NSTX-U

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Non-axisymmetric Control Coil Upgrade: Analysis and Further Development

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Macrostability TSG Meeting
PPPL B318
July 19, 2012

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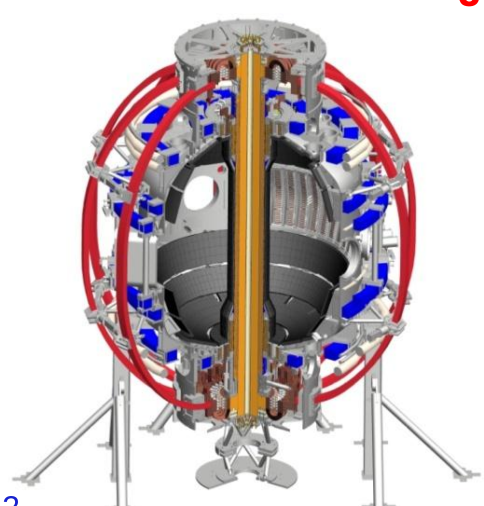

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V1.2

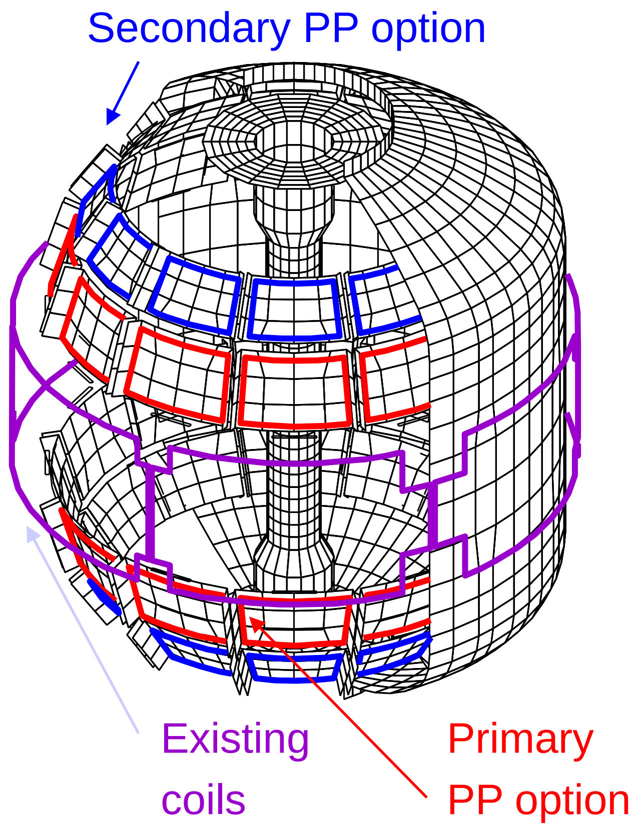
Proposal and Motivation for Non-axisymmetric Control Coil (NCC) started during *last* 5 Year Plan (12/06)- still important

Slide from National Tokamak Planning Workshop (Sept. 2007)

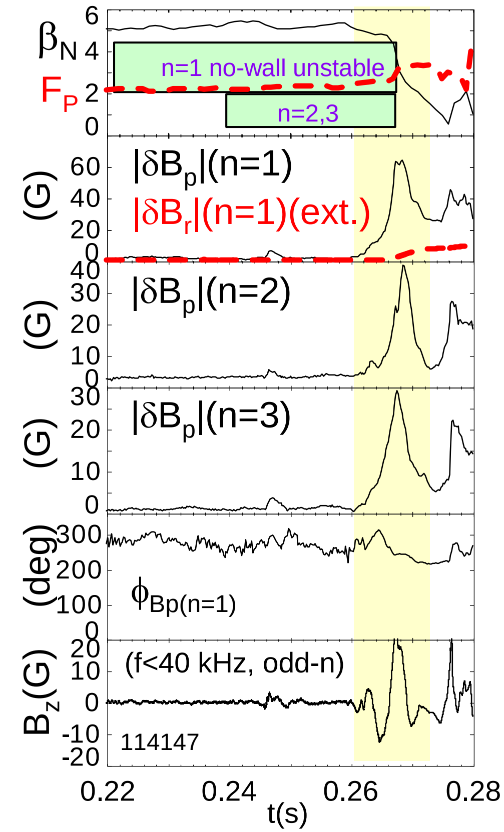
- Planned capabilities 2009-2013
  - Non-axisymmetric control coil (NCC) – at least four applications
    - RWM stabilization (n > 1, higher β_N)
    - DEFC with greater field correction capability
    - ELM mitigation (n = 6)
    - NTV V_ϕ control/increase (($n \leq 6$; $n > 1$ propagation)
  - Non-magnetic RWM sensors; advanced RWM active feedback control algorithms (ITER, etc.)
  - Possible alteration of stabilizing plate materials / electrical connections
  - Scrape-off layer currents (SOLC) / passive plate current measurement

Proposed Internal Non-axisymmetric Control Coil (NCC)

(12 coils toroidally)



RWM with n > 1 RWM observed



(Sabbagh, et al., Nucl. Fusion 46, 635 (2006).)

Last 5YP Macroscopic Stability Research Timeline (2008-2013)

FY07 | 08 | 09 | 10 | 11 | 12 | 13 | 14

Physics

- **Shaping & Control**
  - Optimize β_N > 6 w/high S; β_N control w/rtEFIT
  - β_N control w/stability models
- **RWM**
  - Opt. active RWM control, V_ϕ ; mode deform.
  - Role of n > 1, stabilize RWM w/NCC
  - Adv. RWM control design, NCC dsgn
  - non-mag. RWM detect.
  - non-mag. RWM control
  - RWM stab. physics (ν_i,V_ϕ,ω_A, multi-modes)
  - Adv. RWM control with V_ϕ, q profile control
- **DEFC**
  - DEFC physics model at high β; optimize DEFC
  - Advanced δB correction w/ NCC
- **NTM**
  - Onset+Small Island Studies; seeding physics
  - Advanced modeling; mode avoidance and control
- **V_ϕ physics**
  - NTV physics, ν_i, n=2-6, INTV, NCC design
  - NTV, INTV w/ V_ϕ control; 2nd SPA + NCC
- **Disruptions**
  - Halo current, Thermal Quench Measurements
  - Prediction, Inboard Halo Currents with CS Upgrade

From 5YP Review (July 2008)

Tools

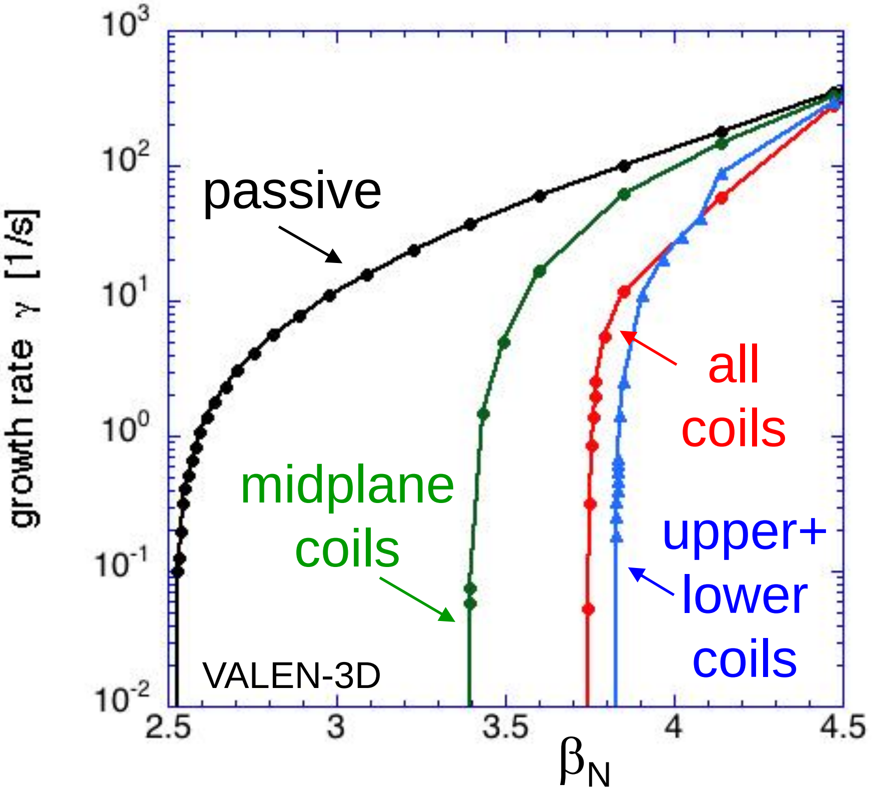
- two toroidal SXR arrays
- 2nd SPA+ NCC
- Adv. RWM, DEFC, V_ϕ ctrl w/ NCC
- non-mag. RWM detection
- CS upgrade
- pCHERS, FIDA, high-resolution edge SXR, internal δB with MSE
- real-time MSE
- 2nd NBI
- MSE-LIF, LLD
- real-time V_ϕ control
- advanced rt-V_ϕ control
- Advanced RWM control algorithms
- Integrated code devel/appl: mmVALEN,Hu-Betti δW, MARS-K, GTC-Neo NTV, NIMROD, M3D, PEST3, rDCON
- div. halo current
- β control; fast IR - PFC disrupt. loads; disruption prediction/detection

V1.1

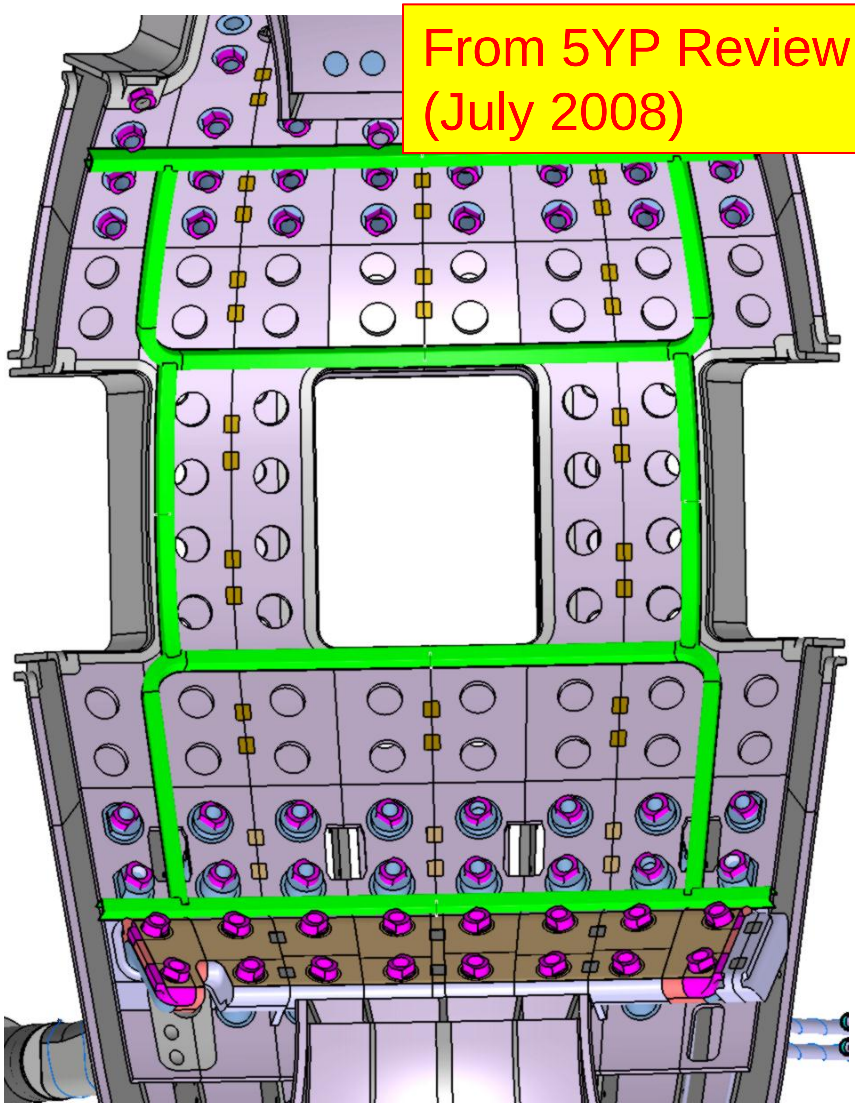
VALEN RWM control models validated on NSTX predict significant β_N increase with proposed ITER internal coil

From 5YP Review (July 2008)

ITER VAC02 stabilization performance



- 3 toroidal arrays, 9 coils each
- ELM, VS, RWM applications
  - Endorsed by ITER STAC
- Configuration similar to proposed NCC coil upgrade for NSTX

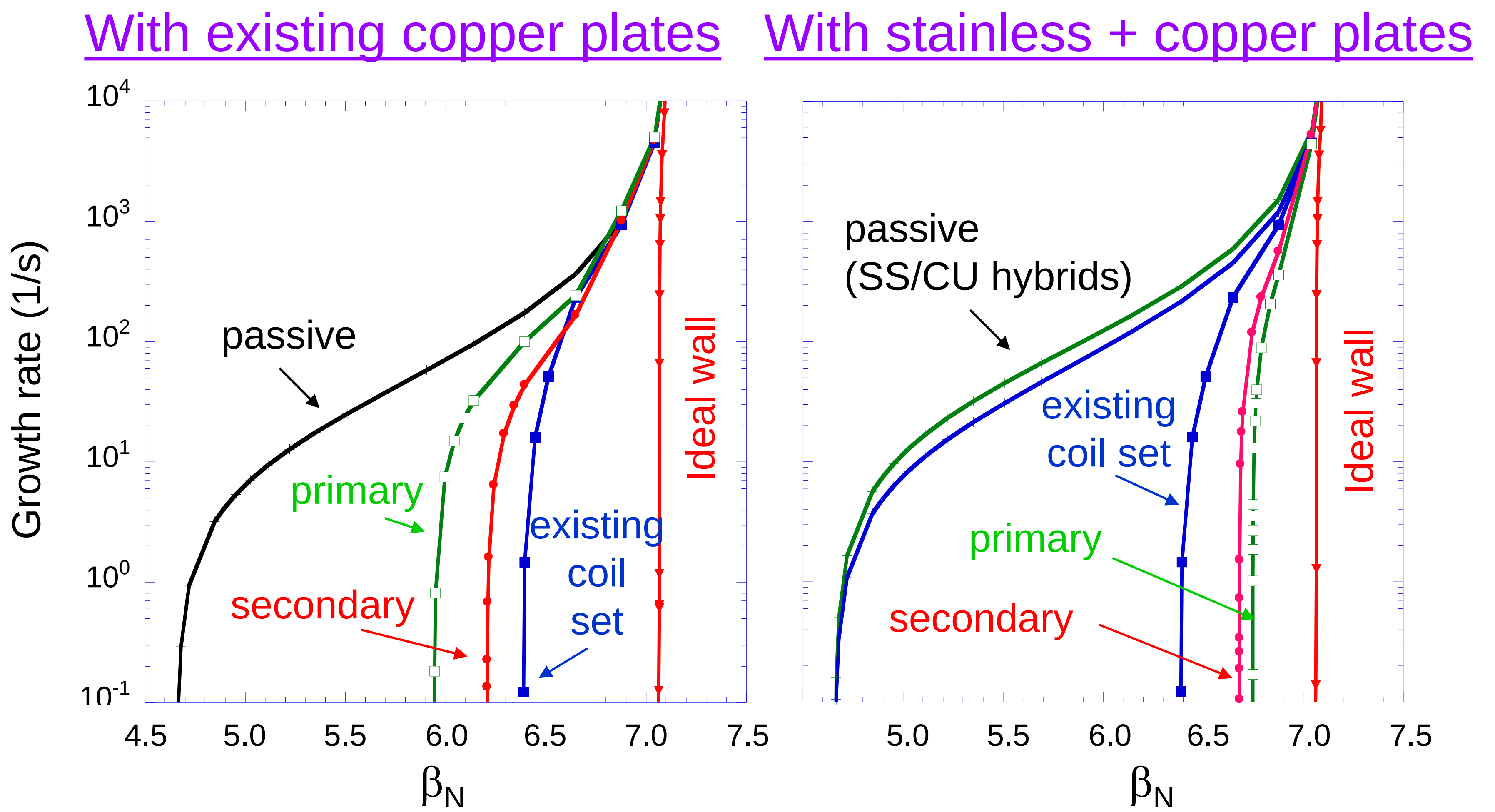


ITER VAC02 design 40° sector

Several options for the NCC were considered, RWM control and ELM mitigation analyses were conducted

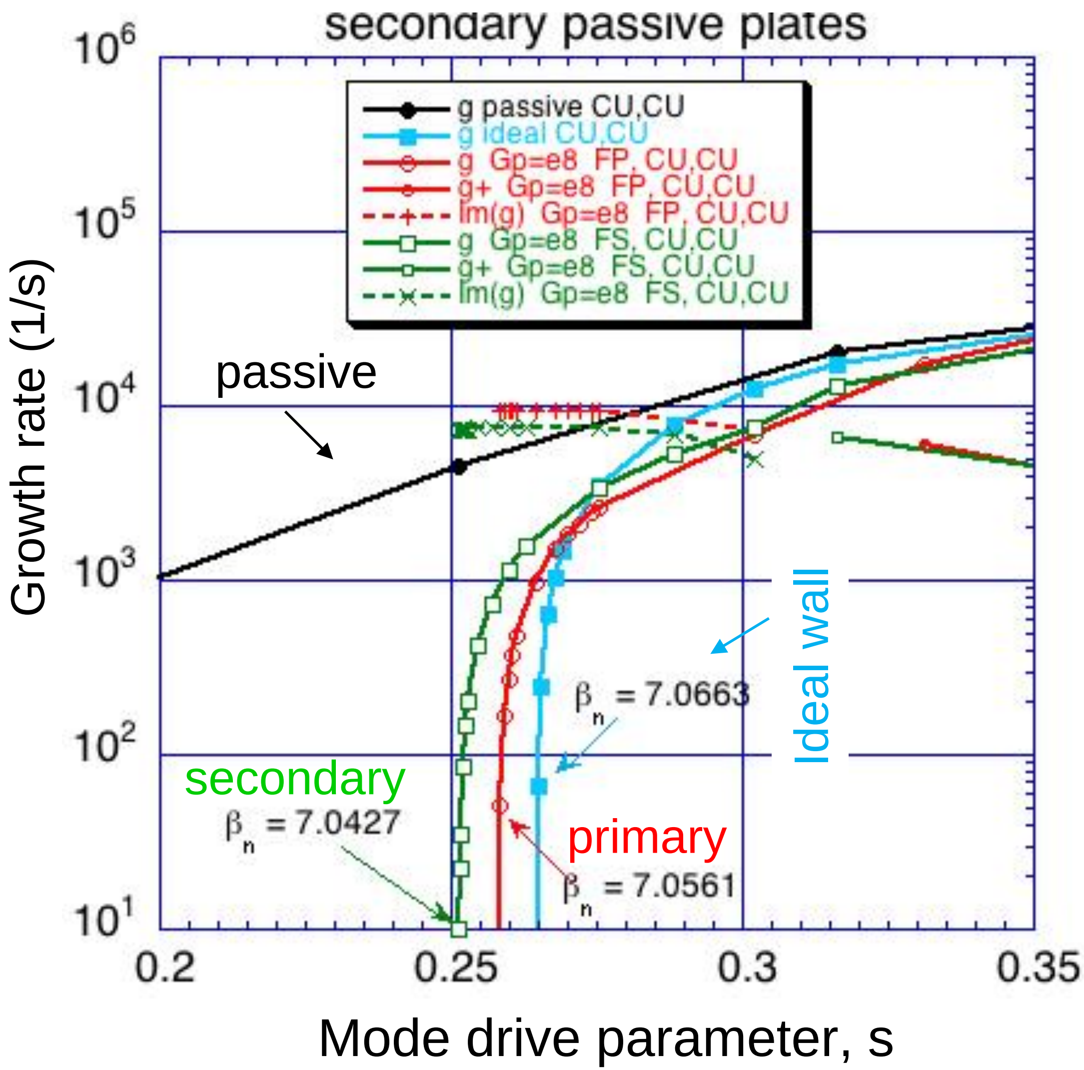
- Options considered
  - Coils external to vessel
  - Coils internal to vessel
    - Between passive plates and PFC tiles
      - Positions at primary or secondary passive plates
    - Behind passive plates
      - With varied passive plate materials (stainless, or lower conductivity material)
- Analyses
  - RWM control computed for these options
  - ELM stability evaluation made for external and internal coil options with copper plates

RWM control performance for internal coils behind passive plates only advantageous if plate material is changed



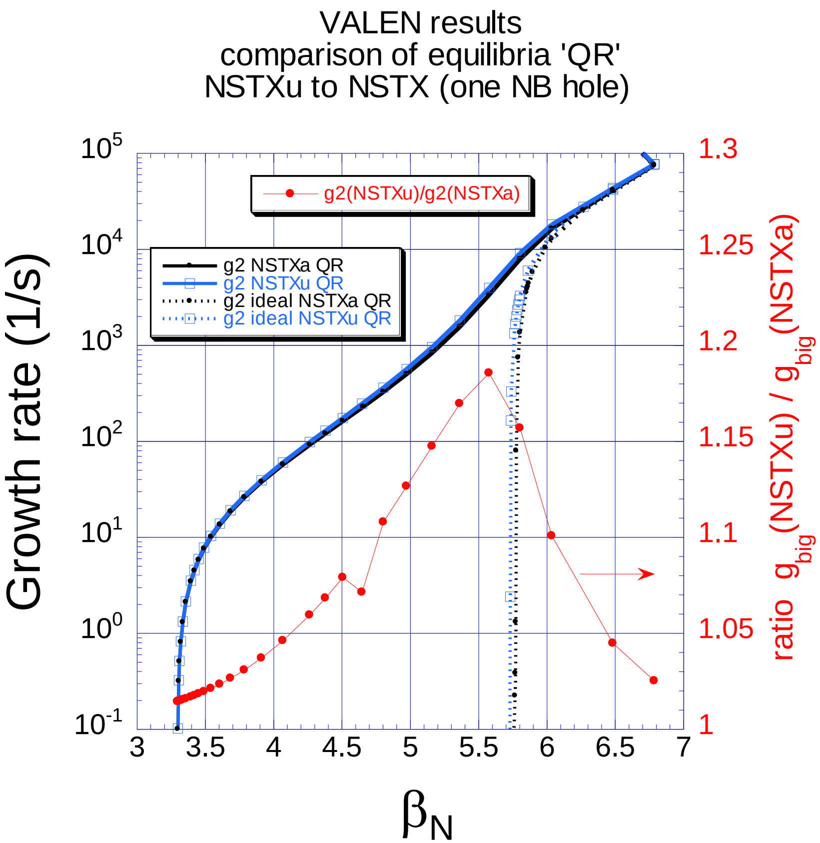
- Coils behind copper plates are less effective than present midplane external RWM coils for mode control

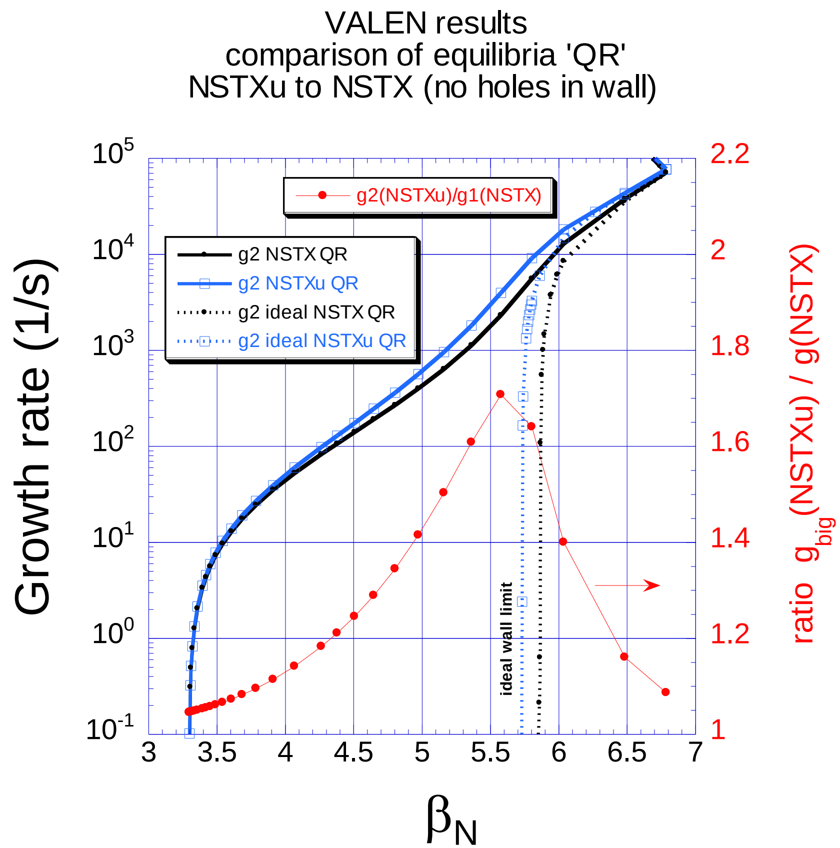
RWM control approaches the ideal MHD with-wall β_N limit when coils are located between plates and PFC tiles



- Coils located between primary passive plates and PFC tiles yield slightly better control than when located in front of secondary passive plates
- <u>Advantage</u>: plate material need not be changed in this scenario

NSTX-U equilibria will effect general NCC RWM control conclusions more strongly than vessel modifications





- Growth rate vs. NBI port model for NSTX, NSTX-U changes, but not so drastically to preclude past conclusions, e.g. on best NCC coil positions for control
  - Same conclusion for most recent calculations using updated 2nd NBI vessel flange model
- Major change in growth rate vs. β_N between NSTX, NSTX-U is due to equilibrium change; change in terms of C_β will be relatively small

ELM mitigation evaluation analysis was performed by T. Evans for NCC prototype coils

- Analysis used vacuum field calculations
  - Conducted over several months
  - Chirikov criterion, perturbation alignment with m = nq resonance, field line loss fraction
  - Comparisons to DIII-D guidance for these parameters that have led to successful ELM mitigation in DIII-D
- Several NSTX equilibria used for analysis
  - To determine variation of ELM mitigation criteria as a function of parameters (e.g. plasma shape, q_{95})
- Several variations of NCC coil prototypes tested
  - Analysis included external coils, internal coils at primary/secondary passive plate positions
- Results summarized 3/8/10 (full talk available)
  - Only the most favorable NCC coil configuration was shown: in-vessel coils at the Z position of the primary passive plates

Edge magnetic field line studies for a proposed set of internal RMP coils on NSTX

T. E. Evans*
General Atomics,
San Diego, CA

NSTX Group Meeting
March 8, 2010
PPPL, Princeton, NJ

*In collaboration with:
J. Jayakuma, R. C. Kalling
General Atomics,
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and

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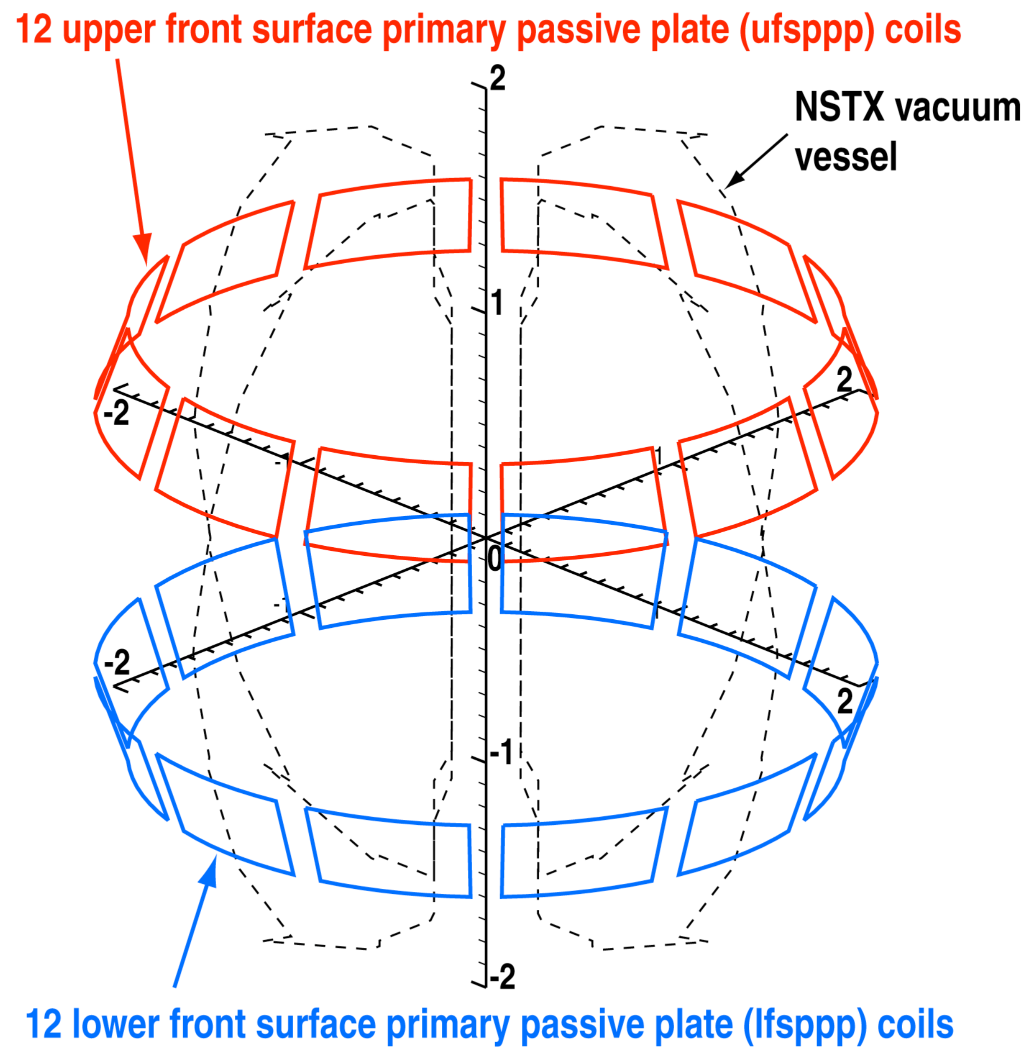
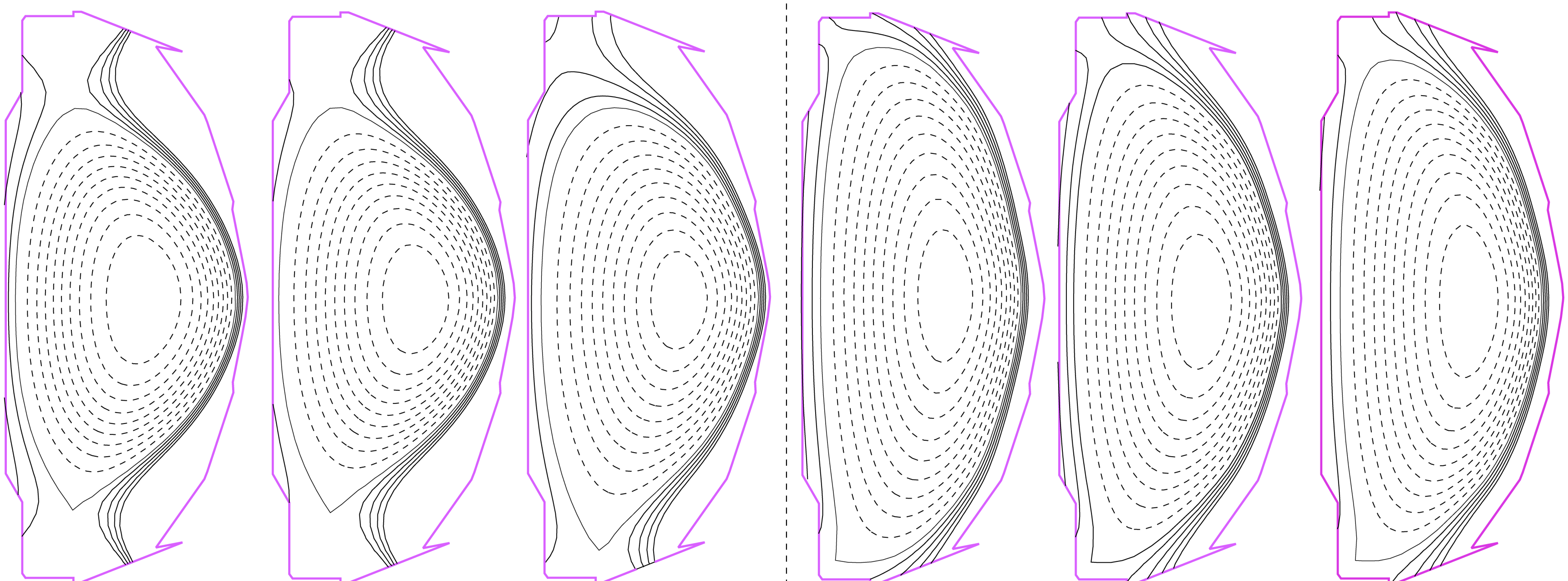


Goals and parameters

- Quantify field line properties for a proposed set of internal RMP coils on NSTX configured for:
  - n = 6 (and some n=3) operations using:
    - Several plasma shapes with different values of q_{95}, dRsep, and κ
- Coil properties:
  - 2 rows of 12 coils
  - Mounted in front of the upper and lower primary passive plates
    - Referred to here as the Front Surface Primary Passive Plate (**FSPPP**) coils
  - Maximum single-turn current, 1 kA (square wave)
- Quantitative measures:
  - Stochastic layer width:
    - maximum width over which the Chirikov parameter exceeds unity
  - Field line loss fraction

A variety of NSTX plasma shapes were studied

Low δL ~ 0.5, X-point controlled by pf2L, more ITER-like | **High δL ~ 0.7, high κ, X-point controlled by pf1a**



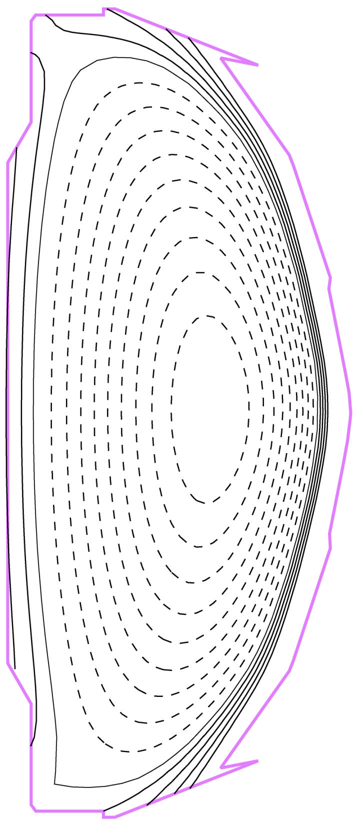
123662:380	125269:465	125272:600 (giant ELM)	125006:343	125200:501	125328:718 (fiducial)
Ip =0.9 MA	Ip =0.8 MA	Ip =0.8 MA	Ip =0.7 MA	Ip =1.2 MA	Ip =0.9 MA
BT = 4.0 kG	BT = 4.5 kG	BT = 4.5 kG	BT = 5.0 kG	BT = 4.5 kG	BT = 4.5 kG
q95 = 5.5	q95 = 8.0	q95 = 7.6	q95 = 13.24	q95 = 7.16	q95 = 9.0
κ = 1.9	κ = 1.85	κ = 2.0	κ = 2.6	κ = 2.4	κ = 2.5
drsep = -0.6	drsep = -0.4	drsep = -2.2	drsep = -0.6	drsep = -0.7	drsep = --1.0

- Comparisons were done using both n=3 and n=6 FSPPP coil perturbations for plasmas with different q_{95}, dRsep, and κ

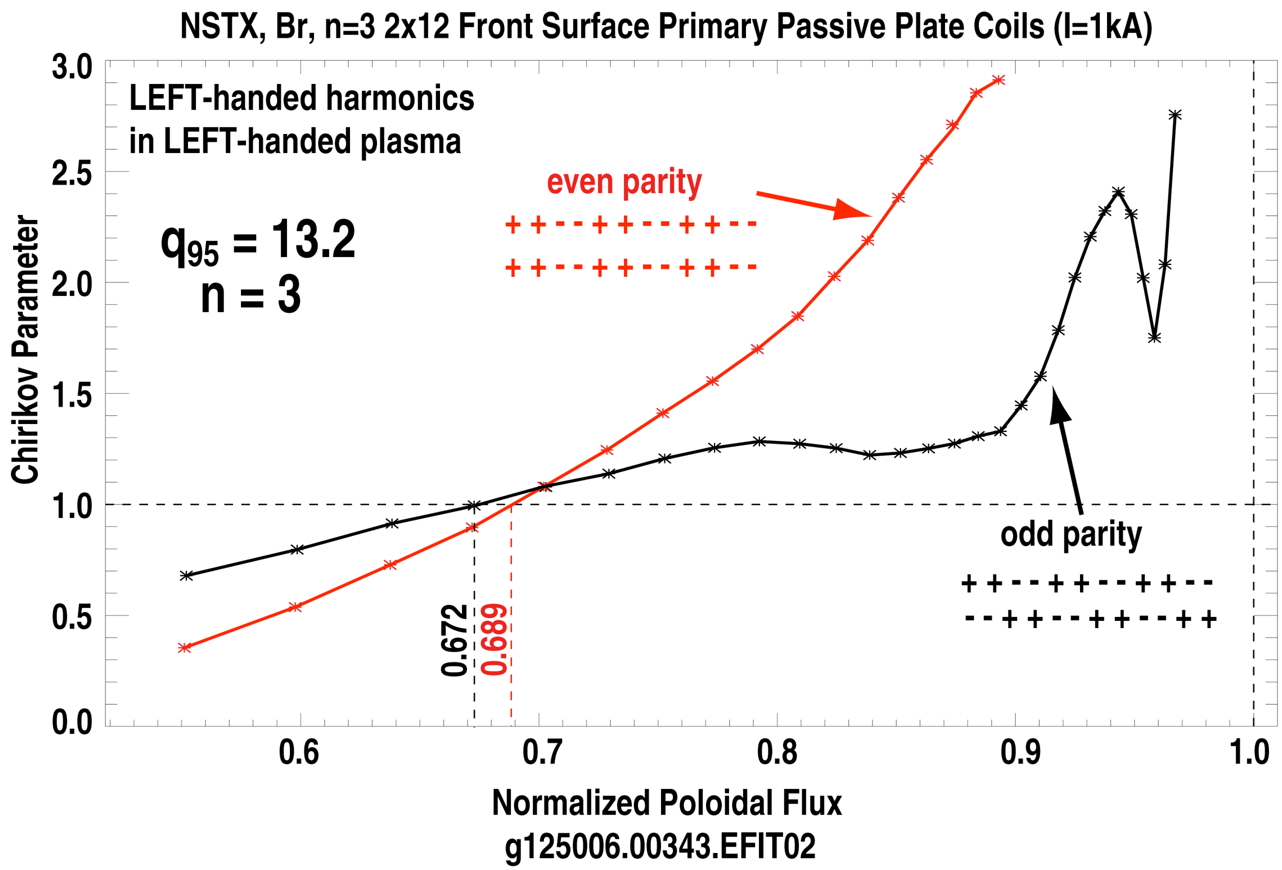
DIII-D NATIONAL FUSION FACILITY

Edge stochastic layer widths exceed 30% with n=3 even and odd parity FSPPP fields in high δ, κ plasmas

High δ_L ~ 0.7, high κ, X-point controlled by pf1a

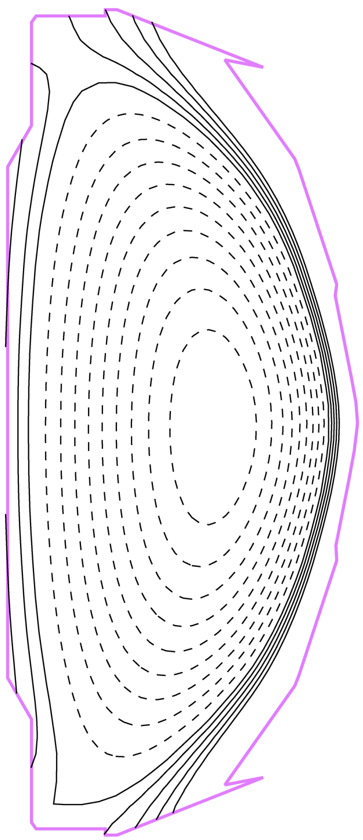


125006:343
Ip =0.7 MA, B_T = 5.0 kG
κ = 2.6, dRsep = -0.6

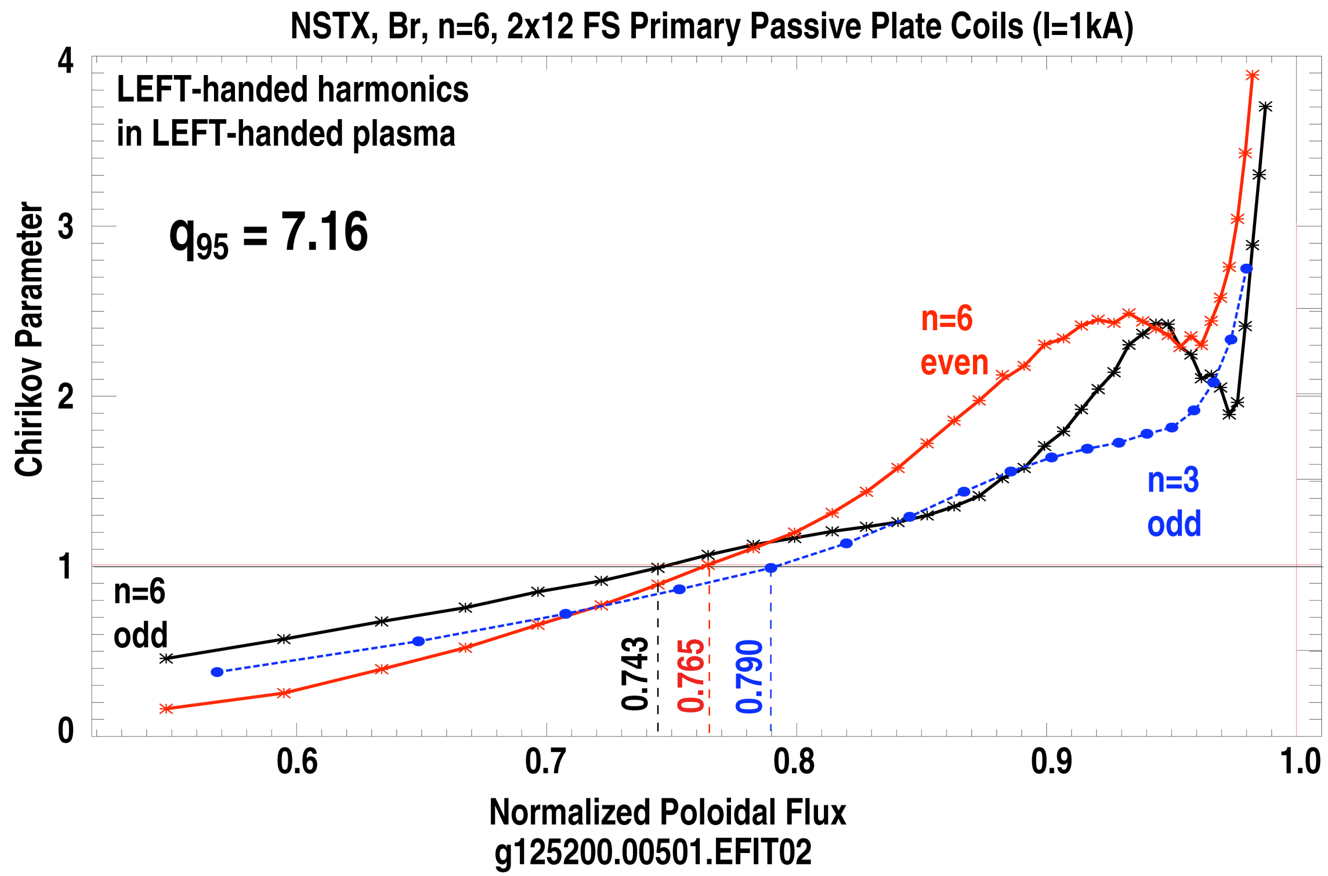


In high δ, κ plasmas n=6 FSPPP fields produce edge stochastic layers similar to those with n=3 fields

High δ_L ~ 0.7, high κ, X-point controlled by pf1a

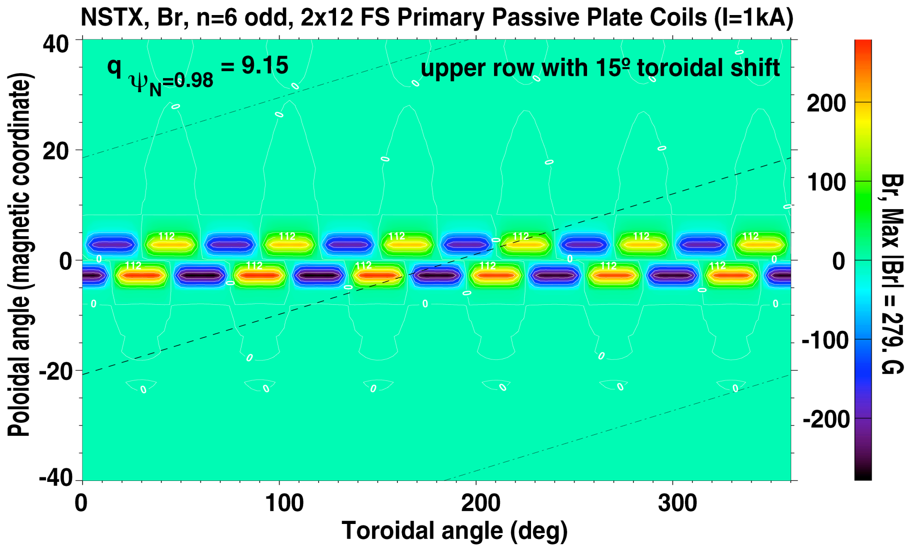


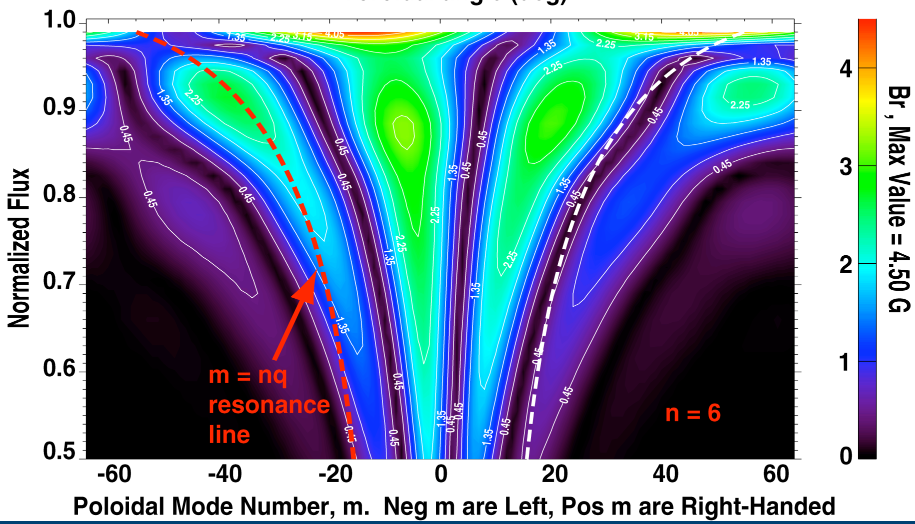
125200:501
I_p =1.2 MA, B_T = 4.5 kG
κ = 2.4, dRsep = -0.7

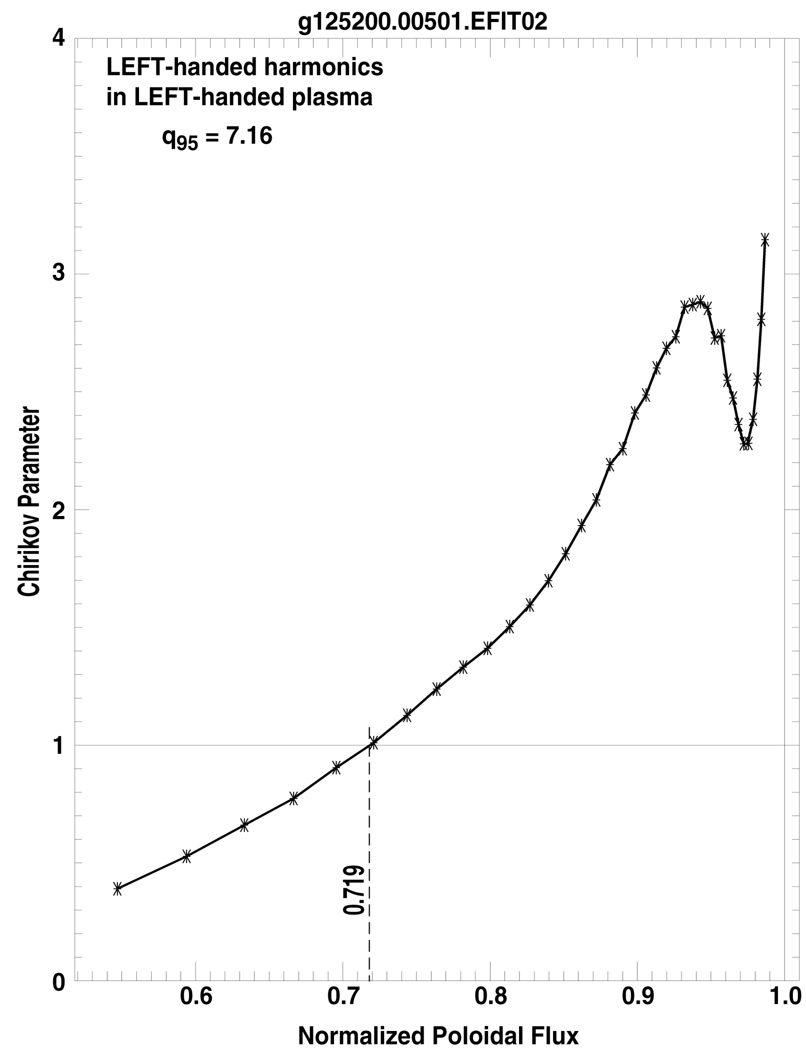


Reference case for n=6 optimization studies

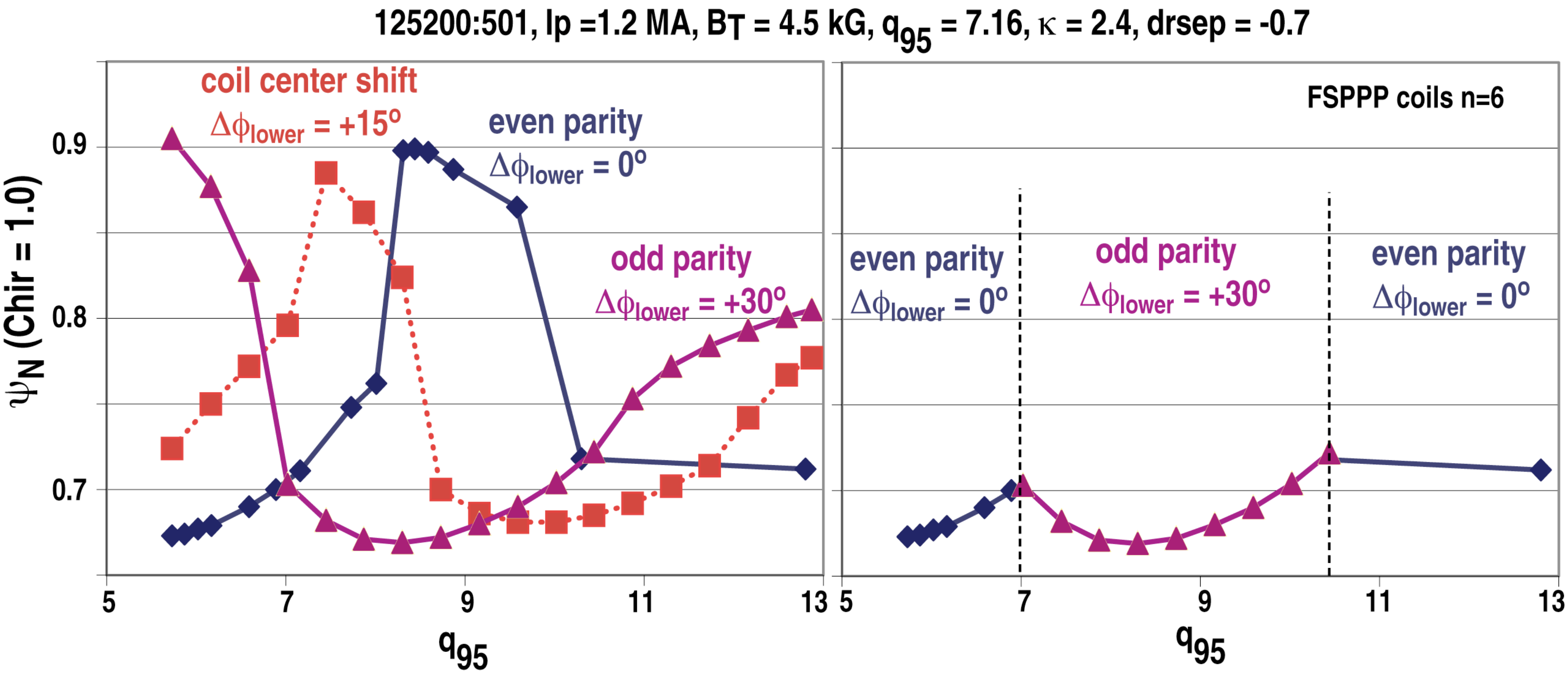
A Δϕ = 15° upper coil shift with respect to the lower coil increases the edge stochastic layer width







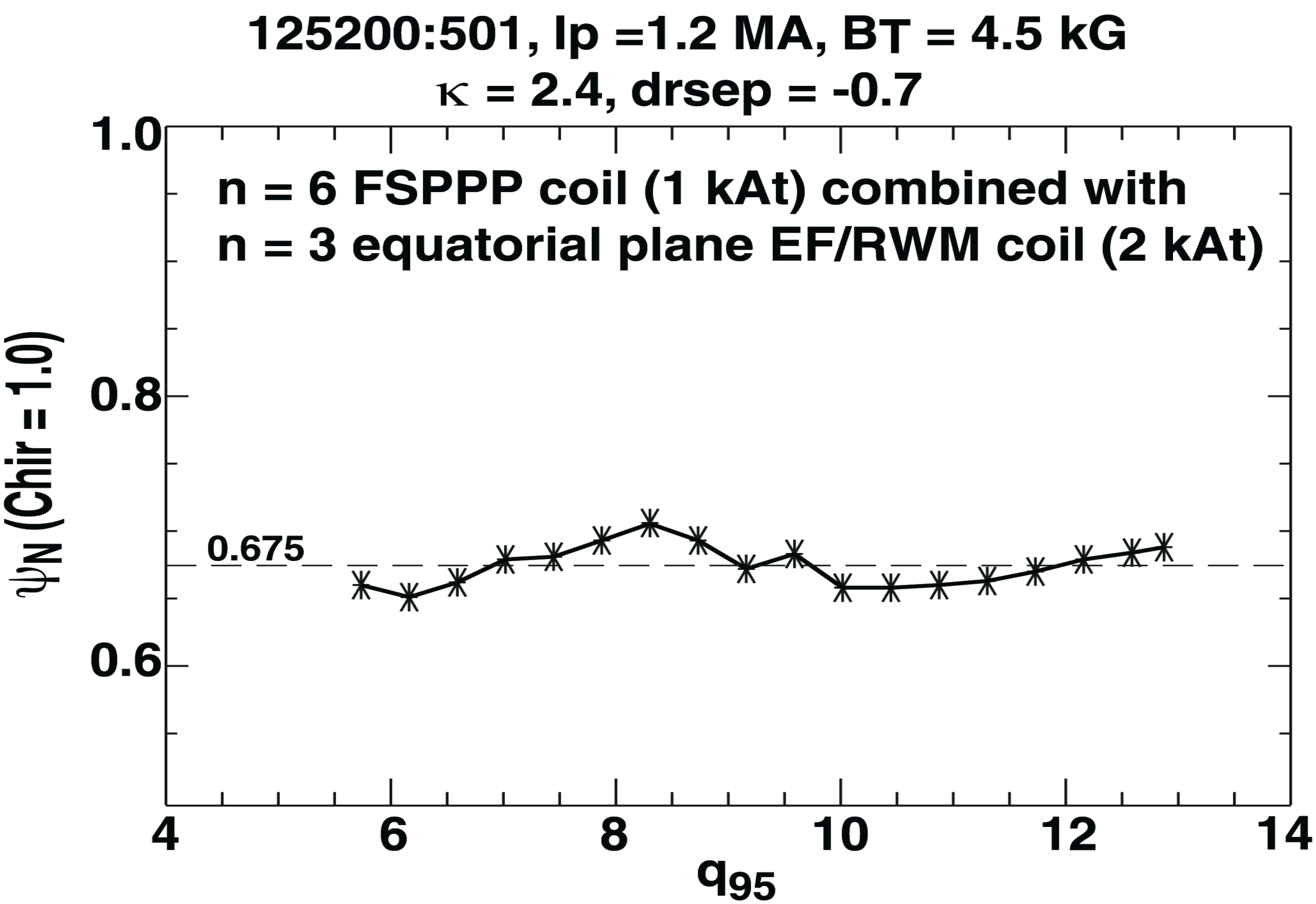
Edge stochastic layer width can be maintained over a wide range of q_{95} by varying the n=6 toroidal phase



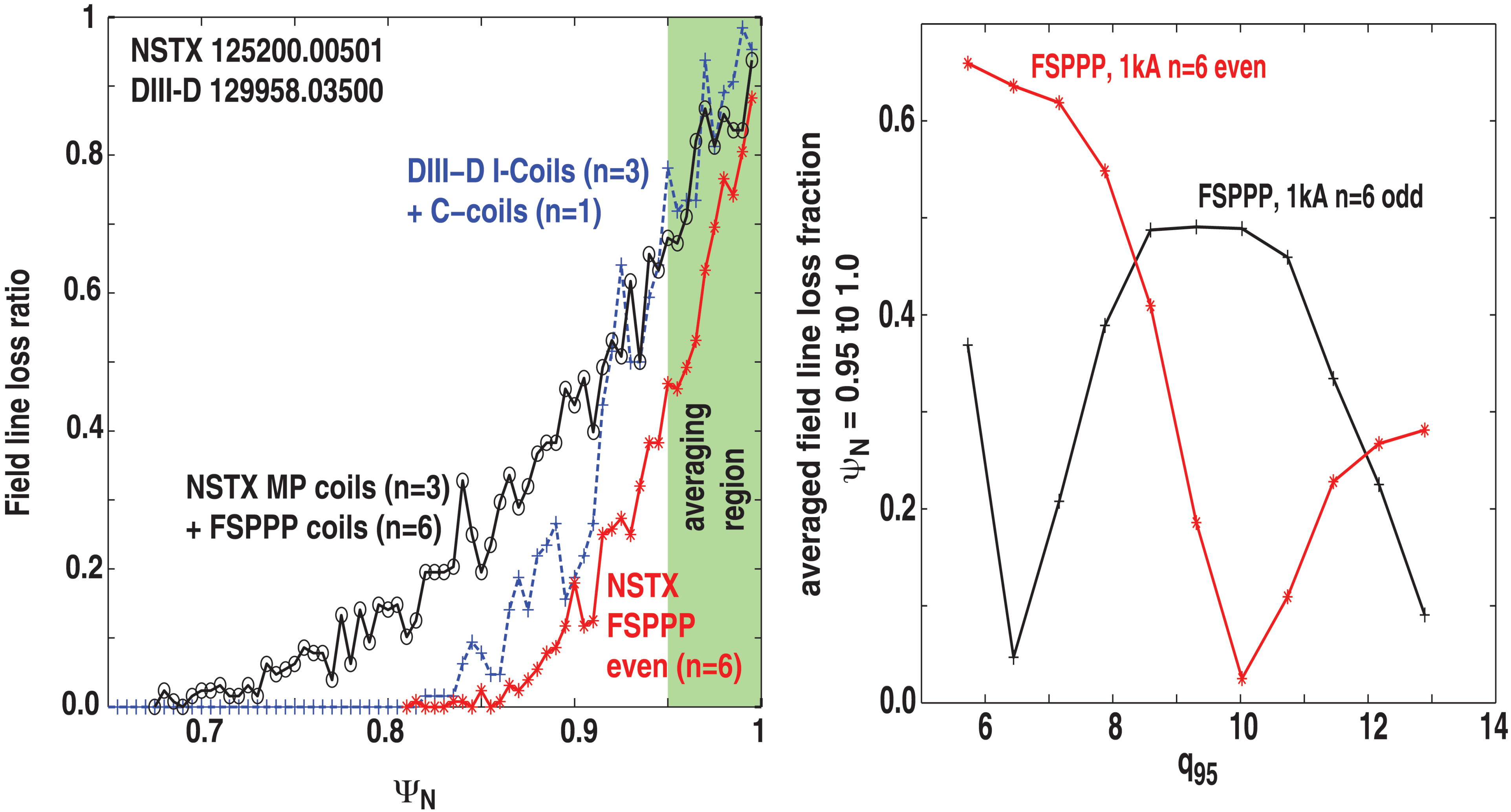
- Edge stochastic layer width ≥ 27% maintained when using:
  - Even parity ($\Delta\phi = 0°$) for $5.3 \leq q_{95} \leq 7.0$ and $10.3 \leq q_{95} \leq 12.8$ and
  - Odd parity ($\Delta\phi = 30°$) for $7.0 \leq q_{95} \leq 10.3$

DIII-D NATIONAL FUSION FACILITY

Edge stochastic layer width versus q_{95} is kept ≥ 30% when n=6 FSPPP coil is combined with n=3 EF/RWM coil



The field line loss fraction exceeds that in DIII-D when the n=6 FSPPP coil is combined with n=3 EF/RWM coil



Summary and additional comments

- In high δ, κ DN plasmas, n=6 FSPPP fields produce a wider edge stochastic layer than n=3 I-coil fields in DIII-D
  - Over a wider range in q_{95} (*i.e.*, $5.3 \leq q_{95} \leq 12.8$)
- Combined FSPPP n=6 and EF/RWM n=3 field line loss fractions exceed those due combined n=3 I-coil and n=1 C-coil fields in DIII-D
  - Preliminary results from DIII-D indicate that as the pedestal collisionality increases ELM suppression is correlated with larger field line loss fractions
- Future FSPPP coil geometry optimizations include:
  - Aspect ratio variations
    - Studies of other RMP coil designs (e.g., DIII-D and ITER) indicate that optimizing the coil aperture to match the poloidal wavelength increases the coil efficiency
  - Angular tilt variations
    - Match the flux surface contours better (especially in lower κ plasmas)
  - Comparisons of optimized n=3 FSPPP coils with n=3 EF/RWM coils
  - Plasma response versus β_N and collisionality

Key physics that was recognized when the NCC was initially proposed is still important; now further topics emerge

Originally envisioned physics

- RWM physics, and control using n = 1, n > 1
- DEFC with greater field correction capability
- ELM mitigation ($n \leq 6$)
- NTV physics, and V_ϕ control (with $n \leq 6$)
  - Increase V_ϕ via $n > 1$ toroidal propagation
- Model-based RWM state space controller
- Non-magnetic RWM sensors (internal modes; ITER)

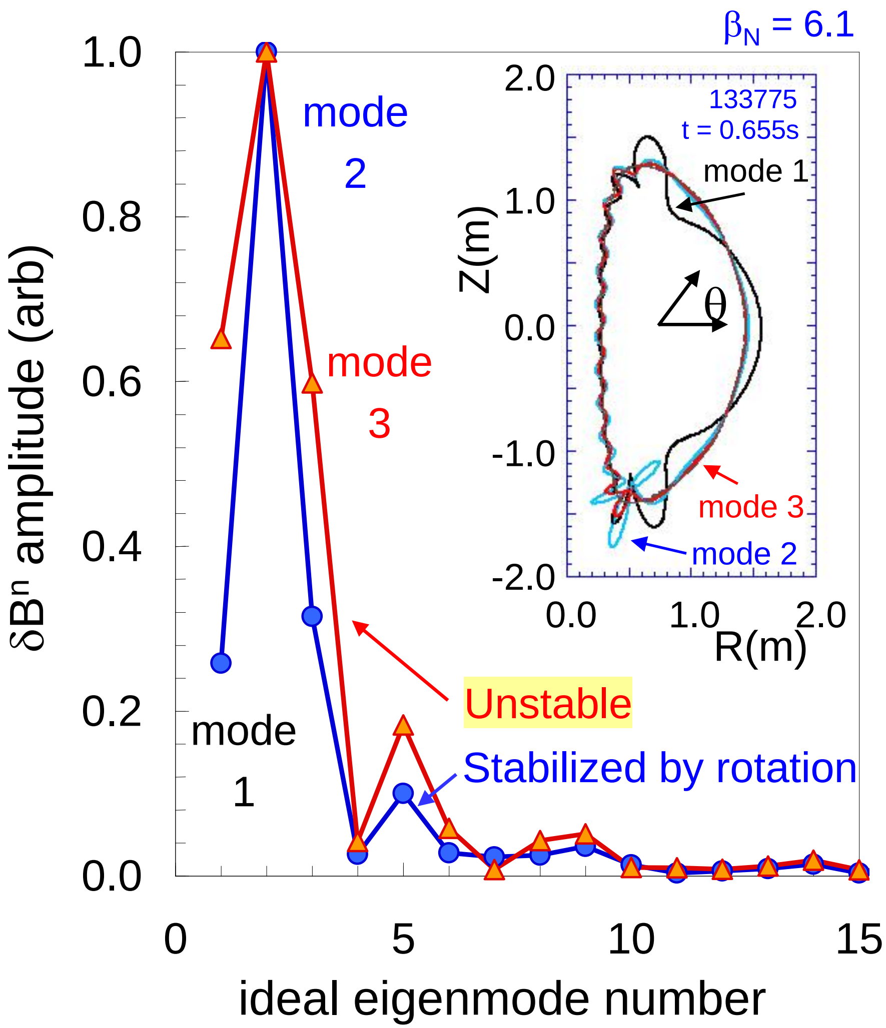
+ Further physics topics

- RWM state space control
  - Multi-mode RWM control and DEFC with observer
  - Physics and control of "non-rigid" mode evolution
- Key ITER, JT-60SA topics
  - RWM state space control of ITER-similar coil set
  - Simultaneous use of actuators sharing multiple control roles
  - Control physics of partial coil coverage; "failed coil" control physics and tests

(continues next 2 pages…)

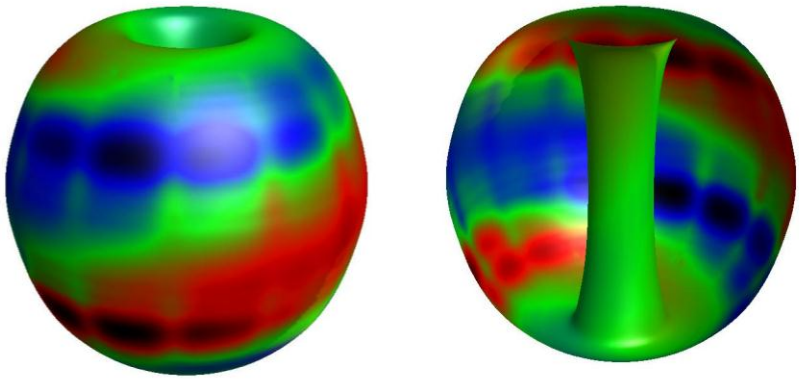
NCC can allow quantitative studies of the importance of multi-mode spectrum for RWM control and DEFC

δB^n RWM multi-mode composition



mmVALEN code

δB^n from wall, multi-mode response



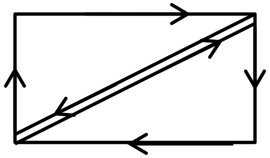
- NCC can provide quantitative evaluation of the importance of multi-mode spectrum (n and m) for RWM control and DEFC
  - Spectrum will gain helicity – important to expand research
- This is just one example of a study unique to NSTX
  - n > 1 mode spectrum observed but importance of control / dynamic correction never tested

The NCC is best justified by defining how NSTX-U can uniquely investigate the associated physics, e.g.….

- 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
- Unique high beta ST operational space
  - Perform advanced stability control using NCC in operating space where disruptivity is *not* maximized at the highest β_N, or β_N / l_i.
- Unique physics coupling in control systems (key for ITER)
  - e.g. RWM, TM stability depends on V_ϕ,q,n,T profiles; V_ϕ control will depend on NTV (V_ϕ,q,n,T profiles) – NCC may improve such control
- Strong, precise, controllable NTV effect observed in NSTX
  - Routine open-loop V_ϕ profile alteration is not routinely performed on other devices
- Control model testing that utilizes NCC in coupled systems
  - For V_ϕ control, β_N control, RWM control, DEFC, RWM passive stability

NCC upgrade can investigate several key physics issues and new ideas based on new capabilities/understanding

- NCC physics
  - Performance analysis performed for both RWM stability (Columbia) and ELM mitigation (GA - Evans) – now need to redo for NSTX-U (including recent physics understanding)
  - Several configurations were considered:
    - Coils internal to vessel, coils external to vessel (i.e. “distant” coils)
    - Coils in front of primary/secondary passive plates, or among plates with altered plate material for some of the plates (e.g. SS)
  - Possible inclusion of diagonal elements for “stellarator” field?



- NCC in light of present day ideas / capabilities
  - Internal “hairpin” coils (similar to KSTAR IVCC design) may ease implementation, give greater flexibility for physics studies
  - New RWM state-space controller allows far greater flexibility of global mode stabilization physics studies with these coils, with a relatively simple control software upgrade
  - New option of coils closer to divertor for control of “divertor” mode (multi-mode physics)
  - New consideration: field spectrum to produce favorable V_ϕ profile by NTV and NBI for kinetic global mode stability (MISK physics)
  - Examine best NCC field spectrum to potentially change edge fast ion profile for RWM and edge mode stability alteration (MISK physics)
  - Idea of “delta coils”: strategically located dipole fields to enhance field spectrum for ELM mitigation, and possibly for time-dependent pulsed fields for ELM studies (T. Evans)