NSTX-U

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

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NSTX-U / DIII-D Collaboration meeting

December 10th, 2013

PPPL

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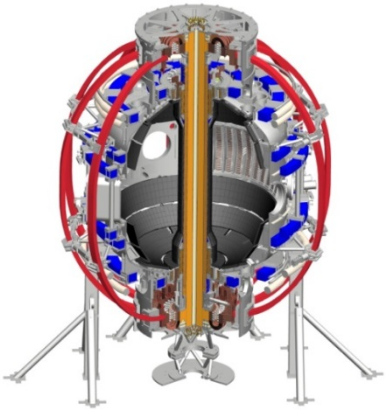

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The Columbia U. group plans to contribute to JRT-14 (which is presently just being defined)

- JRT-14
  - Conduct experiments and analysis to investigate and quantify plasma response to non-axisymmetric (3D) magnetic fields in tokamaks
  - Initial discussion focused on n = 1, considering both linear and non-linear response

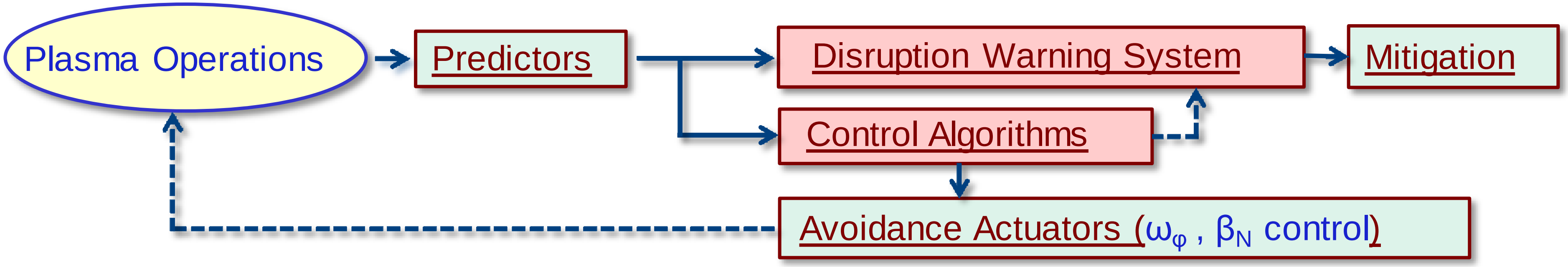
- Present planned Columbia contributions
  - Focused task defined with Todd Evans, Nate Ferraro on determining realistic plasma response magnitudes/profiles in modeling when compared to experiment (w/M3D-C^1) – Steve at GA this week for this
  - Use data from several NSTX experiments on NTV to determine bounds for the plasma response to different applied 3D field spectra: "n = 1", "n = 2", "n = 3" configurations
  - "Bounds" on the RFA would be determined by NTV profile calculations in NSTX experiments using the NTVTOK code
    - Note: NSTX NTV publications (~ 2006) have shown "n = 3" vacuum field is sufficient to calculate NTV, but plasma response needed for "n = 1"

The Columbia U. group plans to contribute to JRT-15 (which is also presently being defined)

- JRT-15
  - Experiments and analysis to quantify the impact of broad current and pressure profiles on tokamak plasma confinement and stability
  - Initial discussion focused/defined JRT-15 along the lines of determining the effect of new actuators (NBI, NTV, etc.) in NSTX-U

- Present planned Columbia contributions
  - Kinetic RWM stability physics: impact of pressure, rotation profile changes from the new beam and also EP anisotropic distribution.
  - Focus on NTV and NBI actuator results in pre-programmed plasma rotation control experiments on NSTX-U
  - Compare experimental results with our present rotation control work (about 6 months work already) with I. Goumiri
    - A significant part will be accuracy of NTV model developed in FY14 comparison to NTV theory in the NTVTOK code
  - Also evaluate equilibrium reconstruction variation with NBI modification of J, q profile with varied NBI

NSTX-U is planning a disruption avoidance system, in which real-time MHD spectroscopy or kinetic physics can be used



Plasma Operations

Predictors

Disruption Warning System

Mitigation

Control Algorithms

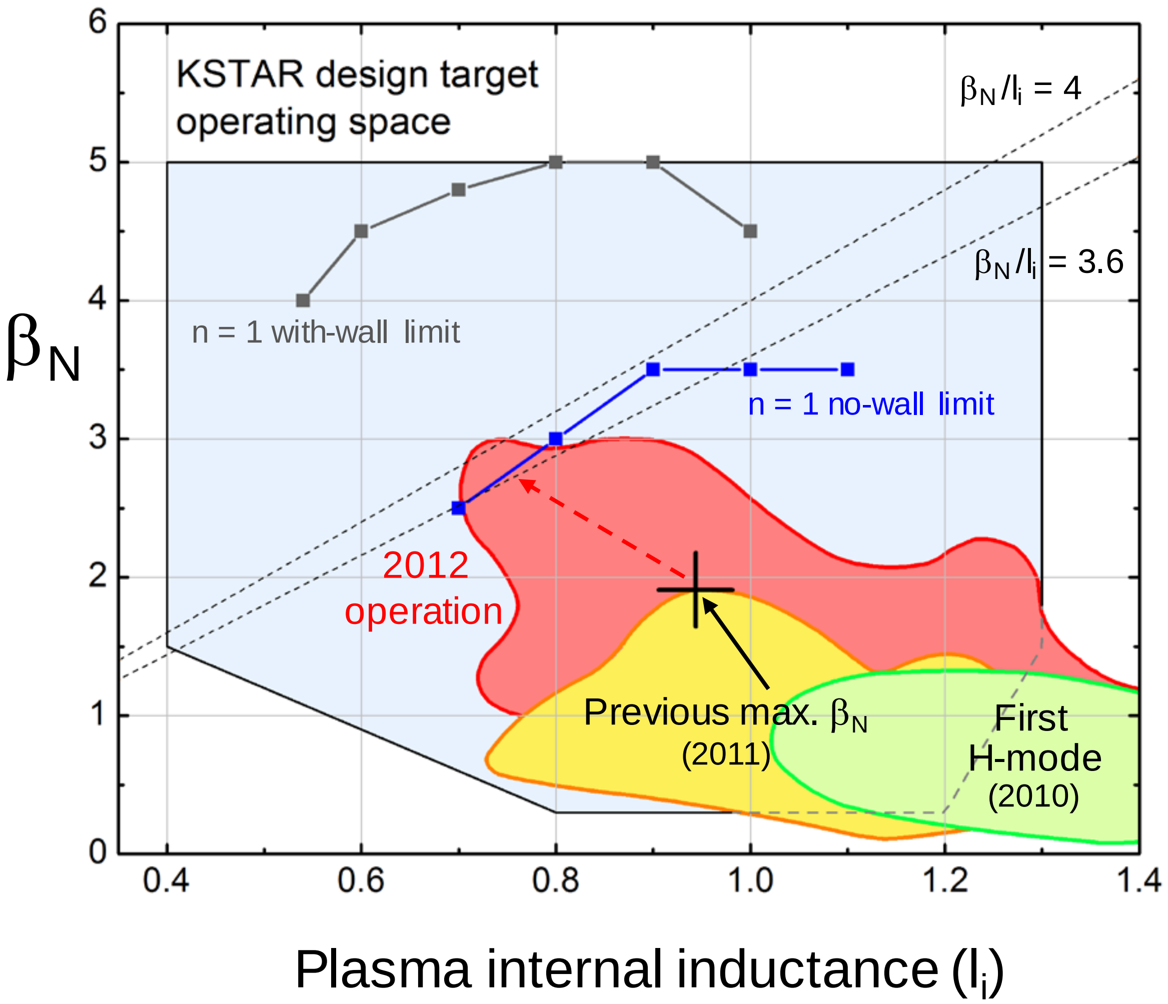
Avoidance Actuators (ω_φ , β_N control)

- Both NSTX and DIII-D have a PCS based architecture
  - Exception handling (Egemon)
  - Active mode control
  - Active profile control (rotation control via beams, NTV braking) informed by kinetic physics
  - Real-time MHD spectroscopy

Columbia U. NSTX-U grant proposal research plans – drive collaborative research

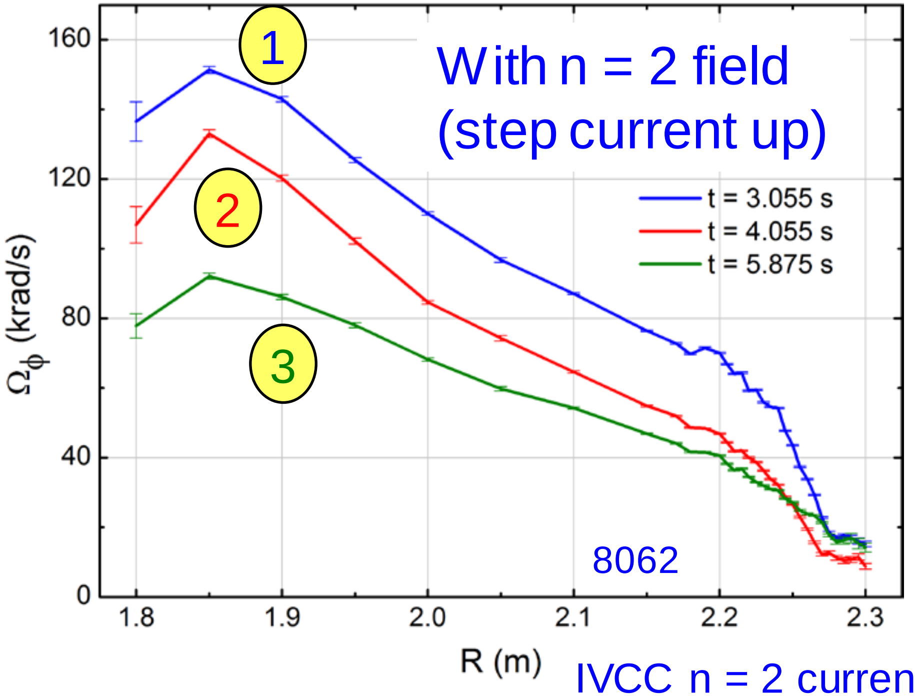
- Physics research areas on NSTX-U
  - Global MHD mode stabilization physics (incl. kinetic RWM physics)
  - Global MHD mode active control
  - Non-resonant plasma rotation alteration / physics / control (NTV)
  - NCC coil design
- Related/coordinated research on DIII-D and KSTAR
  - Aimed at verifying kinetic stabilization; limiting modes with TM stable
  - 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 for ITER cases, future devices
  - New ITPA MDC-21: global mode stabilization / disruption avoidance)
- <u>Near-term analysis</u>: continue analysis / publication of NSTX results, with related device/code benchmarking

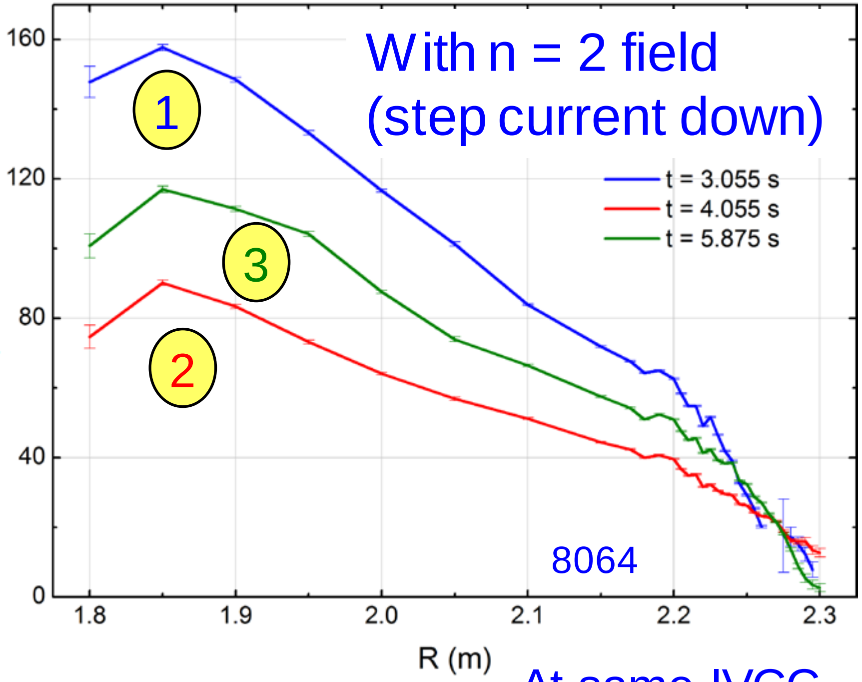
Plasmas have reached and exceeded the predicted "closest approach" to the *n* = 1 ideal no-wall stability limit



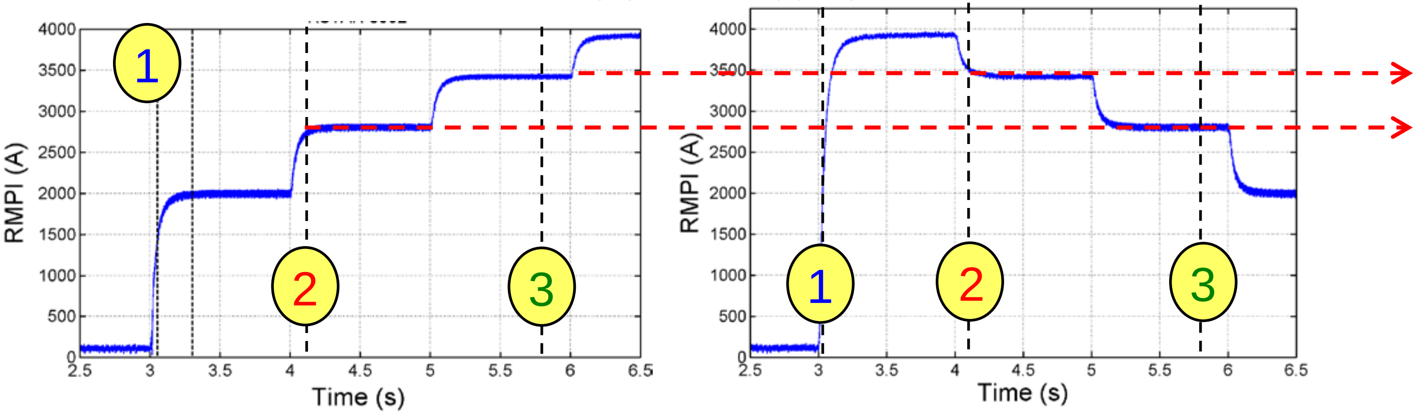
- I_p scan performed to determine "optimal" β_N vs. I_p
  - B_T in range 1.3 - 1.5T
  - β_N up to 3.0
- $\beta_N/l_i > 3$. (80% increase from 2011)
  - a high value for advanced tokamaks, e.g. for DIII-D
- Mode stability
  - Target plasma is at published computed ideal n = 1 no-wall stability limit (DCON)
  - Plasma is subject to RWM instability, depending on plasma rotation profile
  - Rotating n = 1, 2 mode activity observed in core during H-mode

Measured toroidal plasma rotation profile shows non-resonant NTV rotation control using n = 2 field





IVCC n = 2 current



At same IVCC current, rotation profile shows **no hysteresis** – important for control

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 – JRT14 should contribute to this

Model-based, state-space rotation controller designed to use Neoclassical Toroidal Viscosity (NTV) profile as an actuator

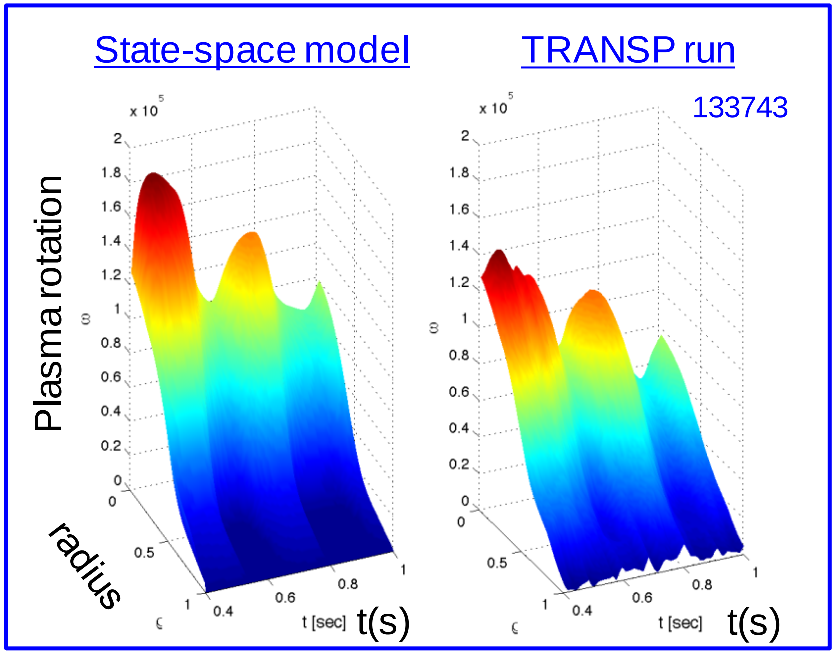
- Momentum force balance – ω_ϕ decomposed into Bessel function states

$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho}\sum_i n_i m_i \chi_\phi \left\langle \left(R\nabla\rho\right)^2\right\rangle \frac{\partial\omega}{\partial\rho}\right] + T_{NBI} + T_{NTV}$$

- NTV torque:

$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^{2}\omega\right]$$

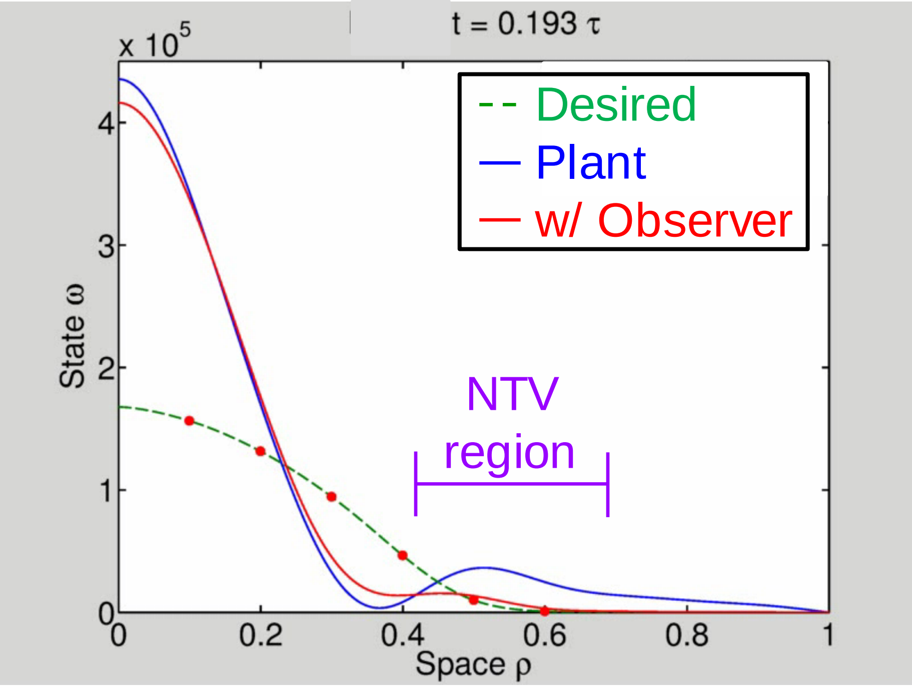
(non-linear)



State-space model

TRANSP run

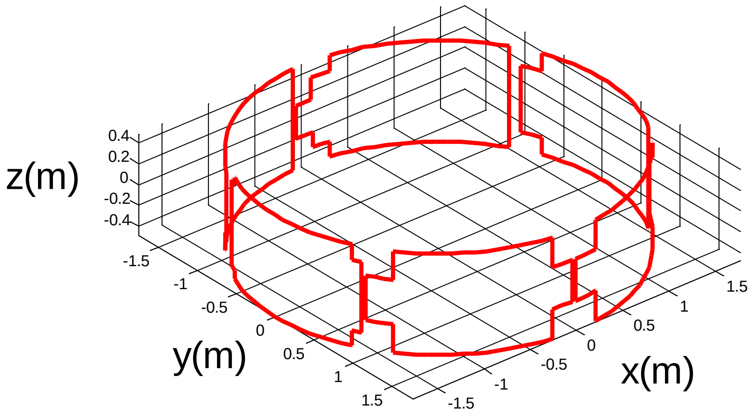
Feedback using NTV: “n=3” $\delta B(\rho)$ spectrum



I. Goumiri

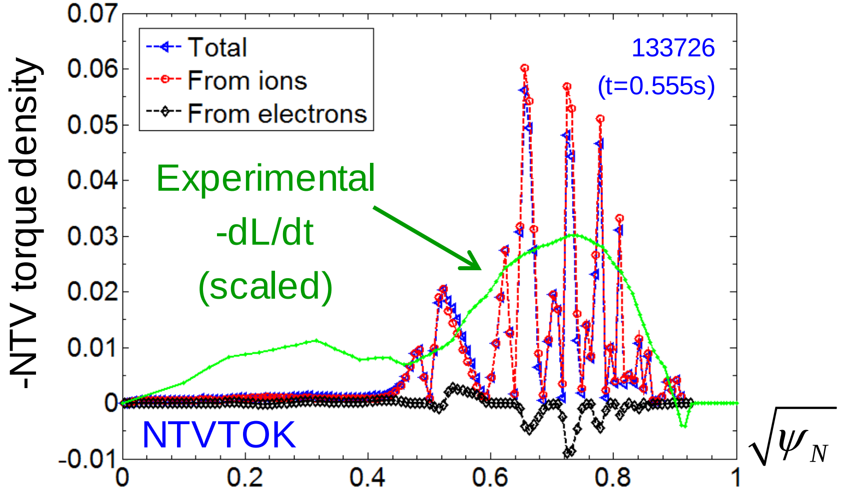
Expanded NTV torque profile model for control being developed from theory/comparison to experimental data

NSTX 3D coils used for rotation control

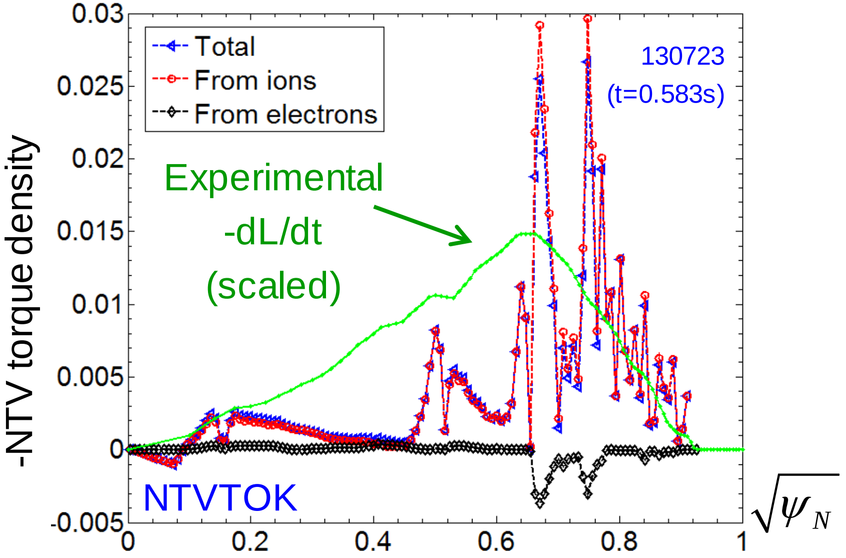


- **New analysis: NTVTOK code**
  (Sun, Liang, Shaing, et al., NF **51** (2011) 053015)
  - Shaing's connected NTV model, covers all ν, and superbanana plateau regimes
    (Shaing, Sabbagh, Chu, NF **50** (2010) 025022)
  - Past quantitative agreement with theory found in NSTX for plateau, "1/ν " regimes
    (Zhu, Sabbagh, Bell, et al., PRL **96** (2006) 225002)
  - Full 3D coil specification, ion and electron components considered, no A assumptions

NTV torque profile (n = 3 configuration)



NTV torque profile (n = 2 configuration)



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, α) 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?

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 (Steve meeting w/ Nate this week, beta test soon)
  - NIMROD: collaboration with S. Kruger and student
    - Model recently fixed, NSTX beta scan equilibria sent to Andi Becerra (met at APS 2013, plan defined with Hegna, Kruger, King)
- 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

Testing kinetic RWM stabilization theory at marginal stability in high β, TM stabilized plasmas (Idea #549)

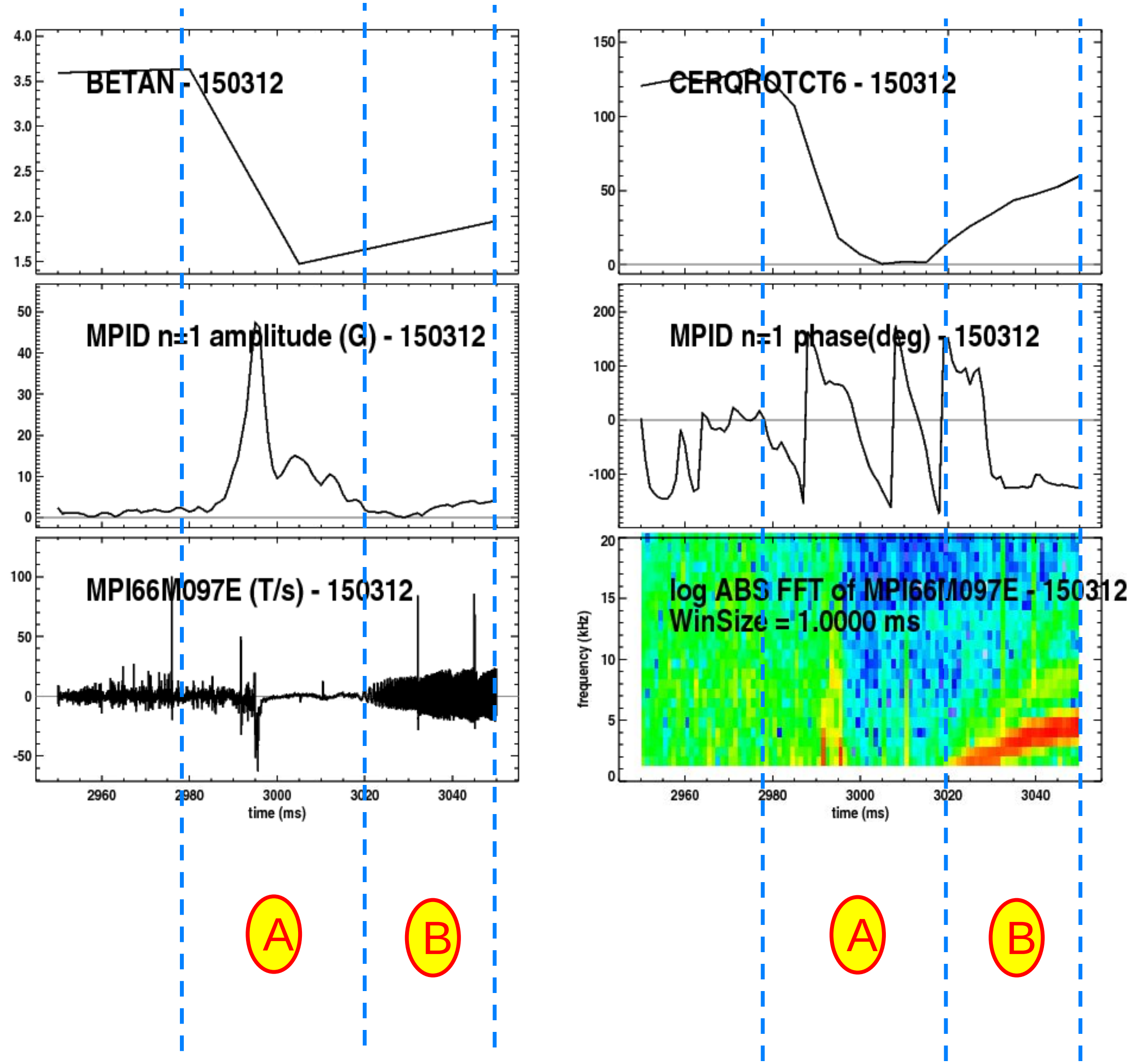
- **Goals**
  1. Test present kinetic RWM stability theory on plasmas very near to, or at RWM marginal stability in DIII-D for confident extrapolation to ITER, DEMO
  2. Determine RWM stability at high beta when TM is stable, or controlled
- **Deliverables**
  1. Direct verification of DIII-D RWM marginal stability point vs. theory, testing kinetic stabilization theory that changes stability dependence on ω_ϕ, ν compared to earlier theory (changes extrapolation to future devices). Success would warrant a PRL-level publication.
  2. Improvement of DIII-D high β_N, high (β_N, q_{min}) steady-state plasmas, and best understanding/extrapolation to analogous ITER and DEMO scenarios
  3. Direct input for new ITPA joint experiment MDC-21 and ITER Organization urgent need - disruption avoidance (combined DIII-D, NSTX, theory effort)
- **General Approach**
  1. Leverage plasmas at/near RWM marginal stability created in past MPS (150312, 149782)
  2. With plasma at RWM marginal stability, vary kinetic stabilization by varying plasma rotation speed and profile, and collisionality; Use targets to minimize ($\delta W_{kin}/\delta W_{ideal}$) (e.g. reduce δ)
  3. Apply ECCD TM stabilization to plasmas approaching RWM marginal stability that transition to TM instability instead of RWM instability

V1.1

(run time request: 1 day)

DIII-D High β_N, q_{min} shots show reproducible rotating RWM dynamics (target plasma #1)

- **Apparent unstable RWMs**
  - Ⓐ Mode growth time and phase evolution consistent with RWM dynamics
  - Ⓑ Evolution to saturated mode activity (reaches 5 kHz at end of this time period)
  - ECEI data indicates that a TM forms at t = 3.015s
    - Significantly after apparent RWM destabilization
    - Consistent with magnetics
  - Request made for SXR data



Next steps for analysis / preparation for experiment

- **Determine key physical cause of difference in RWM stability of high β_N, high q_{min} plasmas vs. more stable high β_N plasmas**
  - Stability analysis of unstable shot (e.g. 150312) completed
  - Compare to high beta, stable shots 133103 (l_i = 0.73, β_N = 3.9) and (RWM marginally stable?) shot 147634 (equilibria being prepared by J. Hanson)

- **Determine best high β_N target plasmas to test TM control**
  - Started discussion with Ege, Rob, Richard, Ted, Michio
    - Minimum B_T may be ~ 1.5 T as in past high q_{min} targets, can raise B_T from here
  - TM stabilization has been demonstrated in high β_N plasmas at 20% over the no-wall limit (e.g. M. Okabayashi, et al. NF **49** (2009) 125003); further development will be important part of this MP.

- **Follow general guidance to use mainline DIII-D operational scenarios if possible**
  - High β_N, q_{min} scenario is a main scenario for steady-state high β_N goals in 5 year plan

Grant Research

List of physics topics / codes in use / planned

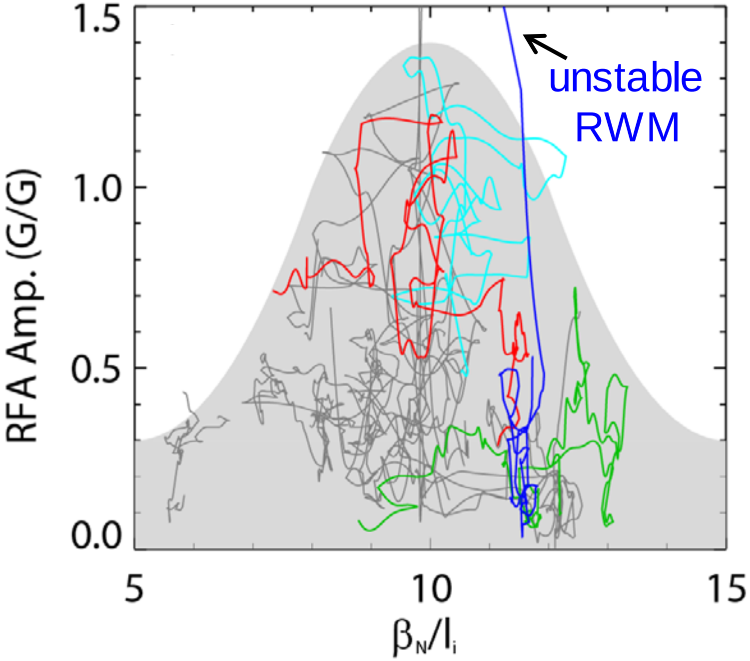
- Kinetic RWM stabilization
  - MISK (linear kinetic RWM stability code)
  - M3D-C^1, NIMROD: further linear benchmarking, and non-linear runs for NSTX-U (e.g. NIMROD: toroidal resistive wall tests)
- Active RWM control
  - RWM state-space controller development (incl. multi-mode)
  - VALEN / mmVALEN (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
- DIII-D/KSTAR data/analysis – 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

Experiments directly measuring global stability using MHD spectroscopy (RFA) support kinetic RWM stability theory

Resonant Field Amplification vs. β_N/l_i

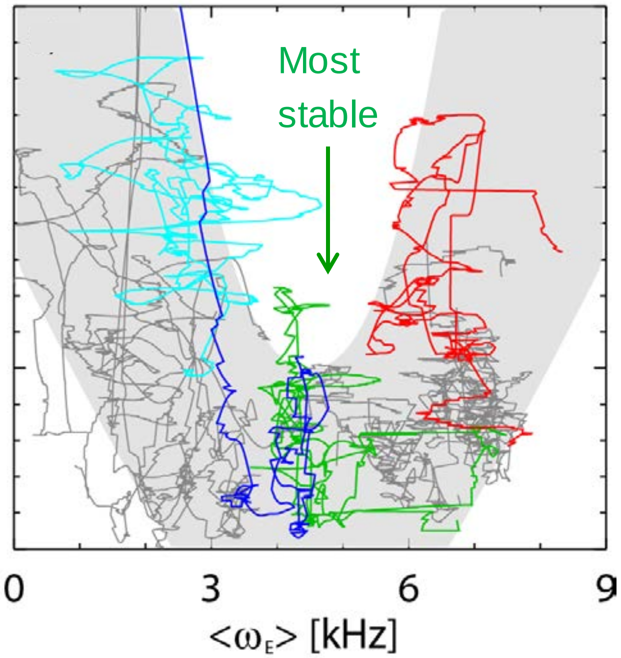


(trajectories of 20 experimental plasmas)

- **Stability vs. β_N/l_i**
  - decreases up to $\beta_N/l_i = 10$, ***increases*** at higher β_N/l_i
  - Consistent with kinetic resonance stabilization

S. Sabbagh et al., NF **53** (2013) 104007

RFA vs. rotation (ω_E)



- Stability vs. rotation
  - Largest stabilizing effect from ion precession drift resonance with ω_ϕ

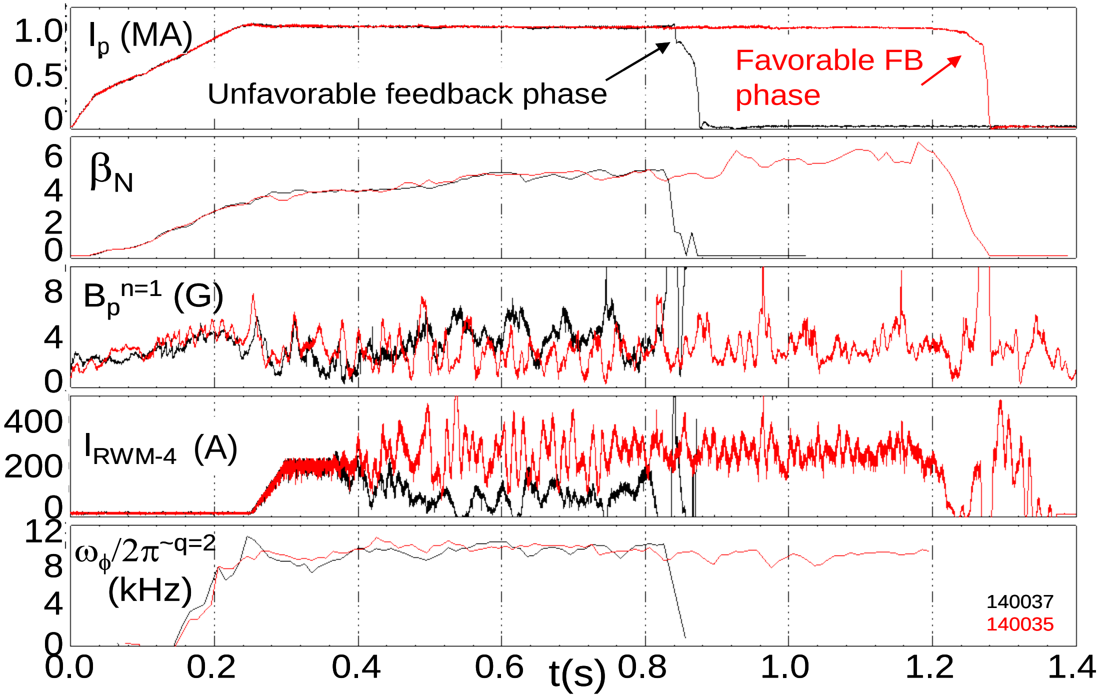
Minimize $|\langle\omega_D\rangle + \omega_E|$

$$\delta W_k \sim \frac{1}{\langle\omega_D\rangle + \omega_E - i\nu_{eff}}$$

- Stability at lower ν
  - Collisional dissipation is reduced
  - Stabilizing resonant kinetic effects are enhanced
  - Stabilization when near broad ω_φ resonances; almost no effect off-resonance

Model-based RWM state space controller including 3D plasma response and wall currents used at high β_N in NSTX

RWM state space controller in NSTX at high β_N



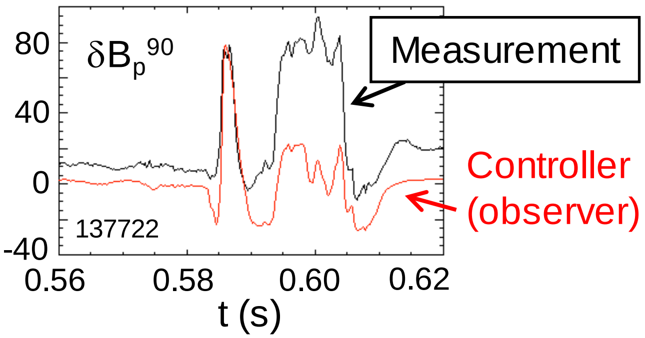
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, and be shielded (e.g. for ITER)

    Katsuro-Hopkins, et al., NF **47** (2007) 1157

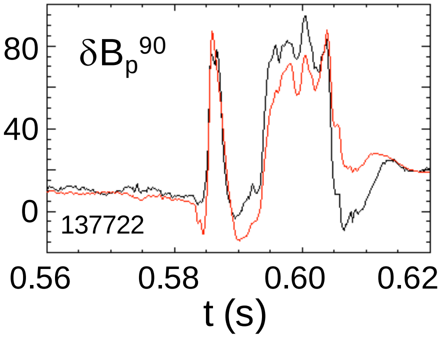
S.A. Sabbagh, et al., Nucl. Fusion **53** (2013) 104007

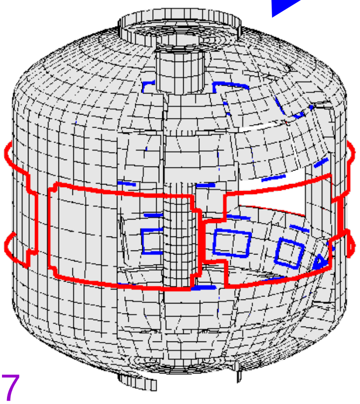
Effect of 3D Model Used

No NBI Port



With NBI Port

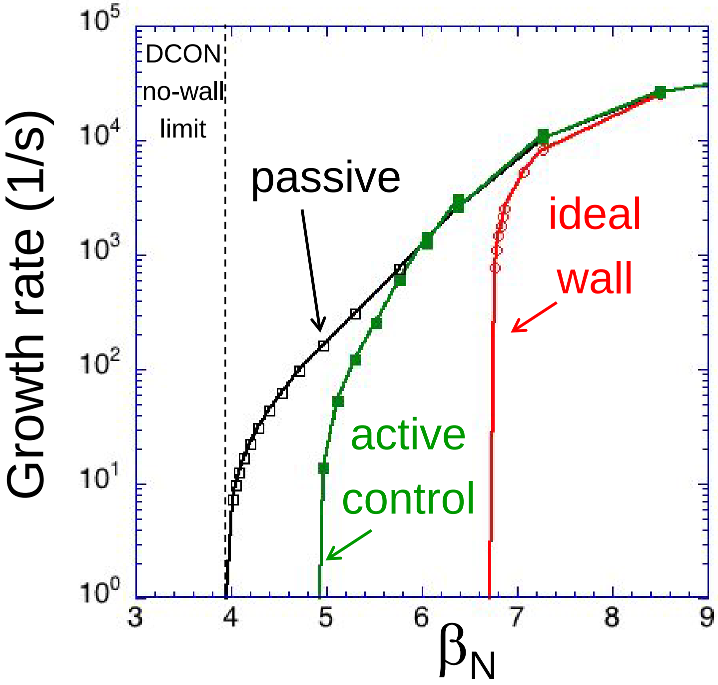




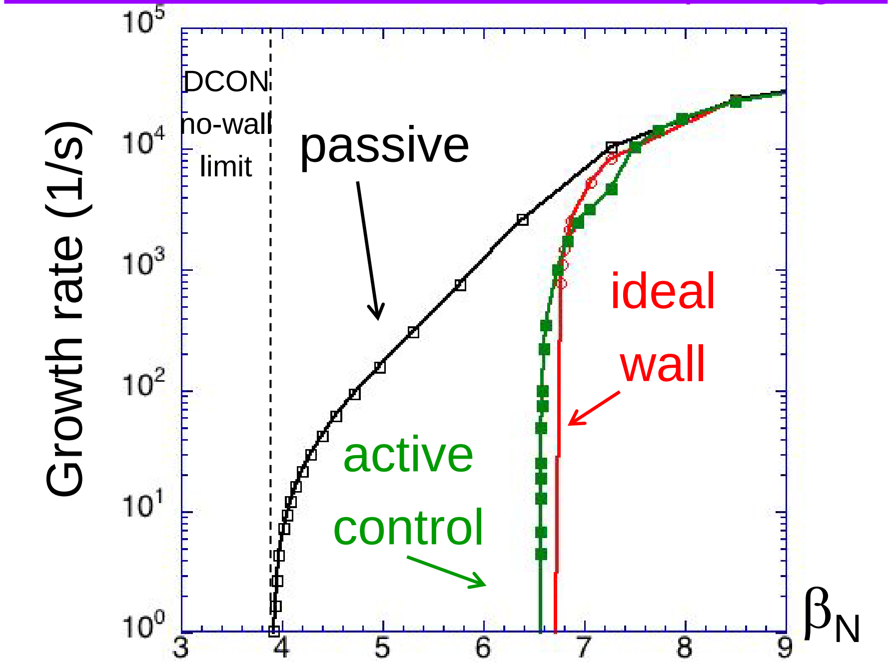
- 3D detail of model is important to improve sensor agreement

RWM active control capability will increase significantly when Non-axisymmetric Control Coils (NCC) are added to NSTX-U

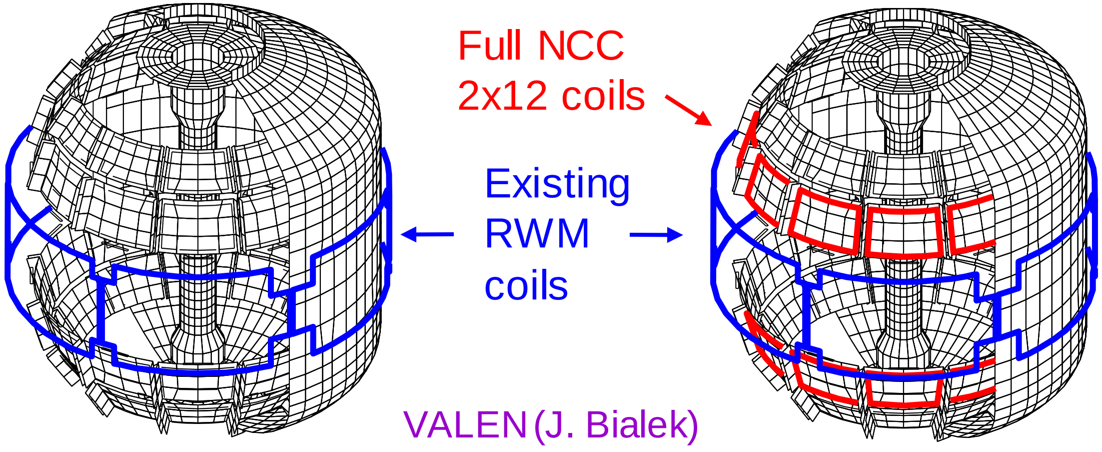
Using present midplane RWM coils



NCC 2x12 with favorable sensors, optimal gain



- Performance enhancement
  - Present RWM coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.25$
  - Add NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.67$
  - Partial NCC options also viable



VALEN (J. Bialek)

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 DIII-D ELM suppression results (Orlov APS '13) 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

Multi-year ITPA MDC-2 benchmarking of kinetic RWM codes reached the group's goals

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

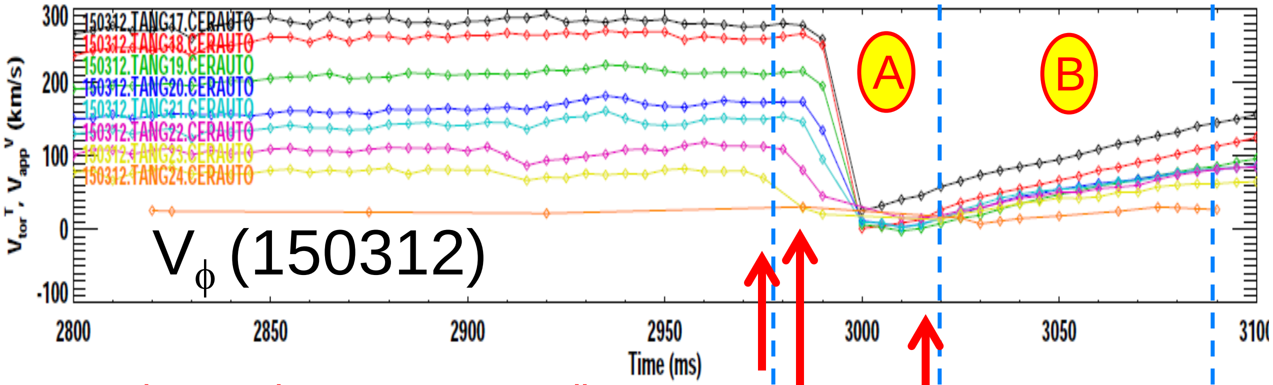
- Recent success in producing agreement between MISK and MARS-K
  - PENT code development added in 2013
- MISK code has been extensively used to quantitatively compare theory/experiment in NSTX
  - 6 publications from NSTX (first is from 2008)
- MDC-2 process has altered both MISK and MARS-K a bit
 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

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.)

DIII-D experiments

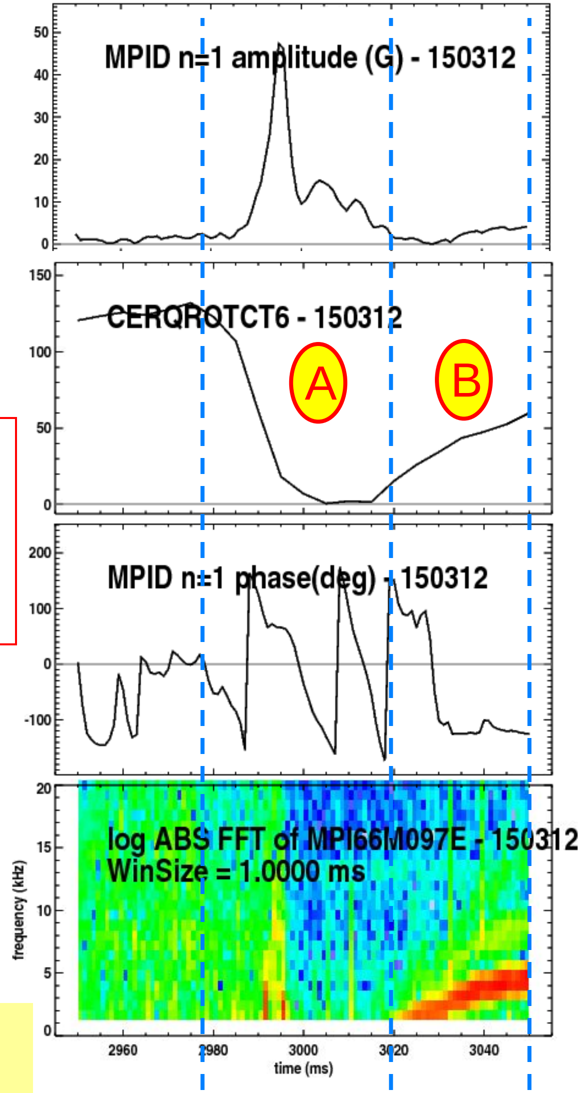
High β_N, q_{min} shots show reproducible minor disruptions, apparently caused by RWM activity (target plasma #1)

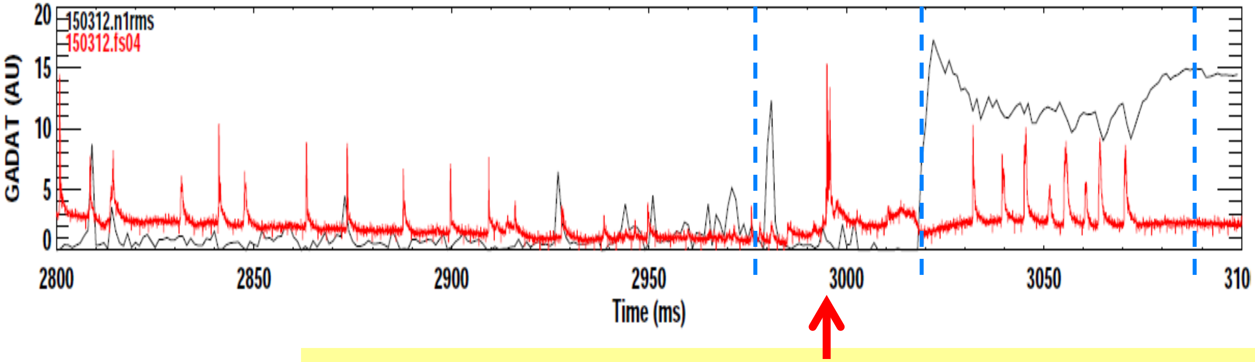


1) Drop in V_ϕ corresponding RWM rotation, amplitude increase

2) V_ϕ collapse is global (consistent with non-res NTV, no TM at this time)

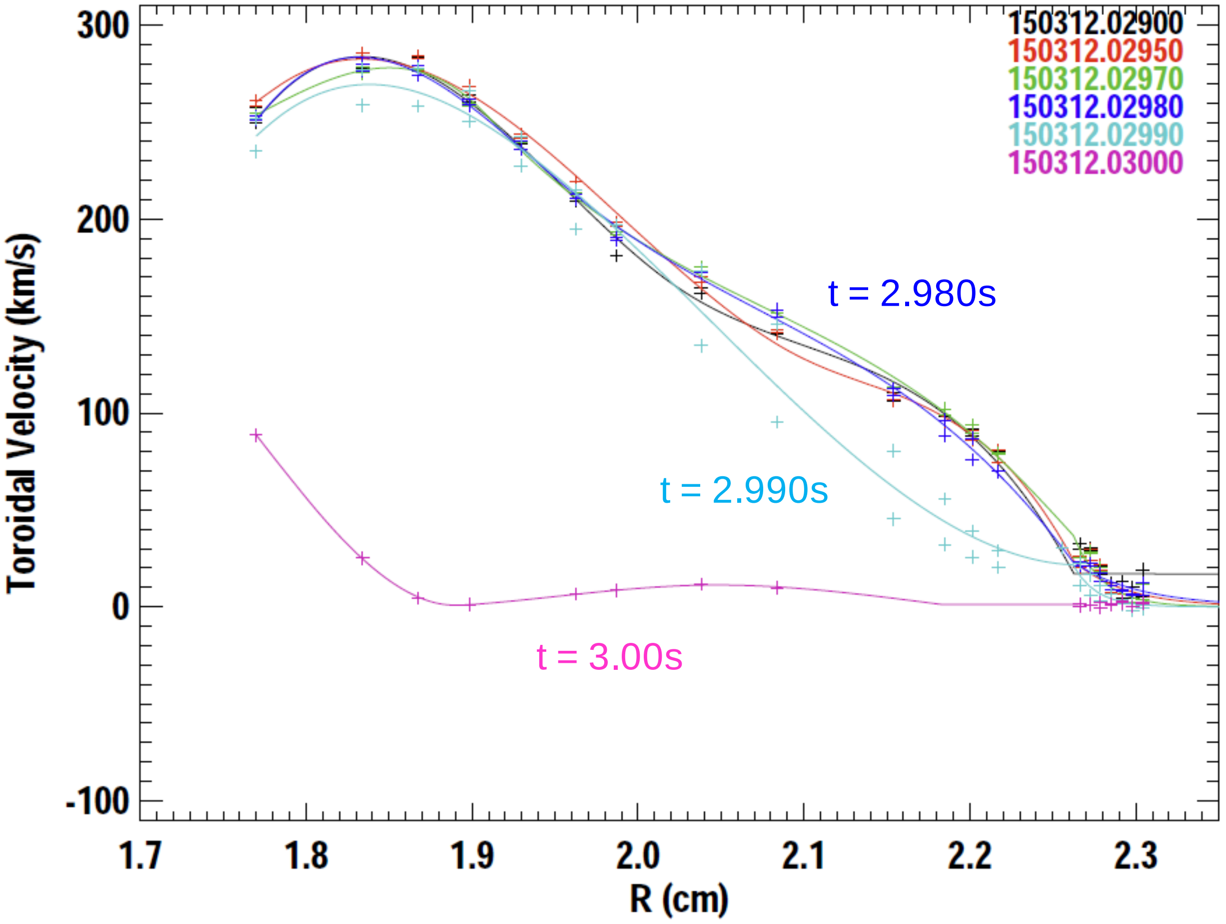
4) ECEI shows TM phase inversion here, spins up as V_ϕ increases

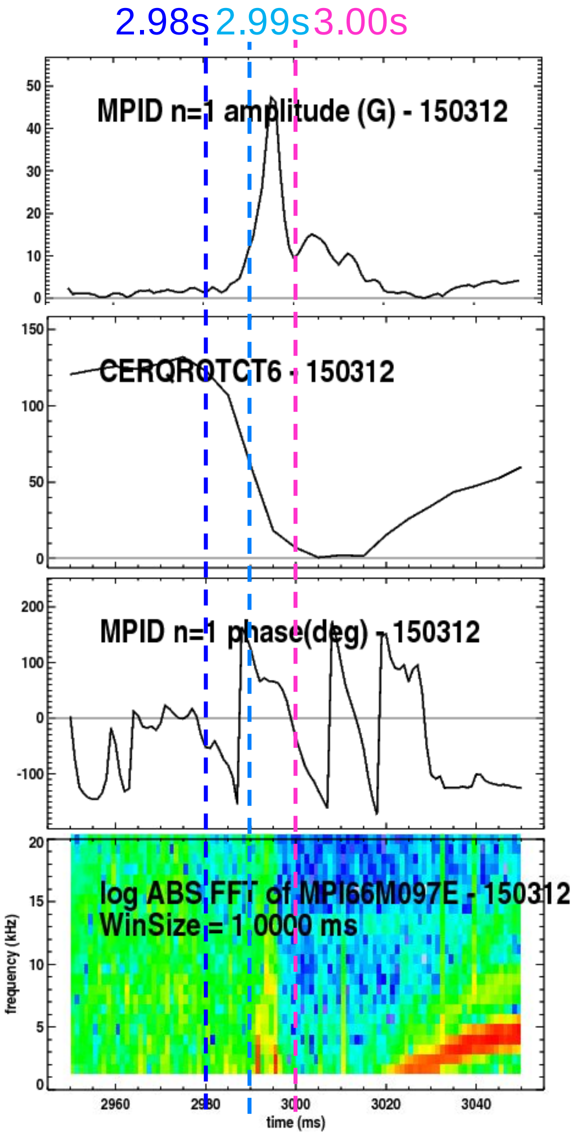




3) "ELM" appears AFTER V_ϕ collapse (apparently not causal)

V_ϕ profile collapse at the time RWM growth appears to be a rapid, global collapse, rather than a resonant lock

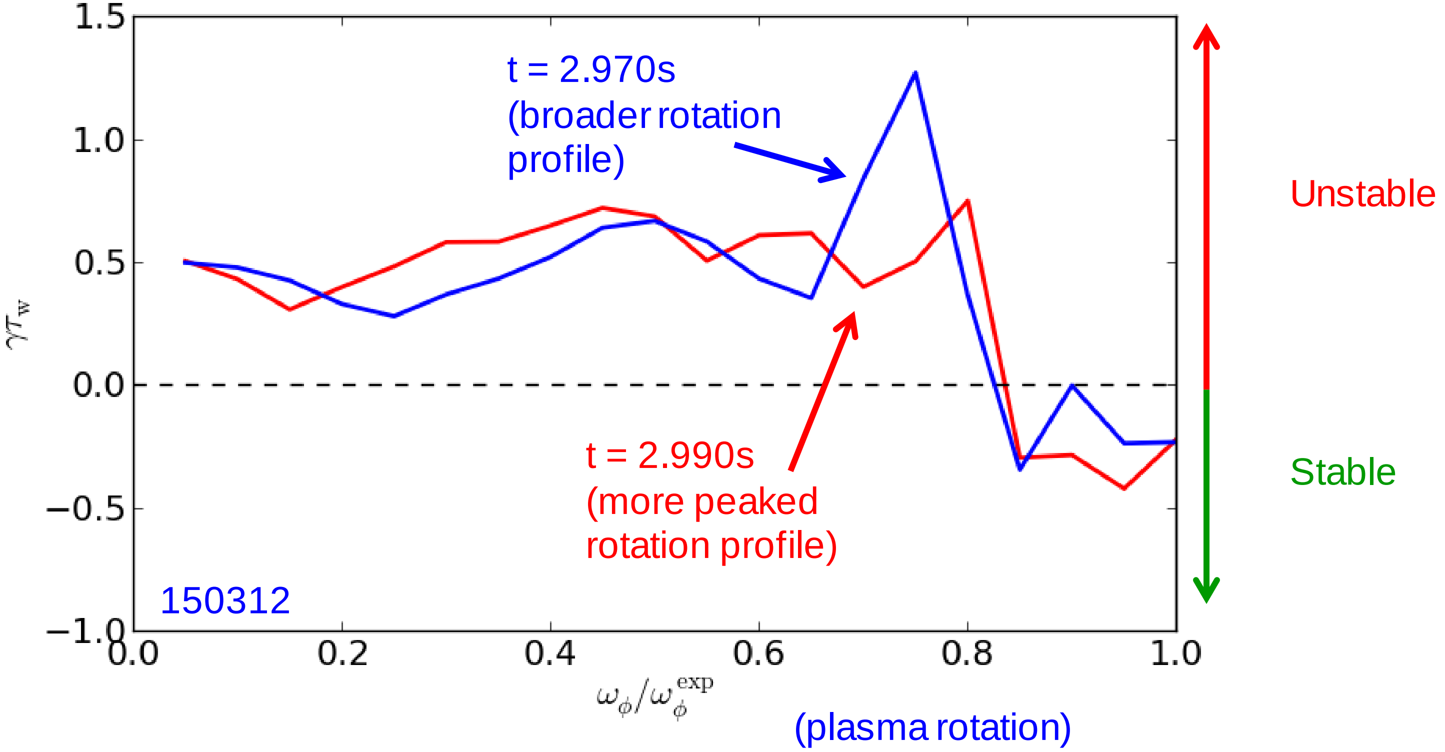




- **Rotation damping characteristic of global RWM rather than a TM which would initially damp near a key rational surface**

(B. Grierson)

MISK kinetic RWM stability analysis of shot 150312 shows the plasma to be near marginal stability



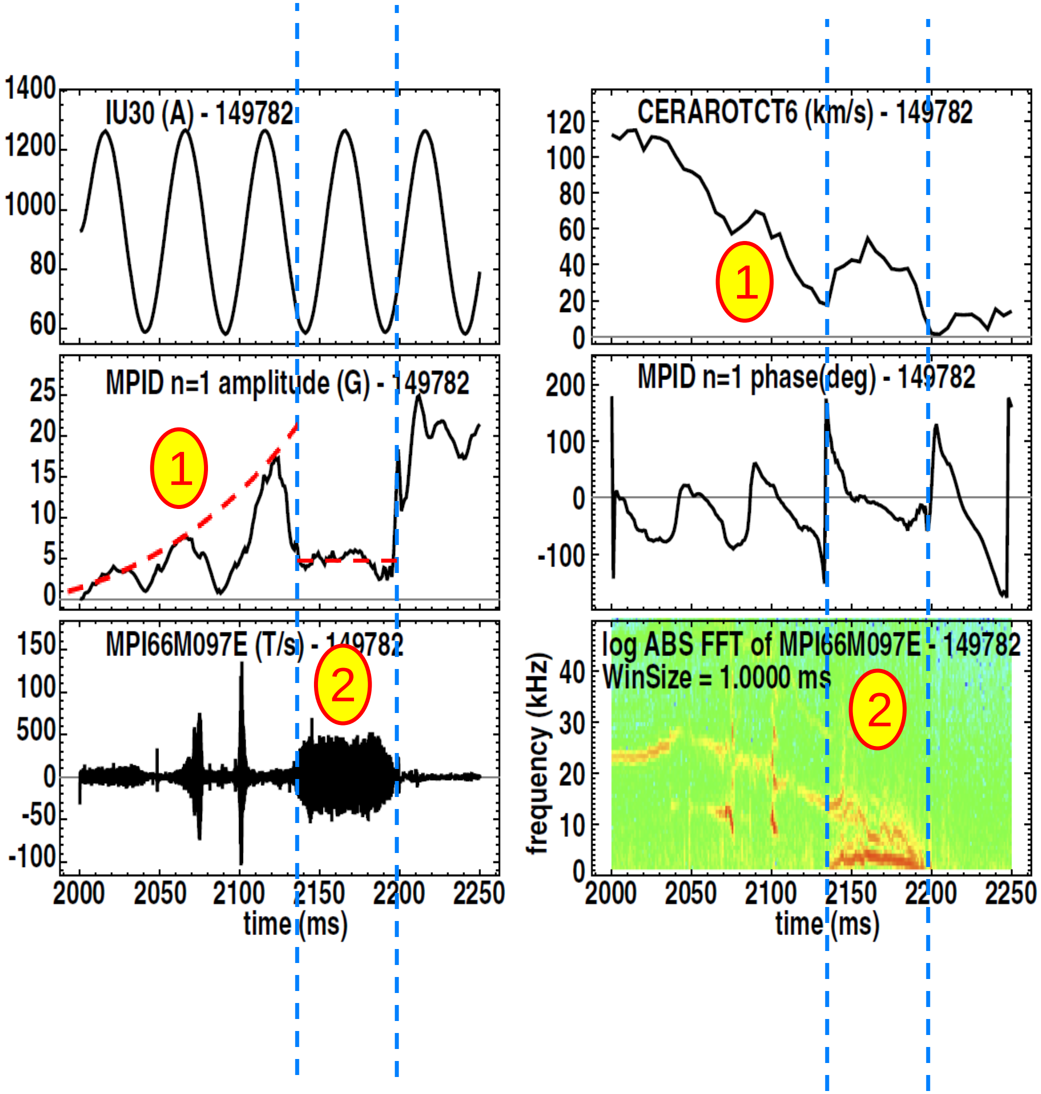
- **Rotation profile scaled from the experimental profile for the scan**
- **MISK analysis shows that these equilibria are near marginal stability (RWM unstable when rotation is reduced by ~ 10 – 20%)**

High β_N targets generated in past kinetic RWM run may become RWM unstable if TM is stabilized (Target plasma #2)

① **RFA of ~ 20Hz n = 1 increase to very high levels**
  - Greater than 30G/kA (past high values typically ~ 10-15 G/kA)
  - Occurs at high β_N – pressure-driven
  - Added counter-NBI power leads to slowing of plasma rotation (but no TM locking evident in $V_\phi(R)$)

② Rapidly rotating n = 1 appears (TM?), clamps RFA amplitude
  - Such activity precludes RWM instability in NSTX

- **Experimental plan**
  - Stabilize TM plasmas like this via ECCD – run at higher B_T >= 1.5 T
  - Vary NBI source balance to change RWM marginal point (proximity to broad kinetic resonances) by changing rotation speed, and rotation profile



Unstable modes with RWM characteristics often lead to strong thermal collapses in high β_N, q_{min} plasmas

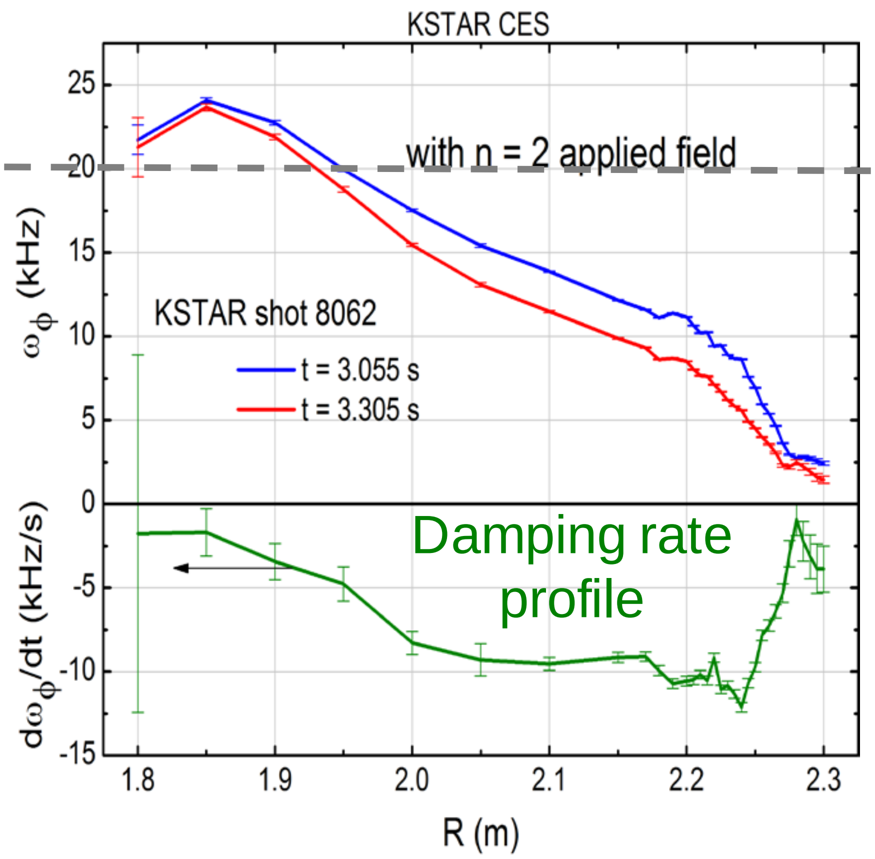
- **High impact:**
  - Cause large, rapid stored energy collapse ΔW_{tot} ~ 60% (200 MJ in ITER)
    - For comparison, large ELMs have ΔW_{tot} up to 6% (20 MJ in ITER)

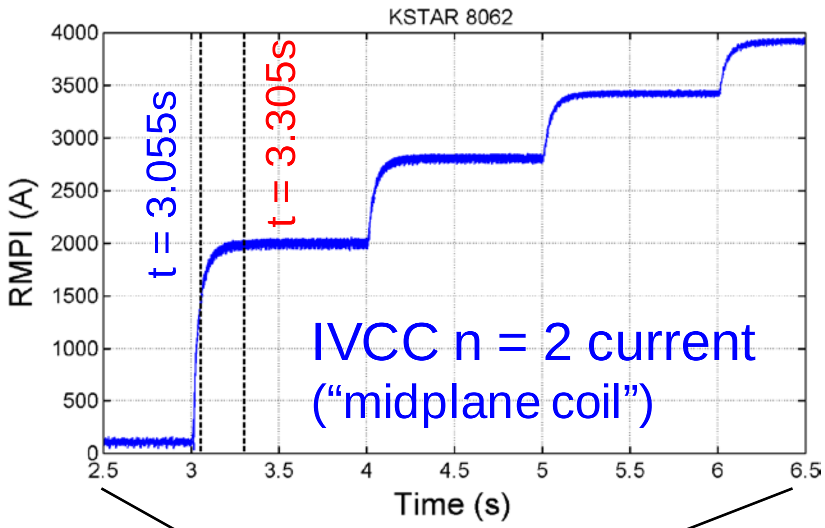
- **High probability:**
  - RWMs and TMs cause these collapses in 82% of the plasmas examined, with an average of 3 collapses every 2 shots (50+ shots examined)
  - RWMs cause collapse 60% of the time, TMs 40% of the time

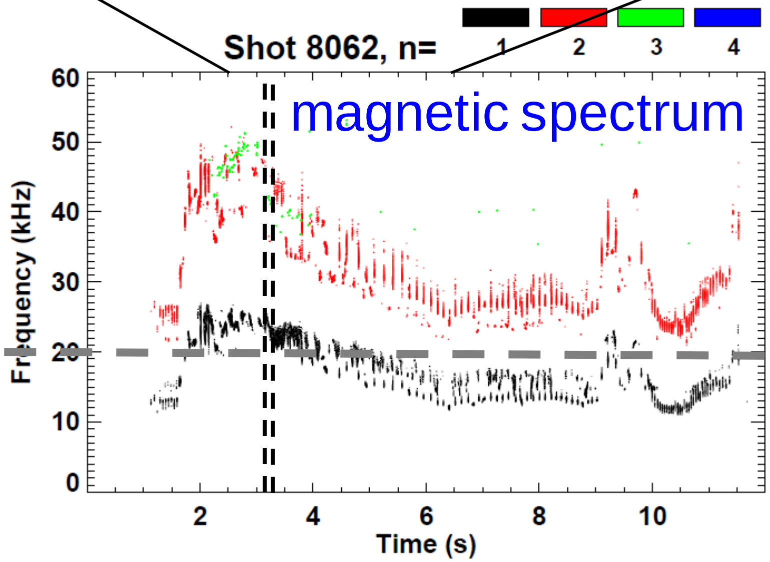
- **The RWMs also destabilize TMs**
  - RWMs lead to large, rapid collapse of rotation, allowing EF penetration – TMs can be destabilized, typically spin up, but can then lock
  - Plasmas are favorable targets for this kinetic RWM stabilization study

KSTAR experiments

Rotation reduction by n = 2 applied field is global and appears non-resonant (NTV); no mode locking

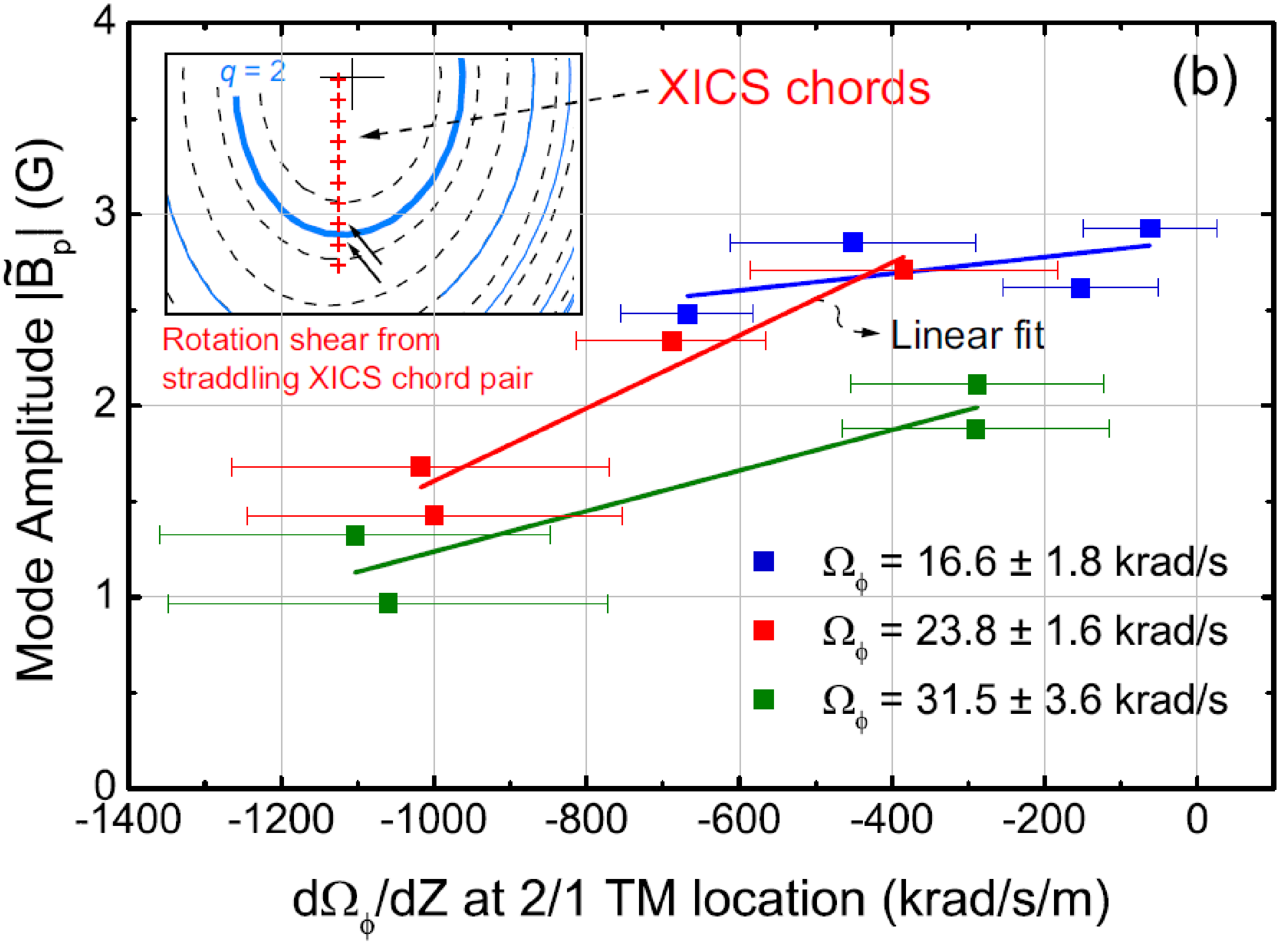






- Rotating n = 1, 2 modes observed in core
  - would not produce the observed rotation profile change (no change in core)

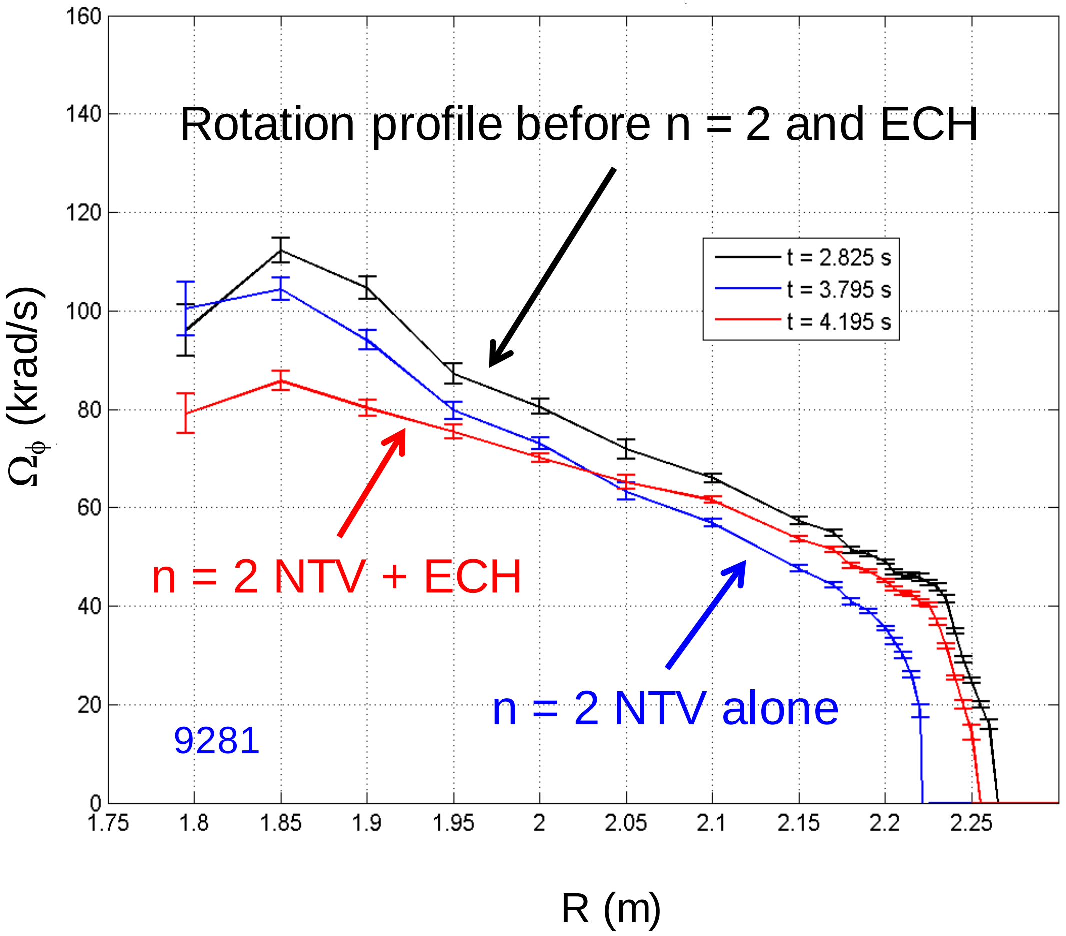
Correlation between plasma velocity shear and 2/1 TM amplitude found



- Mode identification from ECE, ECEI systems
- Observed increase of TM amplitude vs. Ω_ϕ shear decreases at reduced Ω_ϕ

Y.S. Park, S.A. Sabbagh, J.M. Bialek, et al. Nucl. Fusion **53** (2013) 083029

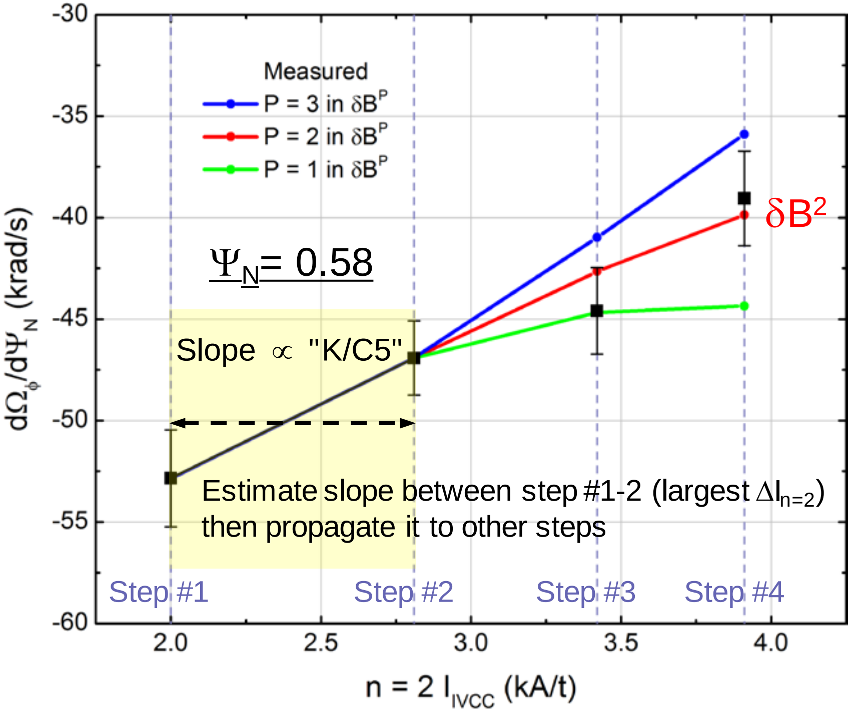
Rotation profile alteration observed with combined IVCC n = 2 NTV + ECH (110 + 170 GHz)



- Combination of effects / timing can change Ω_ϕ shear
  - ❑ Note: n = 2 NTV current was run at only ½ maximum (not max. effect)
  - ❑ n = 2 NTV shows global rotation damping
  - ❑ Addition of ECH drops core rotation, increases edge Ω_ϕ, decreases shear
    - Outward momentum transfer

Steady-state profile analysis to examine NTV dependence on δB

Resulting NTV correlation with different power in δB^P

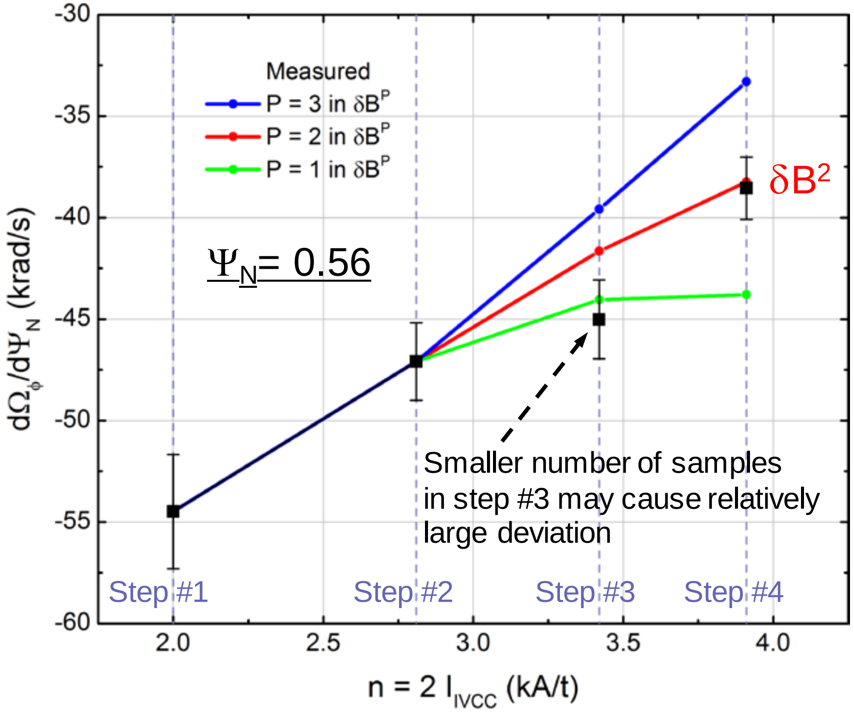


$\Psi_N = 0.58$

δB^2

Slope ∝ "K/C5"

Estimate slope between step #1-2 (largest $\Delta I_{n=2}$) then propagate it to other steps



$\Psi_N = 0.56$

δB^2

Smaller number of samples in step #3 may cause relatively large deviation

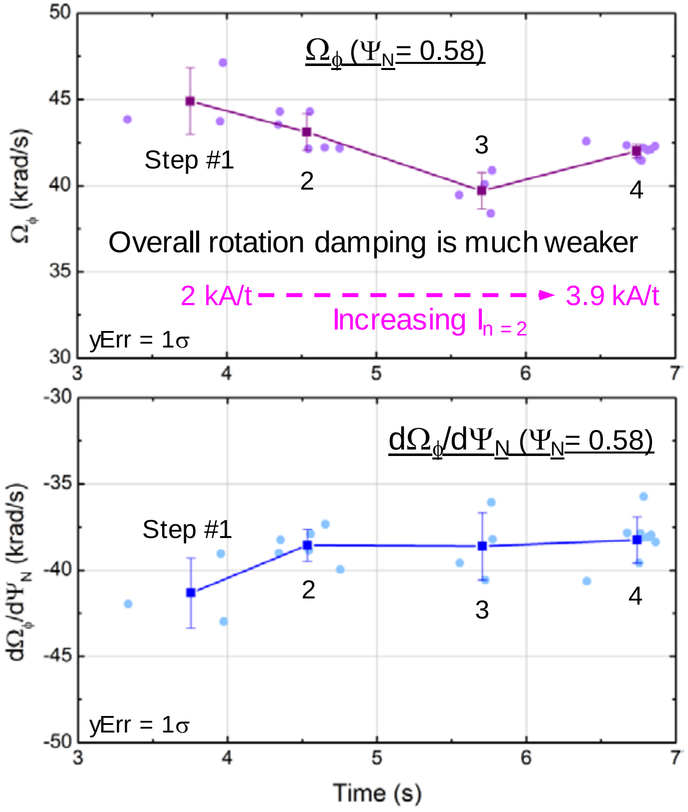
- For the different normalized flux surfaces, T_{NTV} scales well with δB^2 as similar to collisionless "1/ν" regime in NTV theory

$$T_{NTV-(1/\nu)} \propto \delta B^2 \, T_i^{5/2}$$

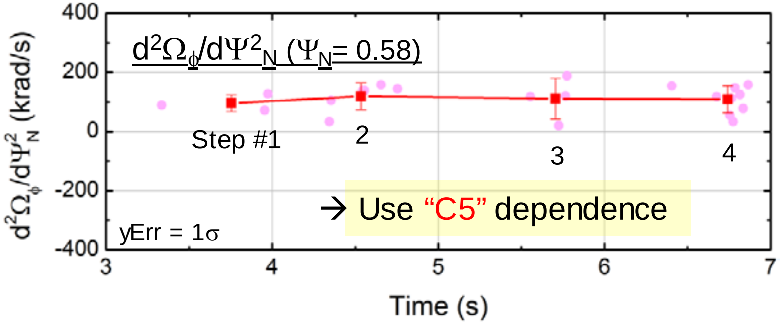
Y.S. Park, APS DPP 2013

Reduced rotation braking correlates with lower T_i when NTV scales as δB^2

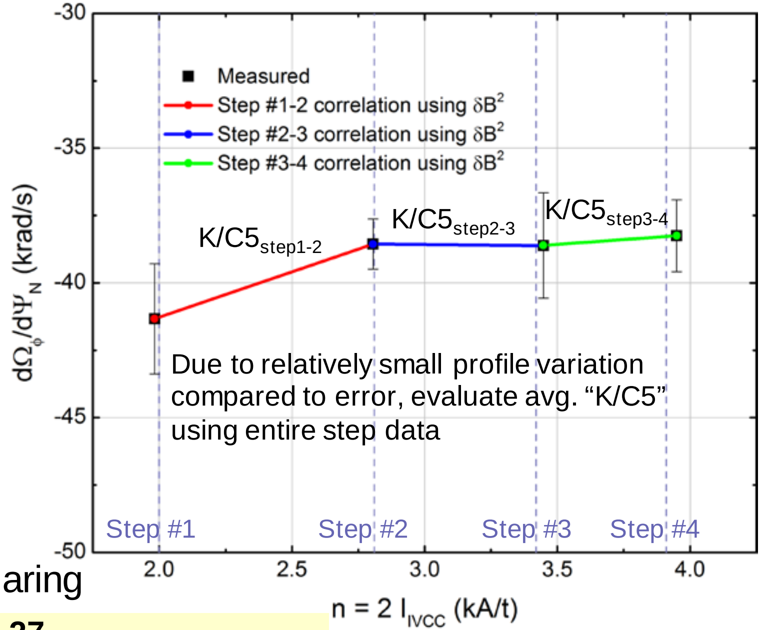
- Analysis of increasing n = 2 current steps with lower T_i (shot 9199)
  - Chosen profiles have $|\Delta T_i| < 50$ eV



Overall rotation damping is much weaker



→ Use "C5" dependence



Due to relatively small profile variation compared to error, evaluate avg. "K/C5" using entire step data

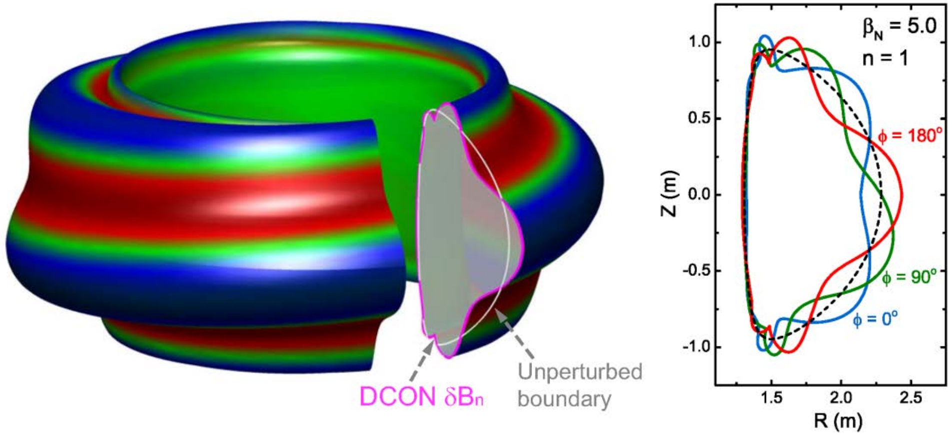
- By assuming the same $C5_{\Psi_N=0.58}$ between two comparing shots,

$$\frac{K^{8062}_{\Psi_N=0.58}}{K^{9199}_{\Psi_N=0.58}} = 6.02 = \left(\frac{T^{8062}_{i,\Psi_N=0.58}}{T^{9199}_{i,\Psi_N=0.58}} = \frac{1262\text{ eV}}{573\text{ eV}}\right)^{\mathbf{2.27}} \approx T_{NTV-(1/\upsilon)} \propto T_i^{2.5}$$

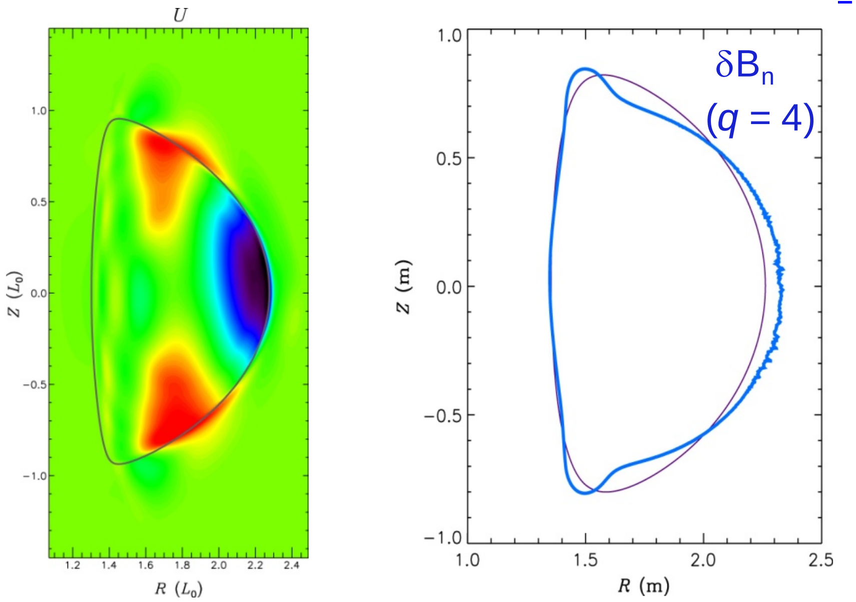
Y.S. Park, APS DPP 2013

M3D-C^1 code example for KSTAR, comparison to DCON

KSTAR DCON n = 1 unstable mode eigenfunction



M3D-C^1 unstable mode velocity stream function and δB_n



- Linear stability analysis using M3D-C^1 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-C^1 compare well
  - For the same input equilibria, "equivalent" wall configurations compared
  - With-wall n = 1 stability limit computed as β_N ~ 5.0 in both calculations
  - Further M3D-C^1 calculations for KSTAR will include improved wall configurations (3D, resistive wall) and analysis for resistive instabilities