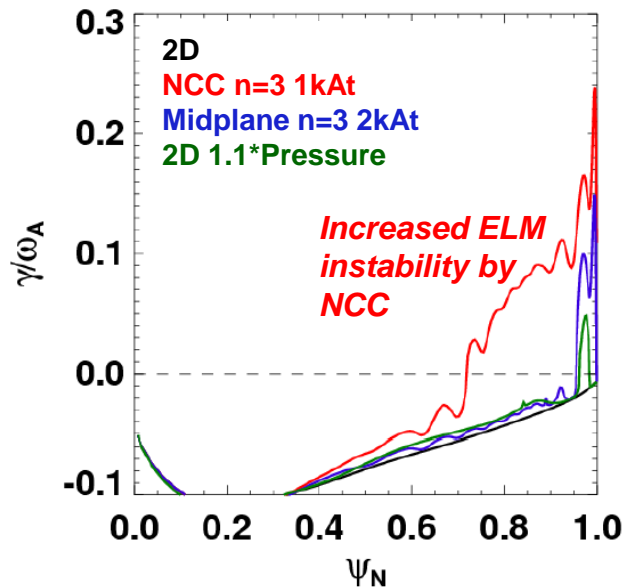# Example 3: Stability analysis using stellarator tools indicates 3D equilibrium effects are important for pedestal ballooning instability

- 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)

J. Canik, S. Gerhardt

ISOLVER+VMEC+COBRA

$\psi_N = 0.903$

Full NCC n=3 (Up-down symmetric)

2D
NCC n=3 1kAt
Midplane n=3 2kAt
2D 1.1*Pressure

Increased ELM instability by NCC
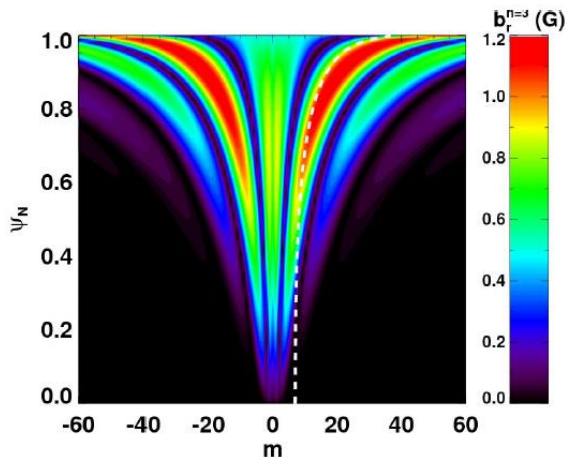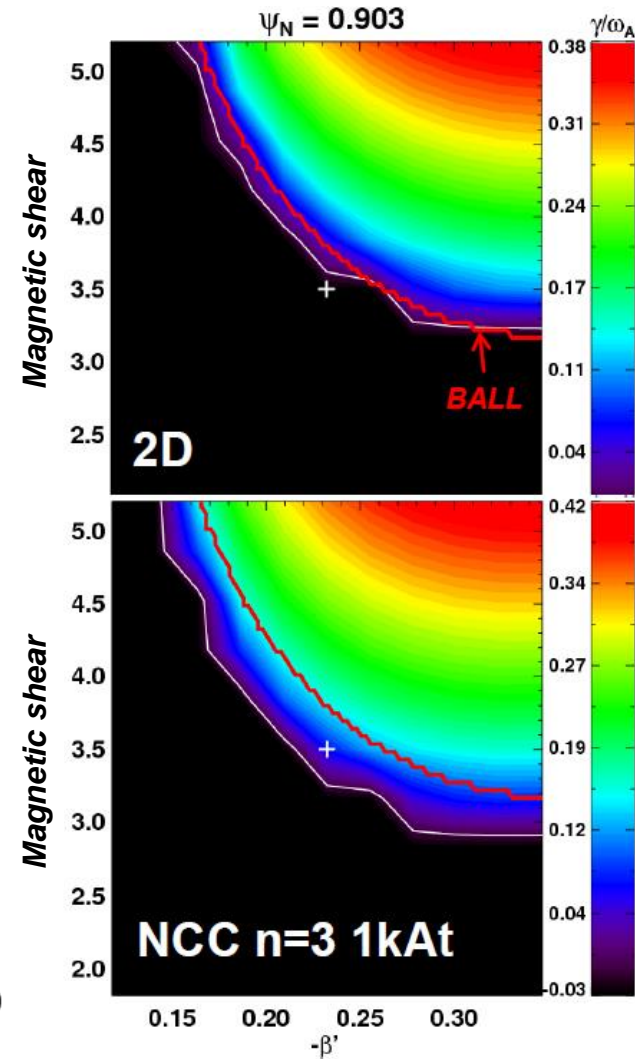
It is important to improve analysis and confirm NCC design merits using present or new tools

Present Tool	Physics included	New physics needed	New Theory Tool
IPEC	Linear perturbed dB spectrum in ideal MHD	Kinetic self-consistent dB Two-fluid self-consistent dB	MARS-K M3D-C1
VALEN3D	Ideal MHD response with full eddy current model	Kinetic MHD response Two-fluid response	MISK M3D-C1
IPEC-PENT, MARS-K, NTVTOK	Bounce-averaged orbits	Full drift-kinetic orbits	POCA
All	No island dynamics	Island dynamics with plasma response	PEST3, Resisitive DCON, M3D
Vacuum field tool for RMP criterion	Vacuum field line tracing, Chirikov, loss fraction	Island overlap, Manifold characteristics	TRIP3D-MAFOT
All	The 0th order transport physics for RMP	The 1st order transport physics for RMP	M3D-C1, XGC0

It will be important to investigate truly optimized coils including other option or by 'inverse' approach

- secondary option:
  - Present NCC design partially stemmed from engineering convenience with '48' passive plates
  - '24' secondary option is not under consideration due to their bad individual coupling
  - However, various combinations with primary option or midplane coil were never seriously investigated - This configuration will be unique in the world with it's full poloidal coverage

- 'Inverse' mapping from FOM to currents on the virtual surface
  - Will yield a vector for Fourier spectrum (m,n) to 'R' FOM considered
  - It can be solved by SVD (linear) or optimization (non-linear) for R by M mapping
  - This theory project can give (1) truly optimized coil and (2) degree of optimization level of actual NCC coil

Secondary option

Primary option