NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

# Plans / collaboration discussion – stability/ control theory/modeling (Columbia U. group)


S.A. Sabbagh[1], J.W. Berkery[1] J.M. Bialek[1], Y.S. Park[1], T.E. Evans[2], S.P. Gerhardt[3], S. Jardin[3], S. Kruger[4], J.-K. Park[3], Z. Wang[3]

[1]*Department of Applied Physics, Columbia University, NY, NY*

[2]*General Atomics, San Diego, CA*

[3]*Plasma Physics Laboratory, Princeton University, Princeton, NJ*

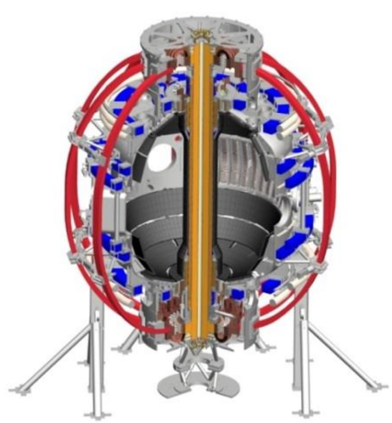
*Tech-X, Boulder, CO*


**NSTX-U Macrostability TSG meeting**

**October 1st, 2013**

**PPPL**

*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*

V1.1

# Columbia U. NSTX-U grant proposal research plans – drive suggestions for theory/simulation collaboration ideas

- Physics research areas on NSTX-U
  - Global MHD mode stabilization physics (incl. kinetic RWM physics)
  - Global MHD mode active control
  - Non-resonant plasma rotation alteration / physics / control (NTV)
  - NCC coil design
- Related/coordinated research on KSTAR
  - Aimed at long-pulse, high beta
  - Higher aspect ratio of KSTAR provides opportunity for comparison to NSTX-U to determine role of A
- Quantitative analysis on ITER cases, future devices
  - Device/code benchmarking efforts (major example – ITPA MDC-2)
- <u>Near-term analysis</u>: continue analysis / publication of NSTX results, with related device/code benchmarking

# List of physics topics / codes in use / planned

- Kinetic RWM stabilization
  - MISK (linear kinetic RWM stability code)
  - M3D-$C^1$, NIMROD: further linear benchmarking, and non-linear runs for NSTX-U (e.g. NIMROD: toroidal resistive wall tests)
- Active RWM control
  - RWM state-space controller development (incl. multi-mode)
  - VALEN / mmVALEN (multi-mode)
- Non-resonant NTV physics (focus on active rotation control)
  - NTVTOK (Shaing et al. formulation, connecting collisionality regimes)
- Equilibrium development
  - NSTX EFIT – further development for NSTX-U
- KSTAR collaboration – closely coupled to NSTX-U
  - Same analysis tools applied on related physics topics to investgate (i) aspect ratio dependence, (ii) long-pulse aspects

# Planned analysis builds from present capabilities and collaborative work

- Equilibrium
  - Free-boundary: NSTX EFIT
  - Fixed boundary: CHEASE (w/Liu), JSOLVER, etc.
- Stability
  - DCON, PEST: ideal linear stability analysis
  - MISK (w/R. Betti): kinetic RWM stability analysis
  - M3D-$C^1$ (w/S. Jardin, N. Ferraro): linear/non-linear stability
  - NIMROD (w/S. Kruger): recent collaboration started - NSTX cases being run
- 3D Physics
  - NTVTOK: NTV code on CU computer, used present NSTX data analysis
  - TRIP3D (w/T. Evans): ELM mitigation – used for KSTAR, etc.
  - M3D-$C^1$ (w/S. Jardin): global mode stability, effect of 3D field on stability, (w/ T. Evans, N. Ferraro, S. Jardin): plasma response
- Control
  - VALEN: RWM / dynamic error field control analysis
  - Multi-mode VALEN: Unstable MHD mode spectrum and control
  - RWMSC: State-space RWM analysis / feedback control

# Multi-year ITPA MDC-2 benchmarking of kinetic RWM codes reaching its goals

| | $r_{wall}/a$ | Ideal $\delta W/-\delta W_\infty$ | $Re(\delta W_k)/\delta W_\infty$ | $Im(\delta W_k)/(\delta W_\infty)$ | $\gamma\tau_{wall}$ | $\omega\tau_{wall}$ | $\delta W_k/-\delta W_\infty$ $(\omega_E = \infty)$ |
|---|---|---|---|---|---|---|---|
| Solov'ev 1 (MARS-K) (MISK) | 1.15 | 1.187<br>1.122 | 0.0256<br>0.0179 | -0.0121<br>-0.0117 | 0.803<br>0.861 | 0.0180<br>0.0189 | 0.157<br>0.160 |
| Solov'ev 3 (MARS-K) (MISK) | 1.10 | 1.830<br>2.337 | 0.0919<br>0.0879 | -0.169<br>-0.090 | 0.471<br>0.374 | 0.114<br>0.051 | 1.98<br>1.10 |
| ITER (MARS-K) (MISK) | 1.50 | 0.682<br>0.677 | 0.241<br>0.367 | -0.046<br>-0.133 | 0.817<br>0.581 | 0.090<br>0.202 | 6.11<br>6.67 |

- Recent success in producing agreement between MISK and MARS-K
  - PENT code development added in 2013
- MISK code has been extensively used to quantitatively compare theory/experiment in NSTX
  - 6 publications from NSTX (first is from 2008)
- MDC-2 process has altered both MISK and MARS-K a bit
  - MISK comparison to NSTX RWM stability experiments continues to evaluate changes

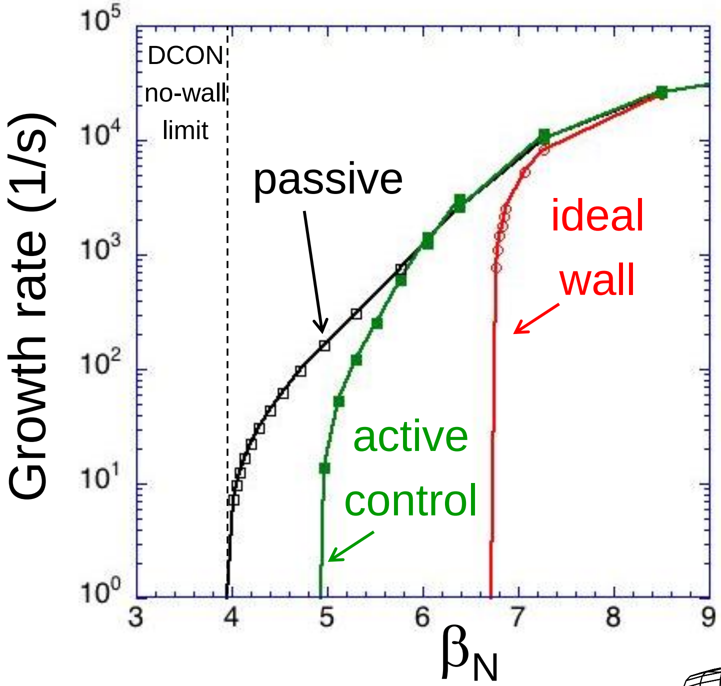
# Discussion topics related to kinetic RWM stabilization

- Stabilization physics due to fast particles should be further addressed
  - Effects of anisotropic (e.g. NBI, RF) particle populations still not fully explored
  - What are destabilization mechanisms (linear, or non-linear) that can be caused by fast particles?
  - Is stabilization accounted due to Maxwellian distributions complete?

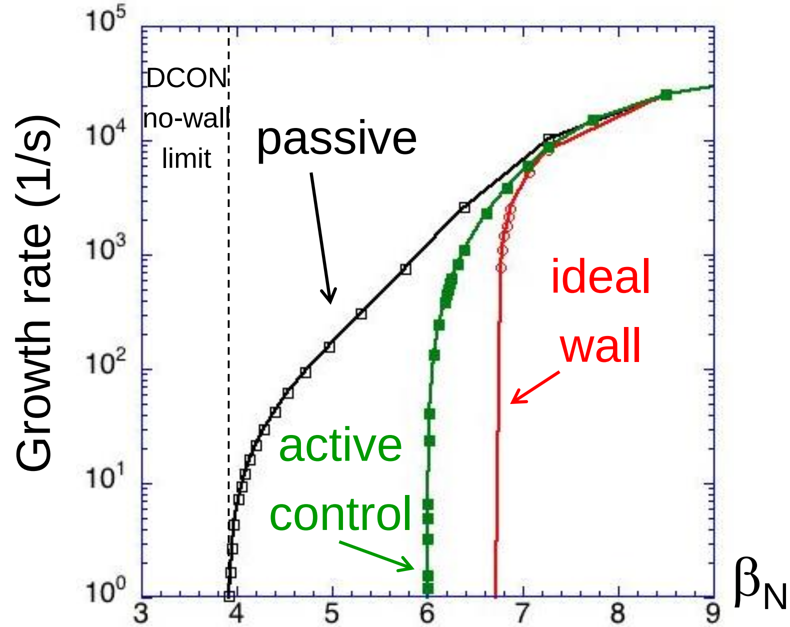
- Long-standing issue – effect of key rational surfaces
  - Generally, numerical integration of ideal eigenfunction very close to rational surfaces does not yield agreement with experiment
  - In fact, omitting regions very close to key rationals yields results that compare better in quantitative comparison to experiment
  - Major task with theory: develop an improved model of the plasma near key rationals

# RWM active control capability increases as partial NCC coils are added (midplane RWM coils included)

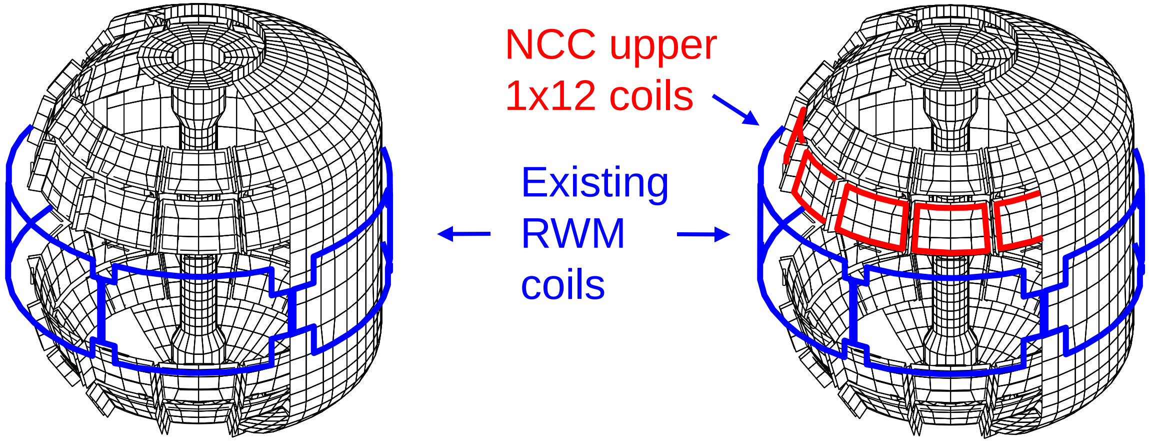
Using present midplane RWM coils



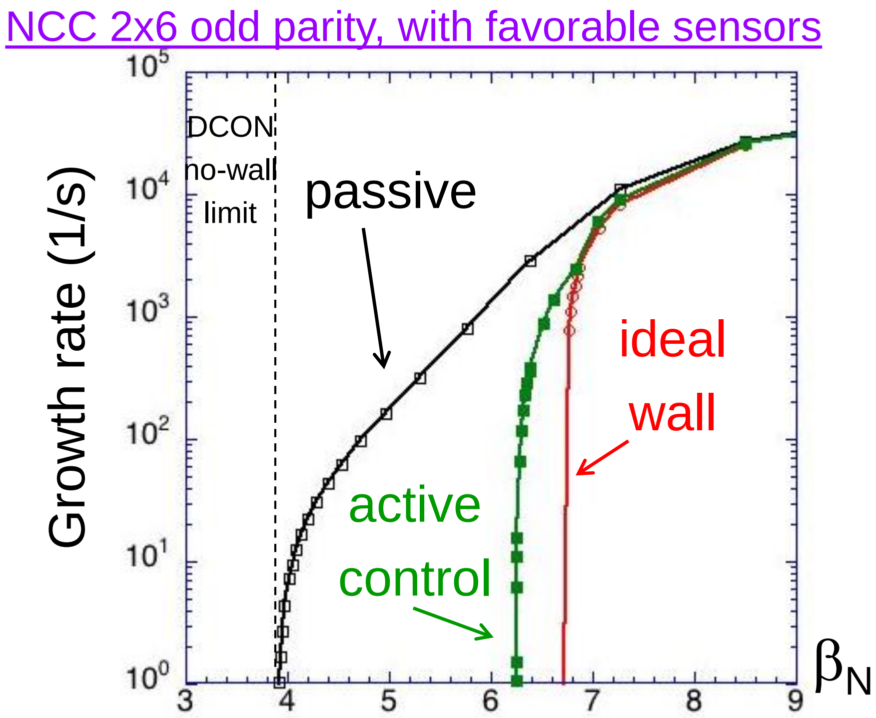

Partial NCC 1x12 (upper), favorable sensors

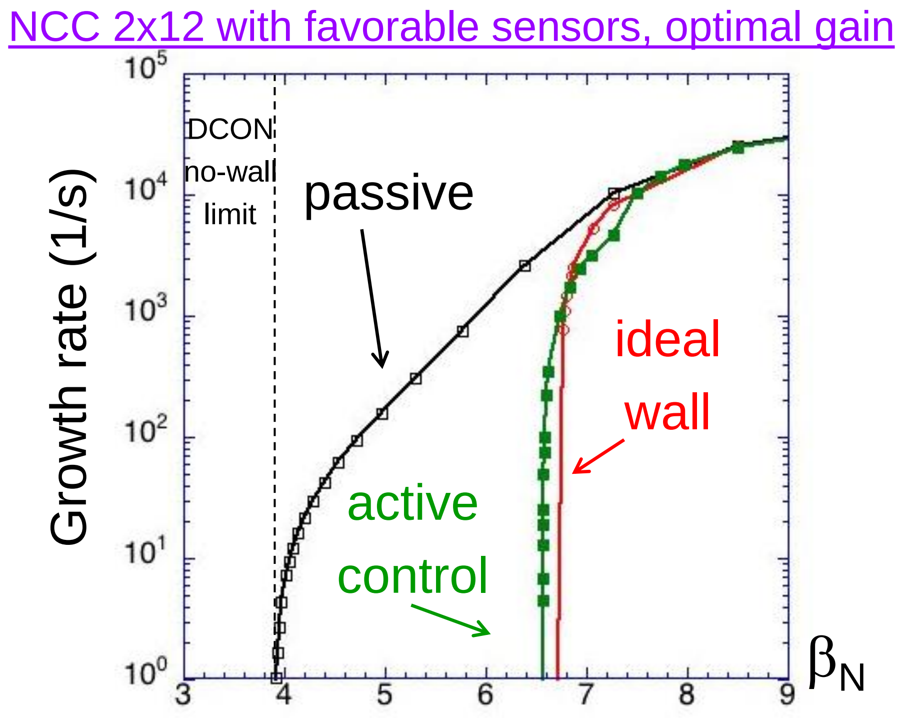



- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.52$

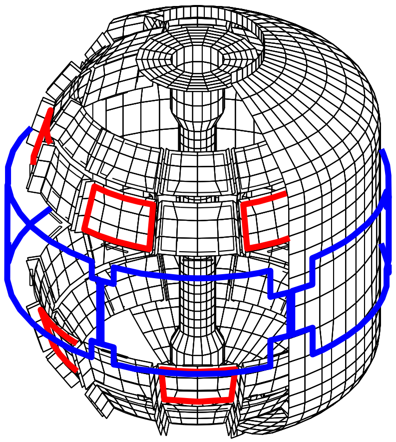


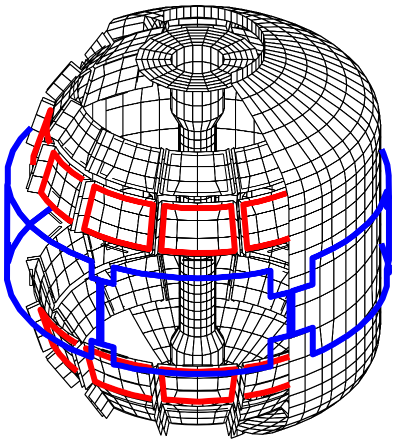
# RWM active control capability increases further with full NCC (midplane RWM coils included)




- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.58$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.67$



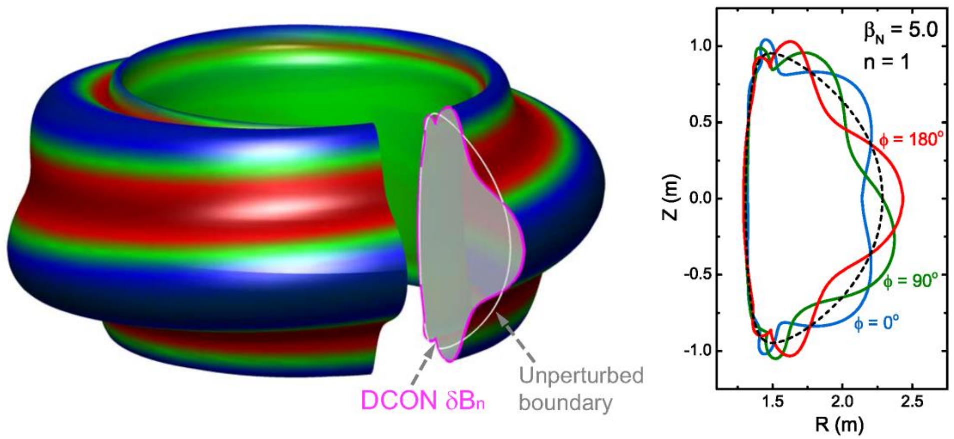


# Comments and discussion topics related to NCC design analysis for NSTX-U

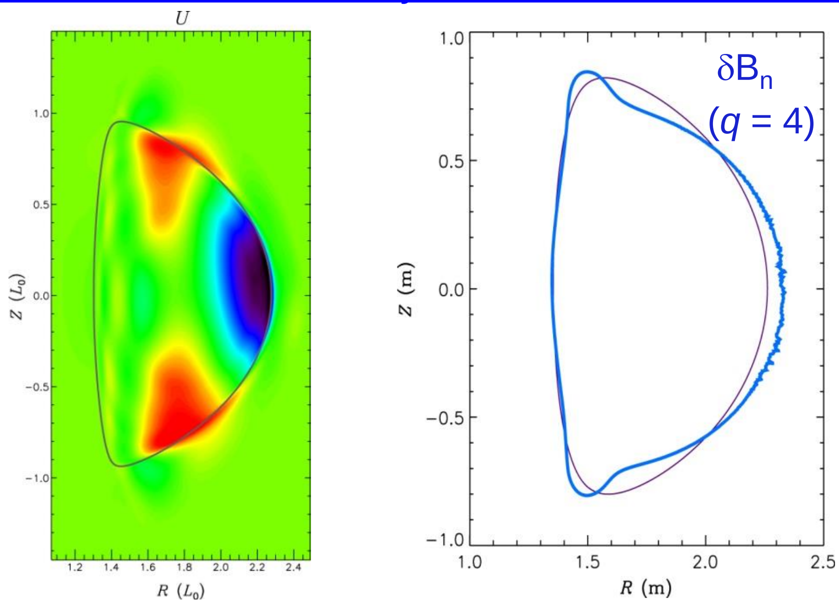
- The present approach of combining key figures of merit to produce a multi-use coil system is the correct one
- We need to be careful that further analysis / results in the coming year that influences the NCC design doesn't greatly decrease multi-use flexibility
  - E.g. recent ELM suppression results from DIII-D indicate that a subset of I-coils are adequate for ELM control – NCC coil design should (and can) expand to test this, rather than downsize
  - Need to avoid similar potential issue based on unproven theory that might restrict physics studies rather than provide a coil to prove them
- Next steps for NCC design for RWM active control (CU plan)
  - Realistic sensors that minimize coupling to passive plates need to be designed and implemented in calculations of present NCC design
  - NSTX-U should have sensors with both weak and strong coupling to passive plates for RWM state-space controller physics studies

# M3D-C¹ code example for KSTAR, comparison to DCON

KSTAR DCON n = 1 unstable mode eigenfunction




M3D-C¹ unstable mode velocity stream function and $\delta B_n$




- Linear stability analysis using M3D-C¹ code (collaboration with S. Jardin)
  - Extended MHD code solving full two-fluid MHD equations in 3D geometry
  - Non-linear code, presently being used in linear mode for initial runs
- Ideal n = 1 stability limit from DCON and M3D-C¹ compare well
  - For the same input equilibria, "equivalent" wall configurations compared
  - With-wall n = 1 stability limit computed as $\beta_N \sim 5.0$ in both calculations
  - Further M3D-C¹ calculations for KSTAR will include improved wall configurations (3D, resistive wall) and analysis for resistive instabilities

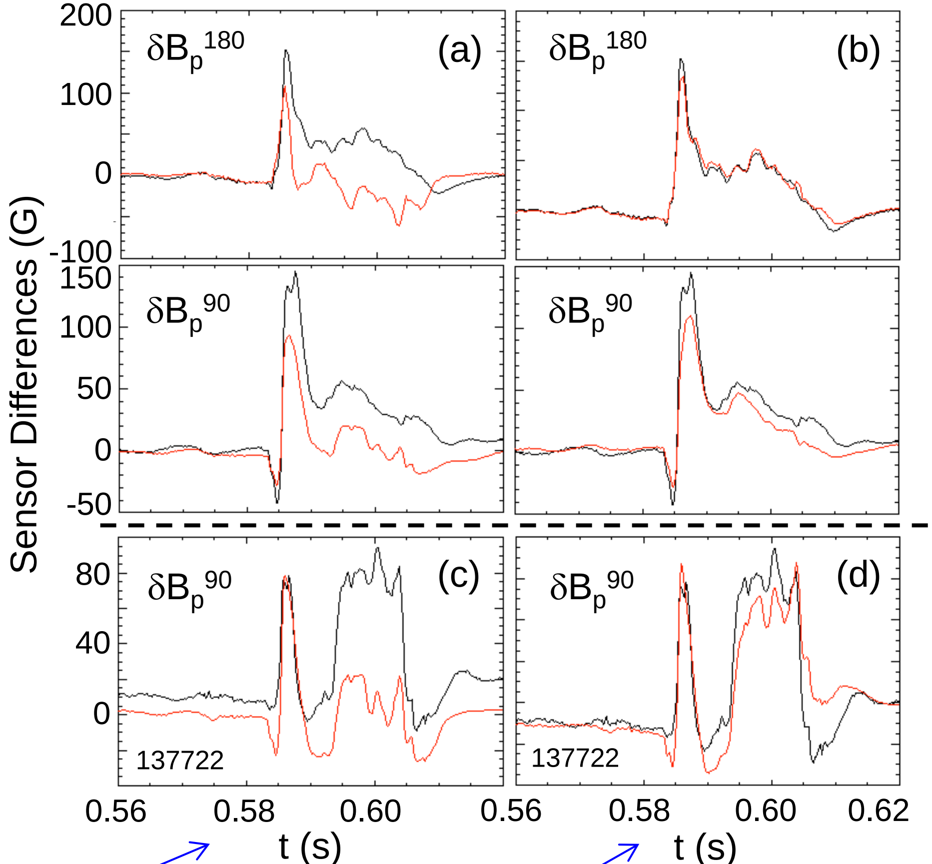
# Discussion topics related to non-linear MHD code analysis

- Stability in the presence of a toroidal resistive wall
  - Much experimental experience in NSTX – can test code using existing data
  - M3D-C[1]: resistive wall model is close (we're ready to beta test!)
  - NIMROD: collaboration with S. Kruger and student
    - Initial tests exposed an issue with model
    - Model recently fixed, first tests on NSTX equilibria should be ready by APS 2013
- Differential rotation between wall and mode is highly desired
  - Physics studies of a fully locked mode are important, but differential rotation is needed to attempt to mimic kink stabilization dynamics
- Kinetic stabilization physics is highly desired
  - For comparison to present tested linear codes (implementation is obviously different!), as well as direct comparison to experiment
  - M3D-C[1], NIMROD in different stages of development in this regard

# Model-based RWM state-space controller used on NSTX improves standard PID control

NSTX: RWM Upper $B_p$ Sensor Differences (G)

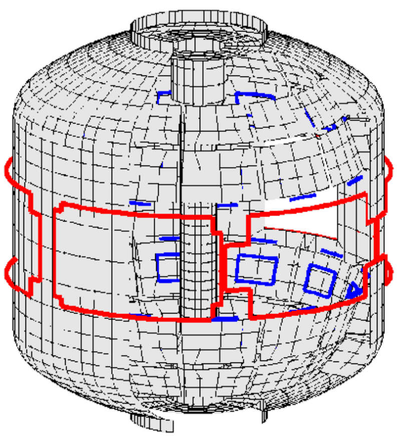
2 States (similar to PID) 7 States




No NBI Port (c)

With NBI Port (d)

- Control approach proposed for ITER
- Can describe n > 1, varied poloidal mode spectrum in model
- 3D mode and conducting hardware features described in real-time
  - Greater detail measured by upgraded sensor coverage is better utilized than with PID



# Discussion topics related to model-based RWM state-space control (RWMSC)

- Present NSTX RWMSC will be upgraded by the Columbia U. group for NSTX-U
  - Upgrade includes independent control of present 6 RWM coils on NSTX-U, multi-mode control capability (n = 1 – 3), upgrade path to NCC, etc.
- Can real-time plasma response model be expanded?
  - Present model is the Boozer (s, $\alpha$) model
    - E.g. kinetic stabilization effects can be included directly through this model
    - However, basic eigenfunctions are chosen a priori and are then altered by this response model. Can this specification be made more generally?
  - Present modes and plasma response model are for ideal linear eigenfunctions. Can more general eigenfunctions be specified? (e.g. non-linear saturated?)
    - What would be the appropriate plasma response model in this case?

# Analysis / code expansion driven by proposed research, NSTX-U device needs

- Equilibrium
  - NSTX-U EFIT: expand diagnostics/model, increase (R,Z,t) resolution, speed
  - CHEASE: (w/Liu), etc.: equilibrium refinement / exchange
- Stability
  - DCON, PEST: ideal linear stability analysis (resistive DCON very close)
  - MISK: continued quantitative development, driven by ITPA MDC-2 NSTX XP data
  - M3D-$C^1$: resistive wall available soon / desire for kinetic effects (compare to MISK)
  - NIMROD: resistive wall / kinetic effects available – collaborative initial tests on NSTX cases with resistive wall underway with S. Kruger and UW student.
- 3D Physics
  - NTVTOK: once NSTX analysis completed, will compare with IPEC and POCA codes
  - TRIP3D: ELM mitigation – use for NSTX-U as desired
  - M3D-$C^1$ (Jardin, Ferraro): desire resistive wall, and kinetic stabilization effects
- Control
  - VALEN: continue NSTX-U RWM control analysis (that has already begun)
  - Multi-mode VALEN: multi-mode spectrum NSTX-U, active control w/RWMSC
  - RWMSC: n > 1 modeling + upgrades, control simulator w/expanded inputs
    - Inputs: Device data, vacuum field, code results (VALEN, M3D-$C^1$, etc. )