High beta, MHD, and non-resonant magnetic braking by NTV in KSTAR

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PPPL-NFRI NSTX-U-KSTAR Collaboration Meeting

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Princeton, NJ

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In collaboration with NFRI National Fusion Research Institute

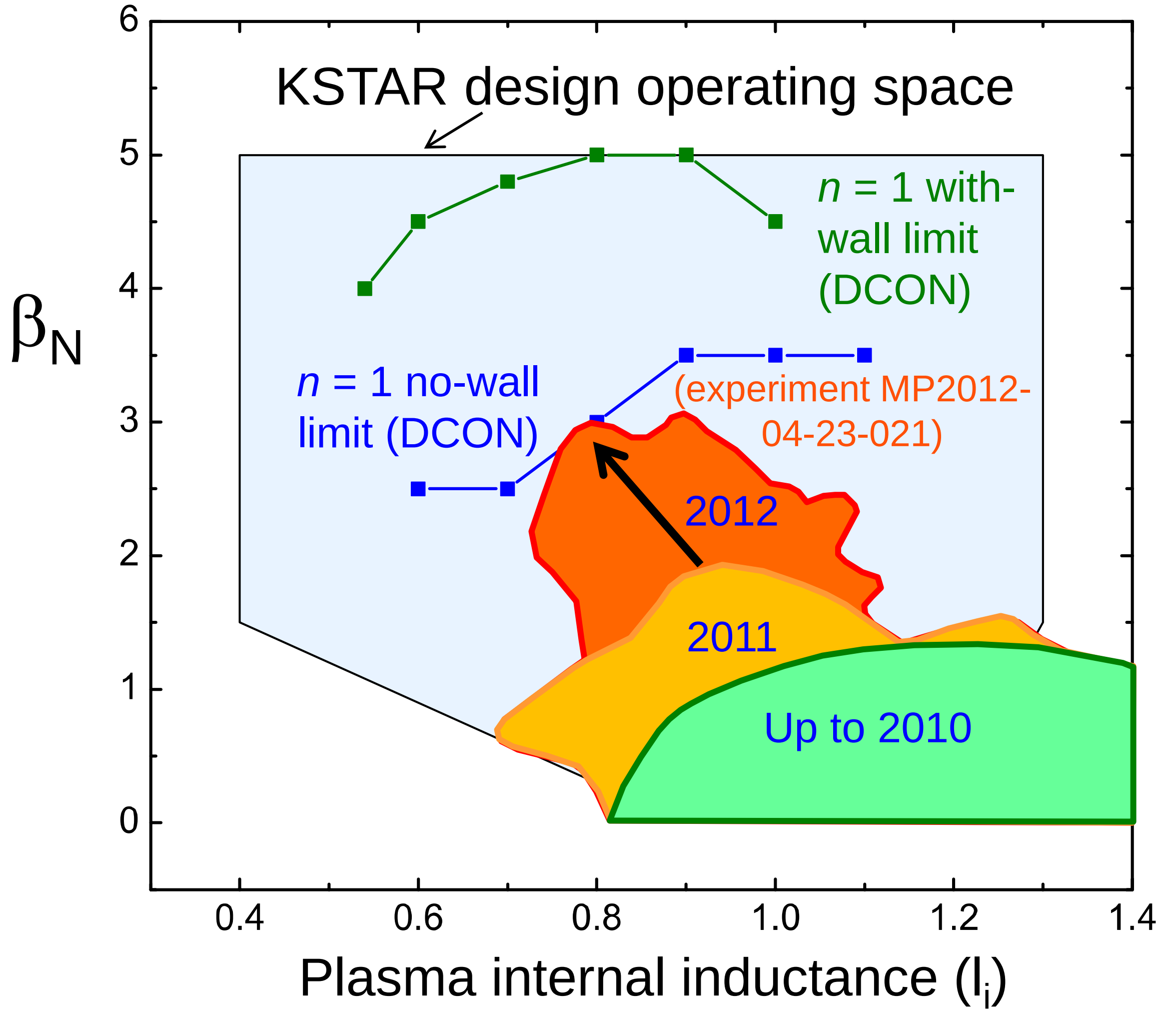
US-Korea collaboration on KSTAR: High beta and 3D plasma stability research

- Addresses key KSTAR Milestones (including)
  - High-performance, long-pulse, steady-state device operation
  - Instability/disruption avoidance and associated physics research
  - Application of results to ITER
- Supportive Partnerships
  - NFRI, PPPL, Columbia U., POSTECH, et al.
- Successful Collaboration Approach
  - Synergistic tokamak physics research utilizing the KSTAR (Korea) and NSTX-U (USA) devices – consistent with 5 year plans
  - Columbia U. group publications
    - 3 IAEA FEC presentations and papers
    - 3 refereed-journal articles, +1 paper just submitted, +1 in process

First plasmas exceeding the ideal no-wall MHD stability limit mark initial KSTAR advanced tokamak operation

- Motivation
  - Understanding and maintenance of MHD stability at high β_N, over long pulse duration are key KSTAR, ITER goals
  - Altering plasma rotation to study MHD stability, and to operate in most ITER relevant low rotation regime are key
- Outline
  - High β_N results exceeding the n = 1 ideal no-wall limit
  - Open loop control of plasma rotation using 3D fields
  - ELM mitigation using n = 2 field via midplane IVCC
  - Plasma control improvements
  - Global mode stabilization performance calculations

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

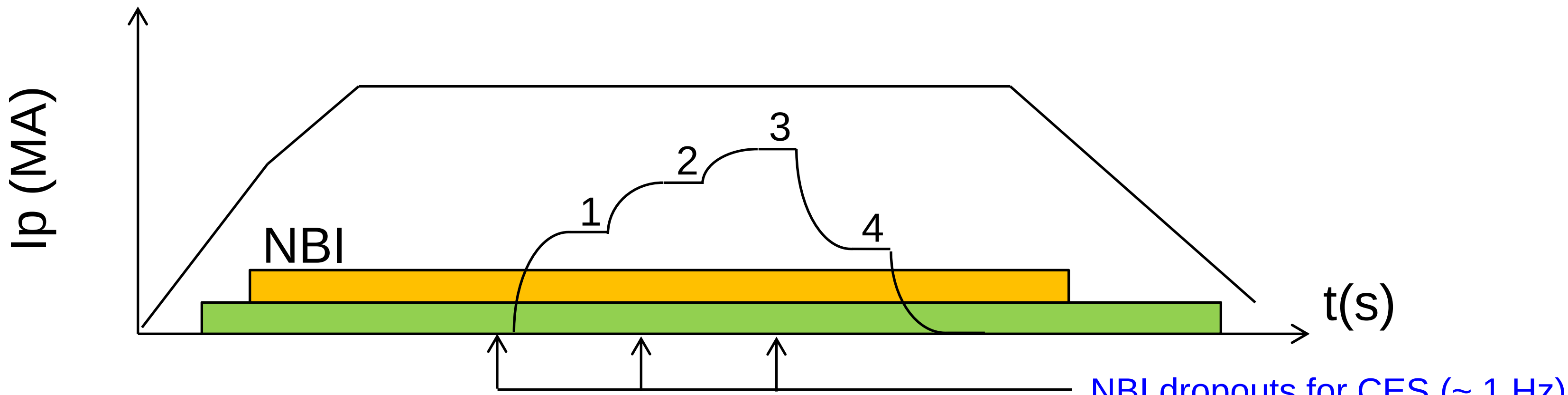


- I_p scan performed to determine "optimal" β_N vs. I_p
  - B_T in range 1.3 - 1.5T
  - β_N up to 3.0
- β_N/l_i = 3.8 (75% increase from 2011)
  - a high value for advanced tokamaks, e.g. for DIII-D
- Mode stability
  - Target plasma is at published computed ideal n = 1 no-wall stability limit (DCON)
  - Plasma is subject to RWM instability, depending on plasma rotation profile
  - Rotating n = 1, 2 mode activity observed in core during H-mode

- TRANSP for these plasmas (R. Budny (PPPL))

Pre-programmed n = 2 field used to alter $V_\phi(R)$ non-resonantly in using in-vessel control coil (IVCC)

- Test plasma characteristics vs. toroidal rotation by slowing plasma with non resonant n = 2 NTV using IVCC



Simplified expression of NTV force ("1/ν regime")

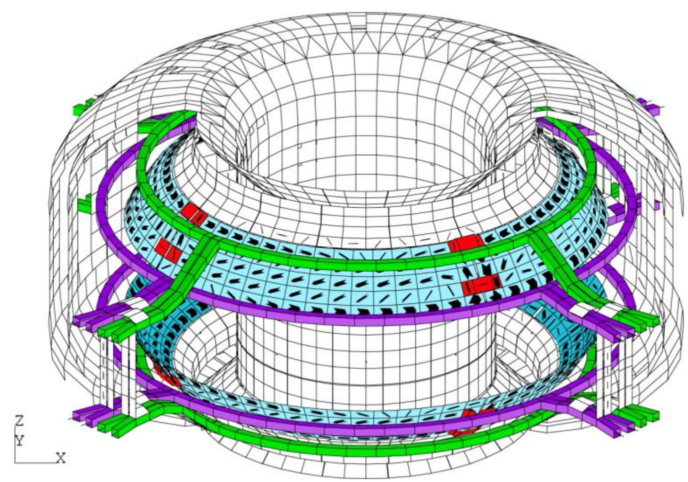
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\omega_\phi - \omega_{NC}) I_\lambda$$

$T_i^{5/2}$

Steady-state velocity

Inverse aspect ratio

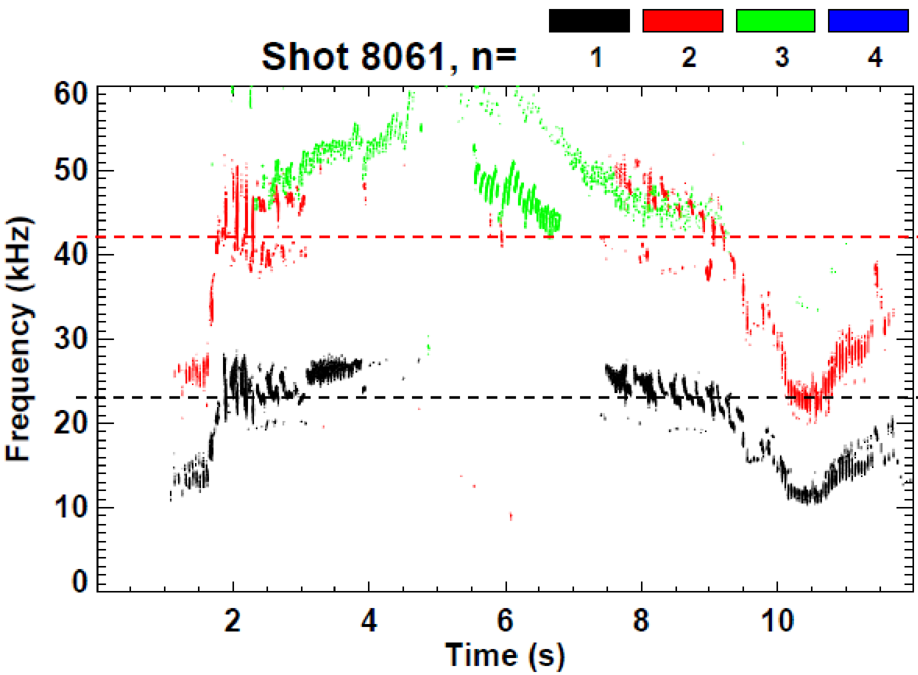
K.C. Shaing, et al., PPCF **51** (2009) 035004



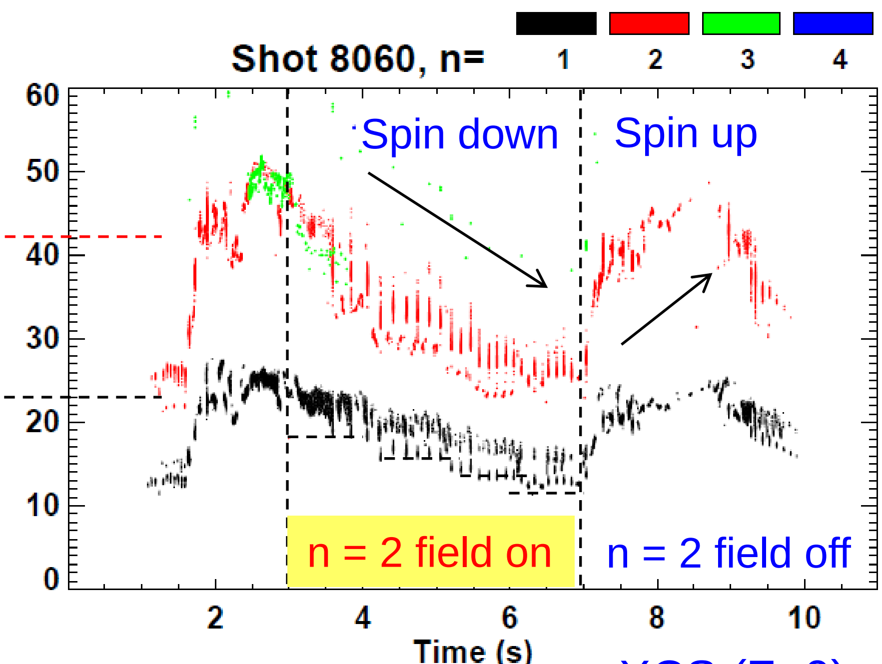
- Pre-requisite for study of NTV physics in KSTAR – comparison to NSTX (low A)

Effect of step increases in n = 2 IVCC current observed in mode frequency, XCS rotation data

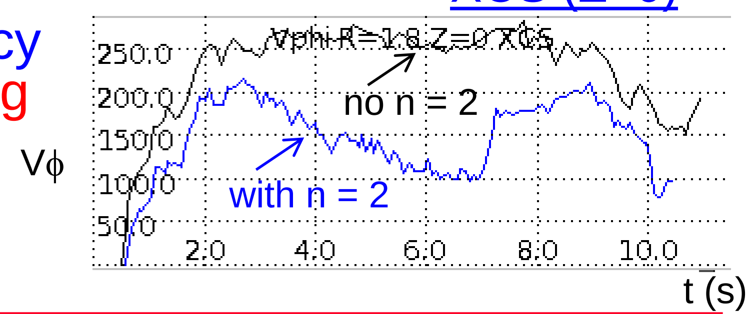
No IVCC n > 0 field



With IVCC n = 2 field

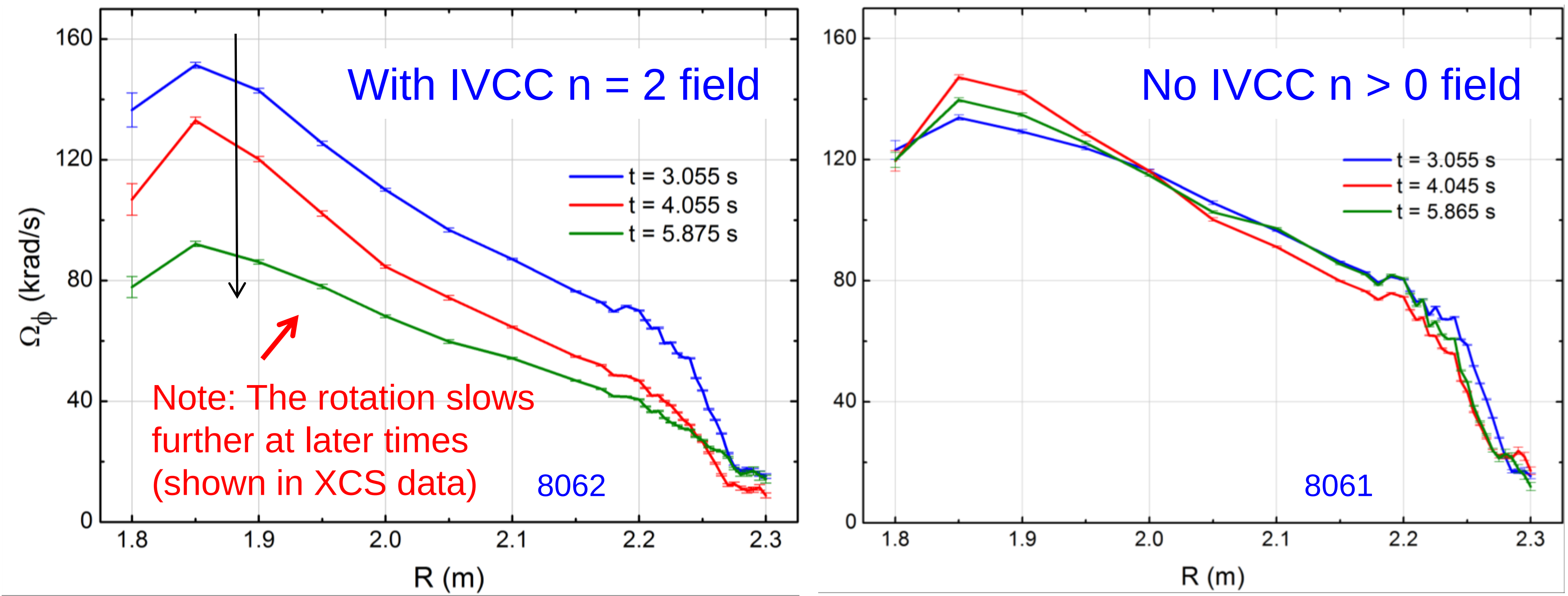


XCS (Z=0)



- Low frequency MHD mode rotation frequency decreased by 40 - 50% without mode locking
- Measureable energy confinement time change with n = 2 field applied

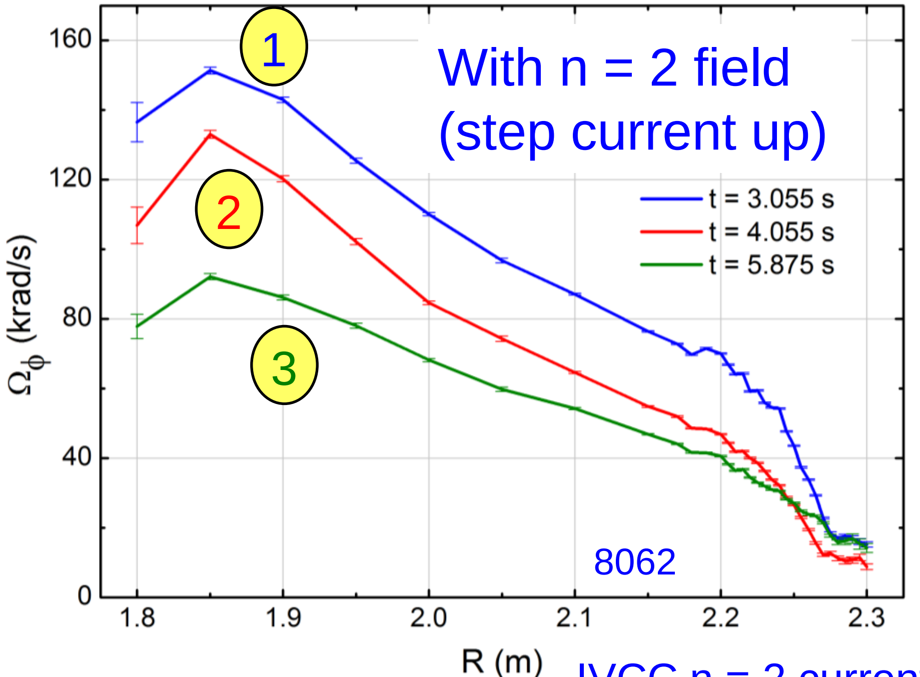
Clear reduction in CES measured toroidal plasma rotation profile with applied n = 2 field

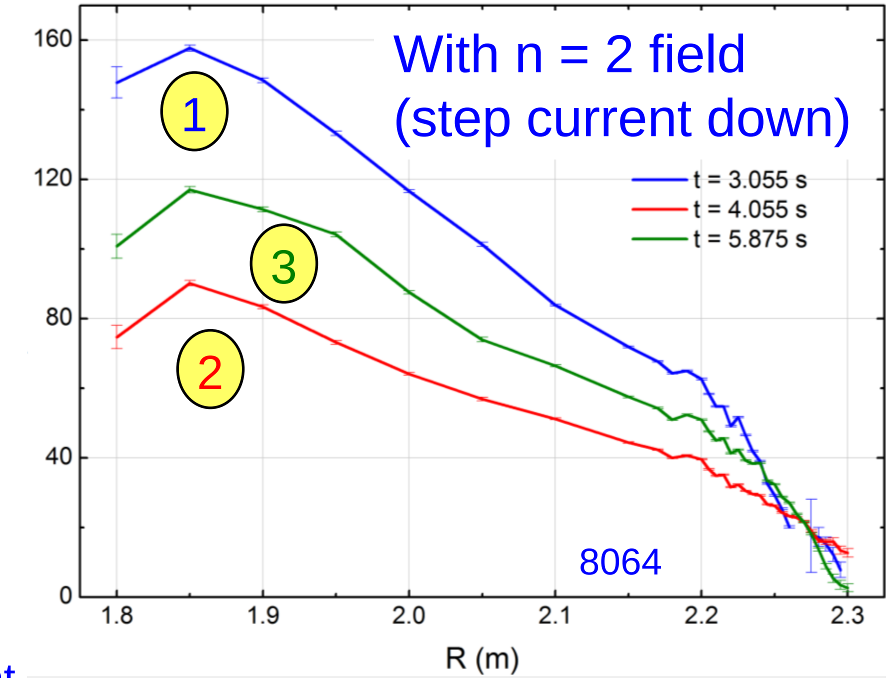


- Significant reduction of rotation speed using “middle” IVCC coil alone
- Significant alteration in rotation pedestal at the edge during braking
  - Slowed rotation profile resembles an L-mode profile (H-mode is maintained)

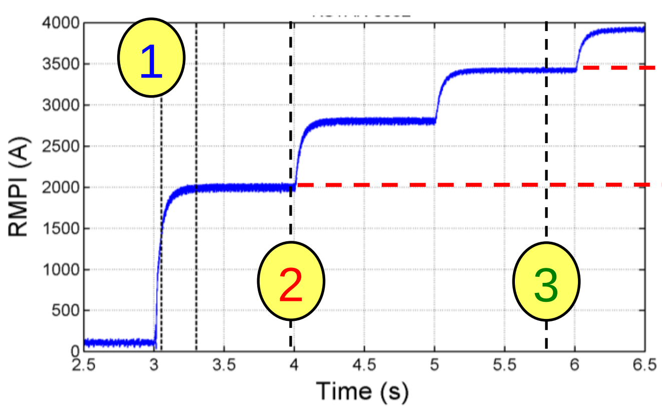
W. Ko (CES)

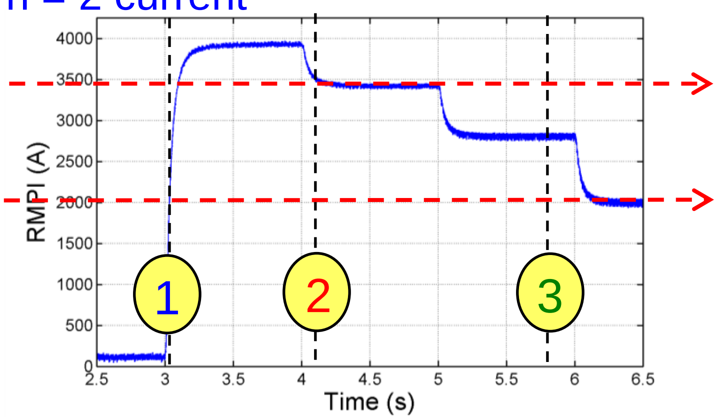
Measured toroidal plasma rotation profile shows plasma spin-up when n = 2 field is decreased





IVCC n = 2 current

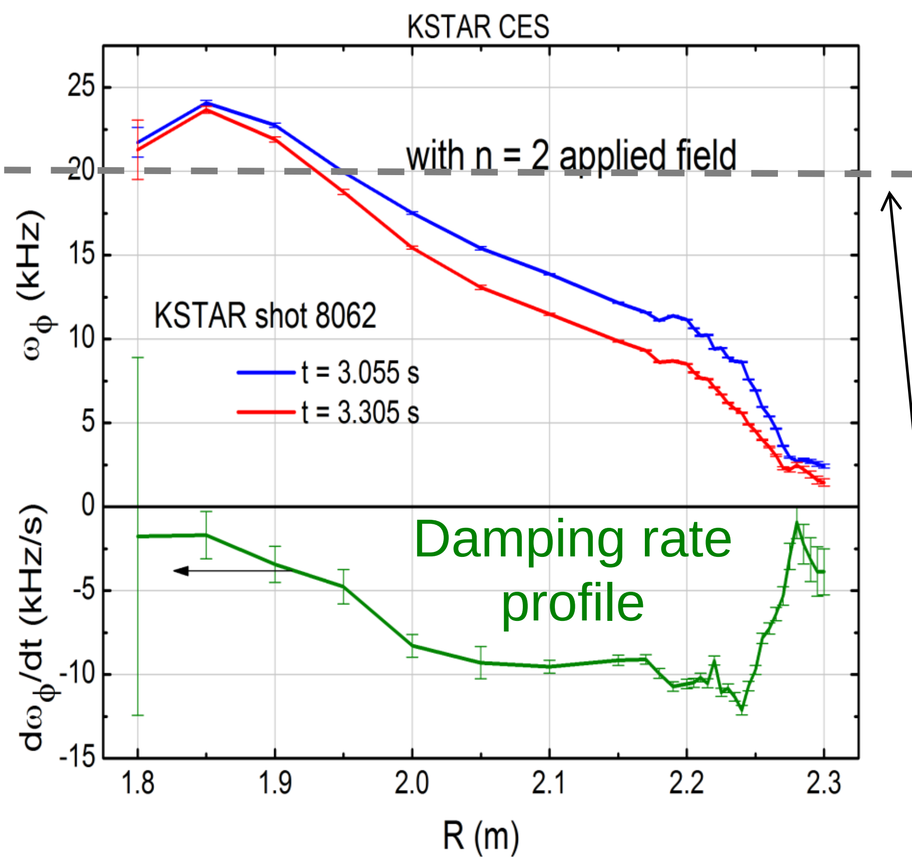


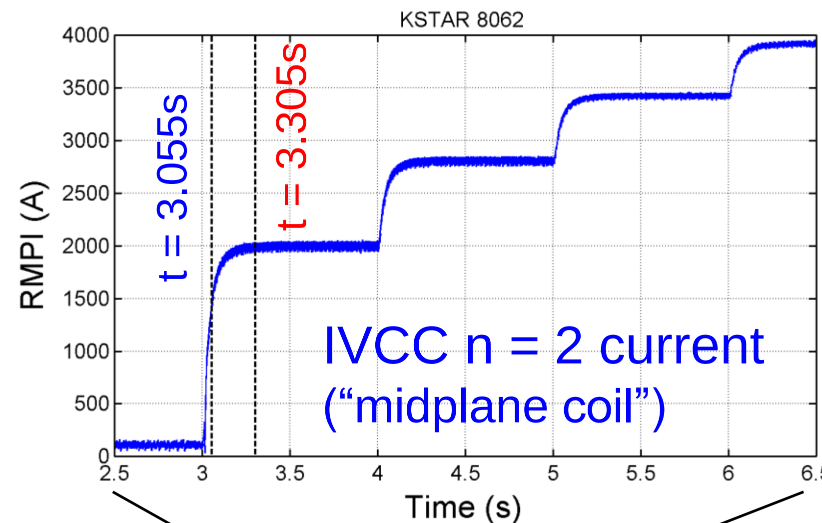


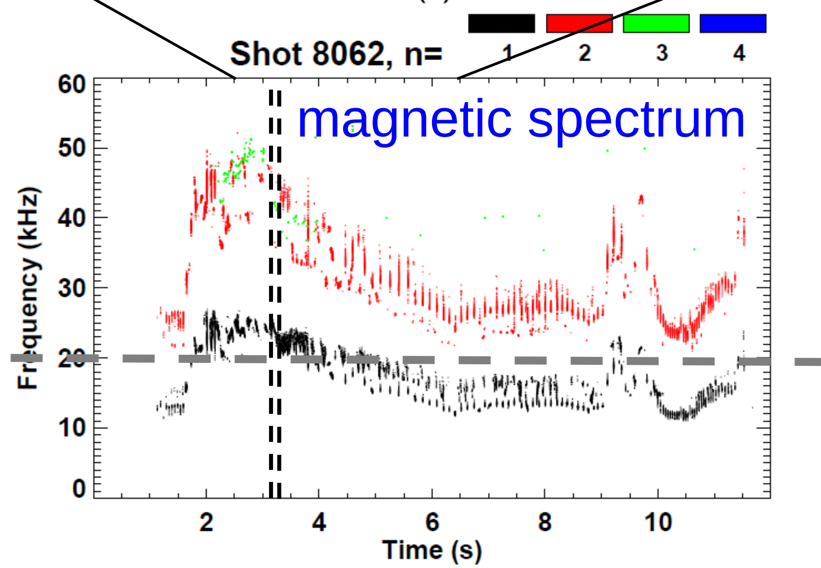
At same IVCC current, rotation profile shows no hysteresis – important for control

W. Ko (CES)

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



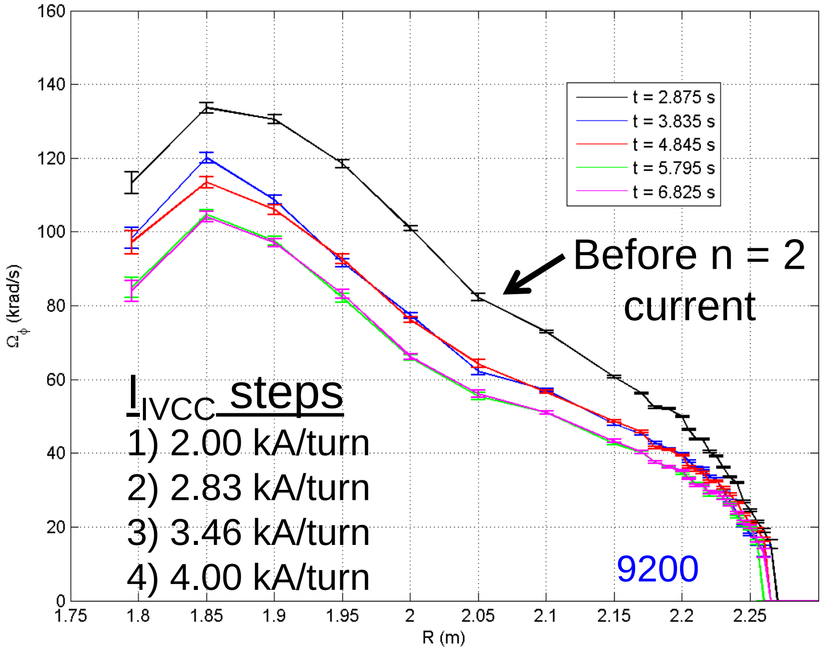




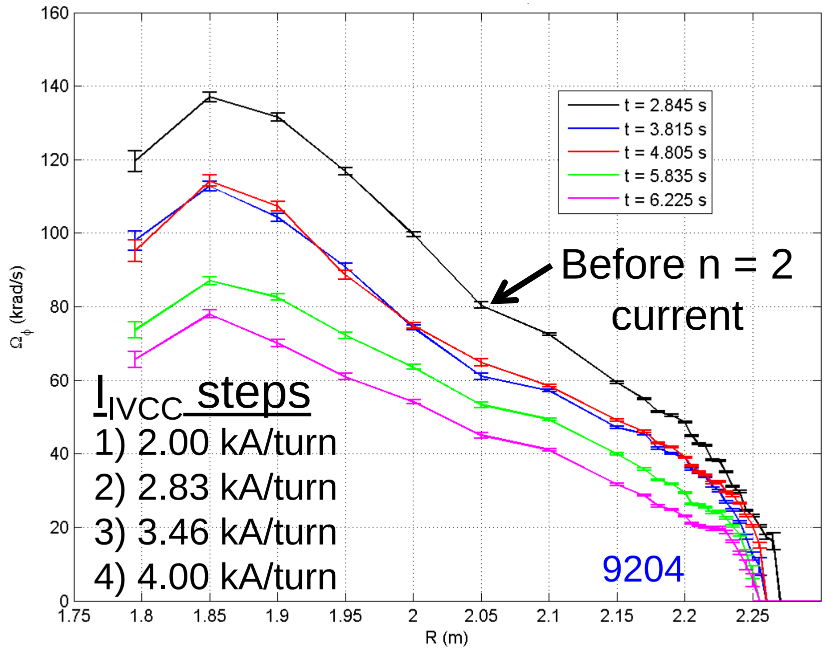
- Rotating n = 1, 2 modes observed in core
  - would not produce the observed rotation profile change (no change in core)

New δB spectra applied in 2013 experiment

Toroidal rotation profile evolution (top/bottom IVCC (n = 2))



Toroidal rotation profile evolution (top/middle/bottom IVCC (n = 2))

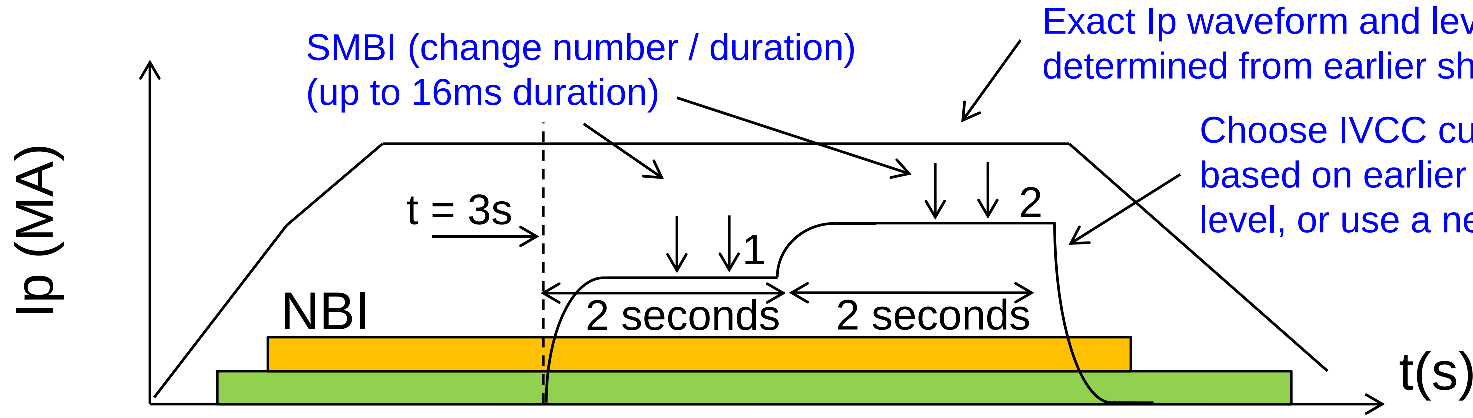


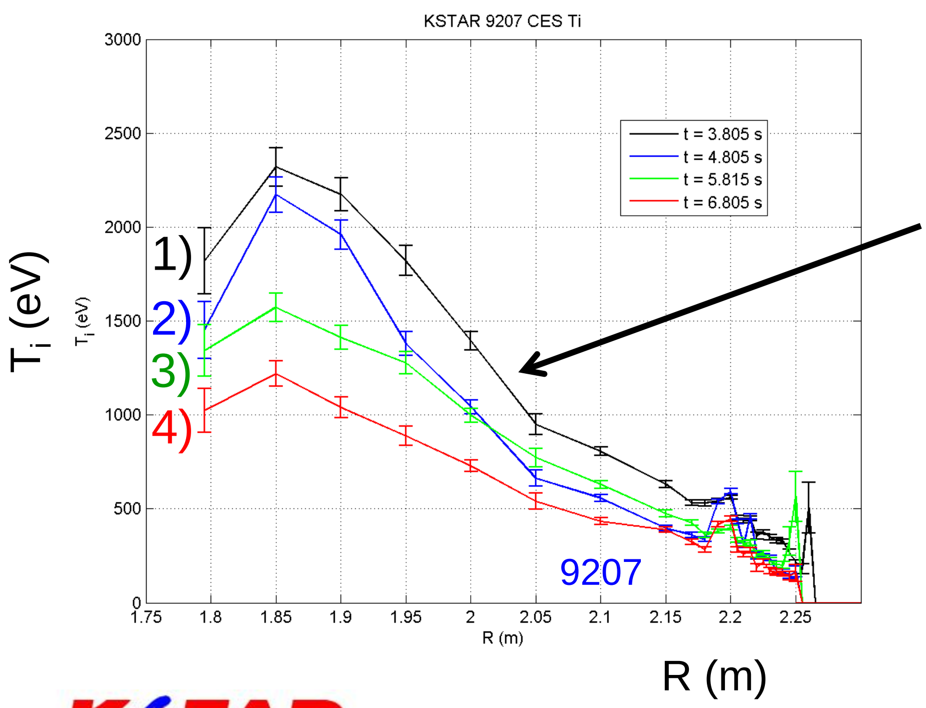
- n = 2 top/bottom IVCC configurations used for first time
  - Knowledge of NTV braking from top/bottom coils alone important for combined use with future n = 1 RWM active stabilization
  - Stronger braking using top/middle/bottom IVCC

Experiment MP2013-05-03-003

SMBI used to alter T_i during n = 2 NTV braking (2013)

2) SMBI: Examine dependence of NTV on collisionality





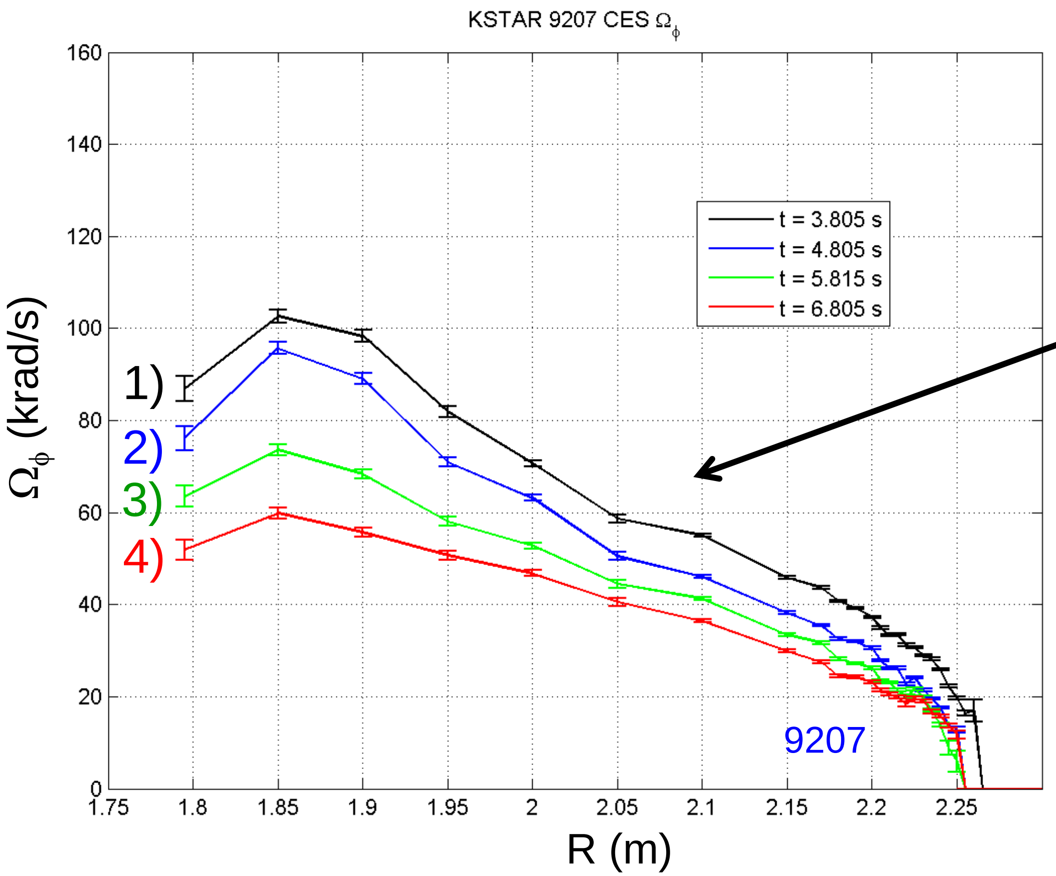
Traces

1) 1^{st} IVCC, before SMBI
2) 1^{st} IVCC, after SBMI
3) 2^{nd} IVCC, before SMBI
4) 2^{nd} IVCC, after SMBI

- Clear change in T_i profile from SMBI

Experiment MP2013-05-03-003

Toroidal rotation was clearly changed due to n = 2 NTV and SMBI



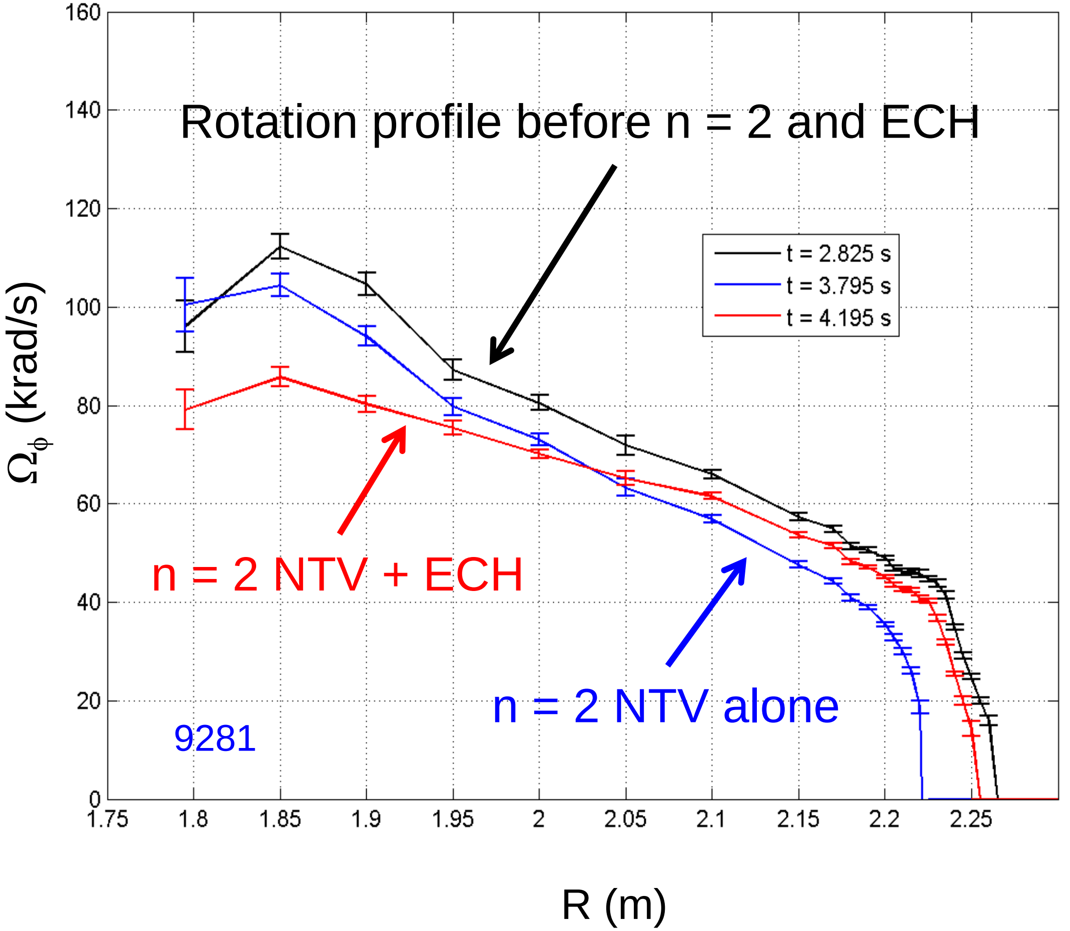
Traces

1) 1st IVCC, before SMBI
2) 1st IVCC, after SBMI
3) 2nd IVCC, before SMBI
4) 2nd IVCC, after SMBI

- Further shot comparison, analysis is needed to determine effect of SMBI on n = 2 NTV braking strength

Experiment MP2013-05-03-003

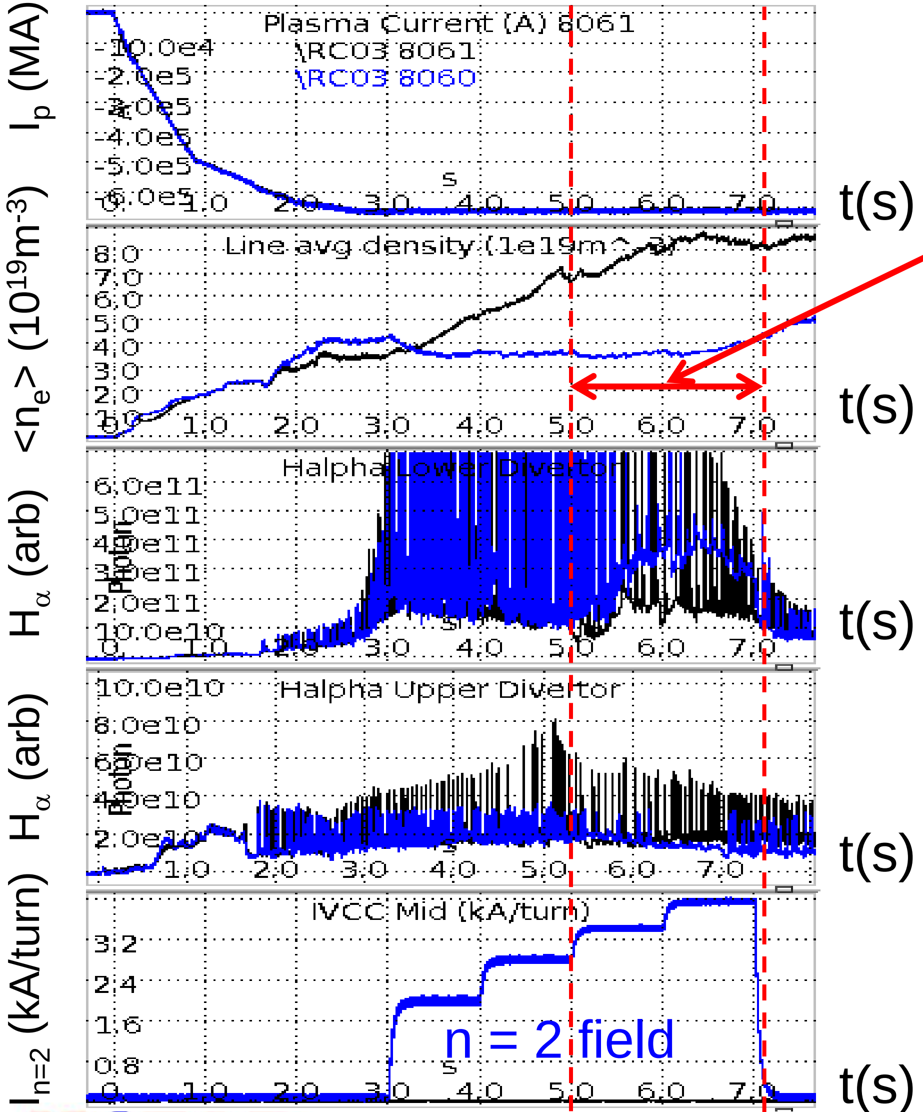
Rotation profile alteration observed with combined IVCC n = 2 NTV + ECH (110 + 170 GHz)



- Only time for two shots
  - Original shot plan had several more ECH shots
  - These shots show combined technique works (not optimized)
- 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

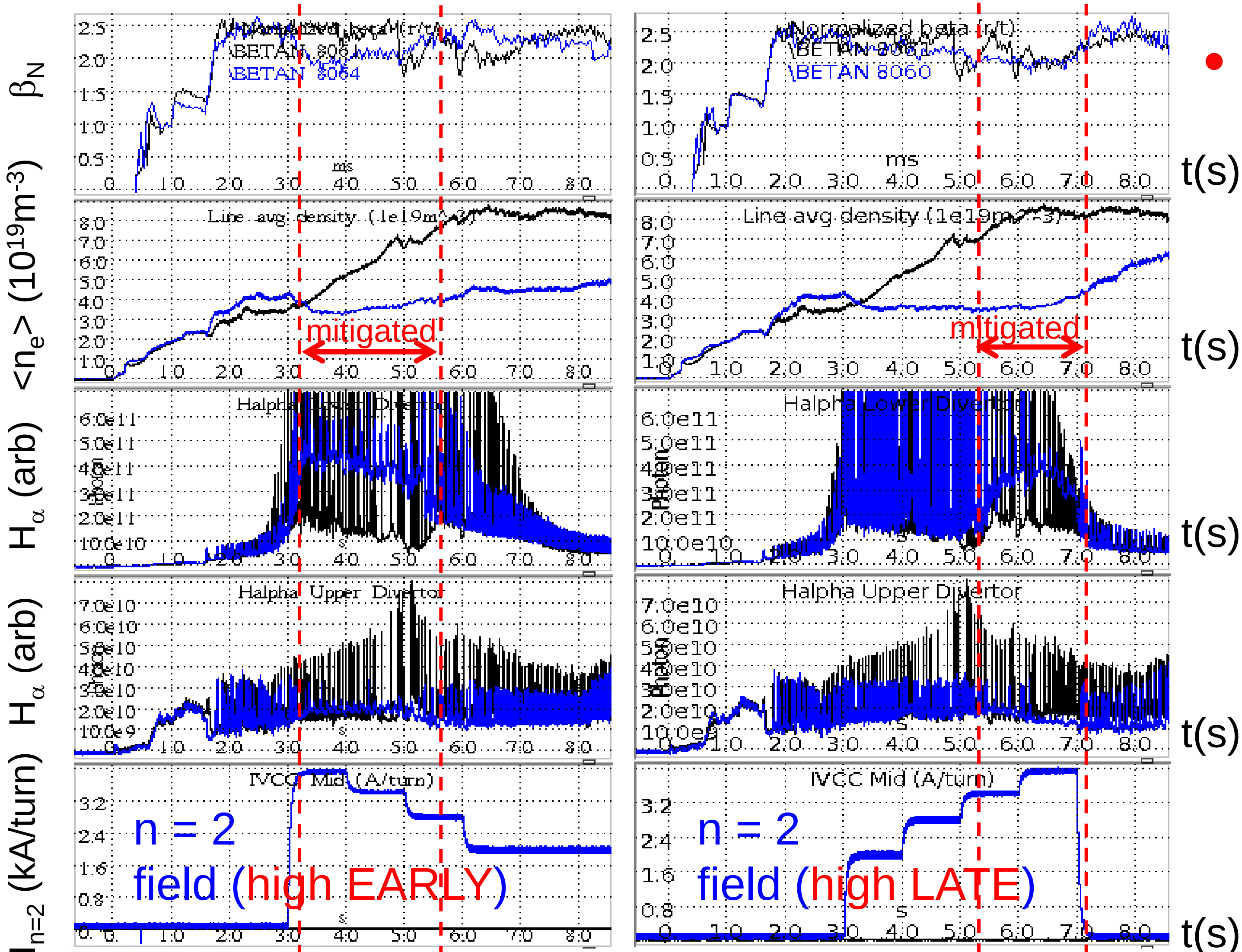
Experiment MP2013-05-03-003

ELM mitigation found when using n = 2 field via middle IVCC only



- Mitigation observed when sufficiently high n = 2 field is applied
  - I_{Ivcc} > 3 kA/turn
    - Note: didn't observe this in 2011 due to 1.8 kA/turn limit
  - Reduction in density observed at start of n = 2 applied field
    - Need to verify validity of density evolution

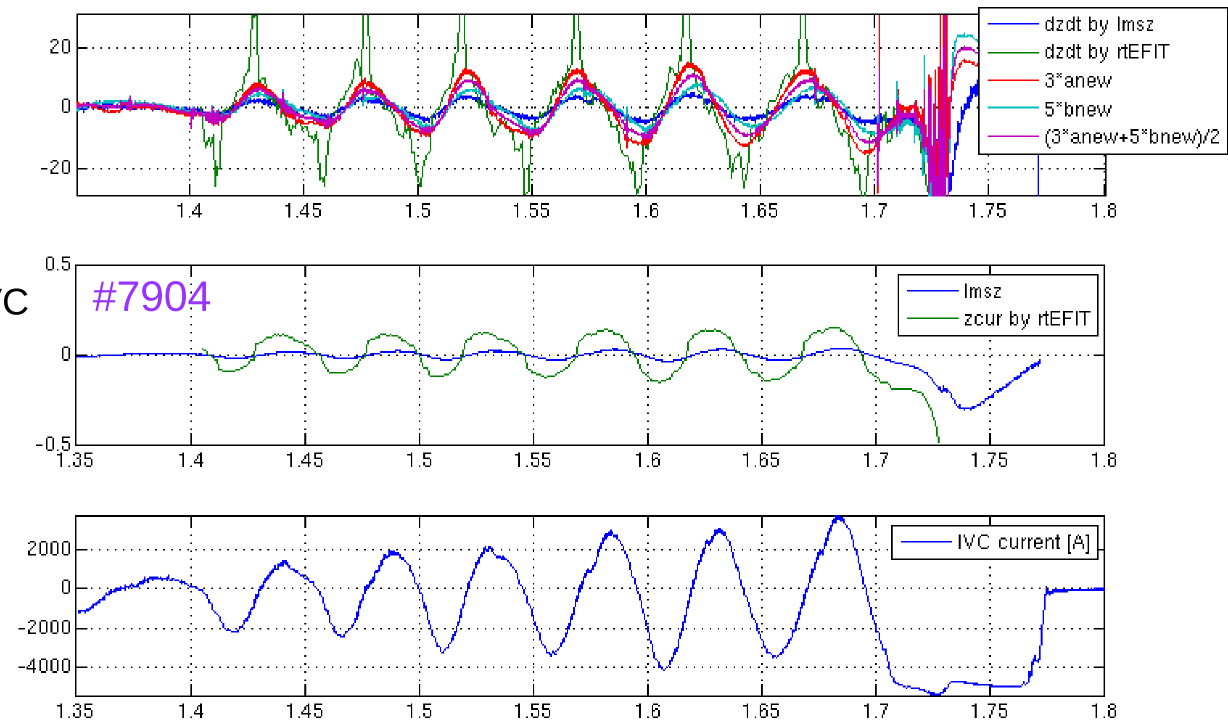
ELM mitigation found using n = 2 field, via middle IVCC only, correlates with field strength

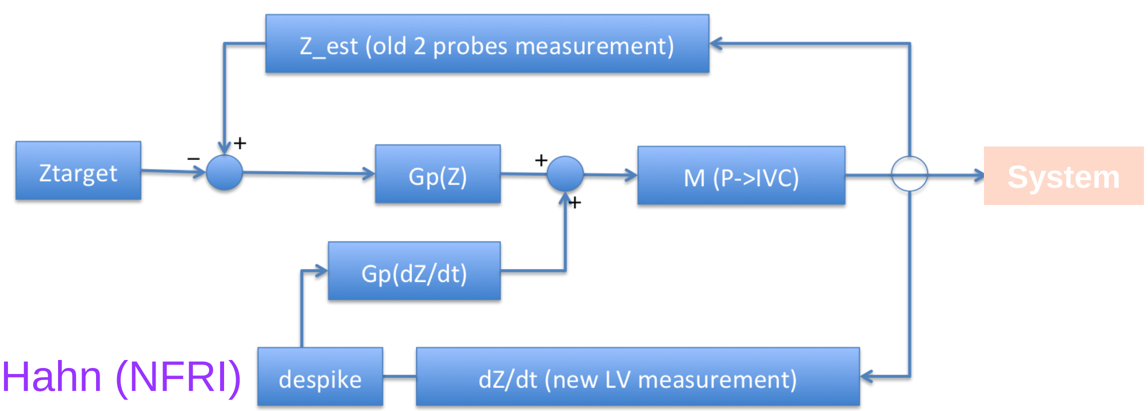


- Mitigation observed when sufficiently high n = 2 field is applied
  - Stored energy, β_N varies
  - However, shot that has continuous ELMing with no n = 2 field has same β_N variation

Vertical control design modifications made in PCS

- New dZ/dt estimator was verified against 2012 real-time EFIT Z_{cur} measurement
  - Sensitivity of LMSZ, the old estimator, is poor for high triangularity shots
  - 2013 version compensates IVC current pickups only
- "Limited" algorithm now has new dZ/dt feedback loop, tested at the dedicated experiment (Aug. 7th)
  - Gain's determined by "relay feedback control technique 2 tries
  - $G_p = 3.48$, $G_d = 0.05$
- Caveats :
  - Compensation on spikes sync'ed with ELMs

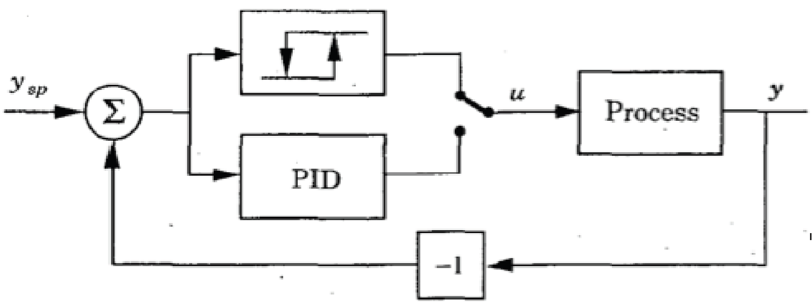




D. Mueller (PPPL), S.H. Hahn (NFRI)

Relay feedback algorithm helped determine gains set

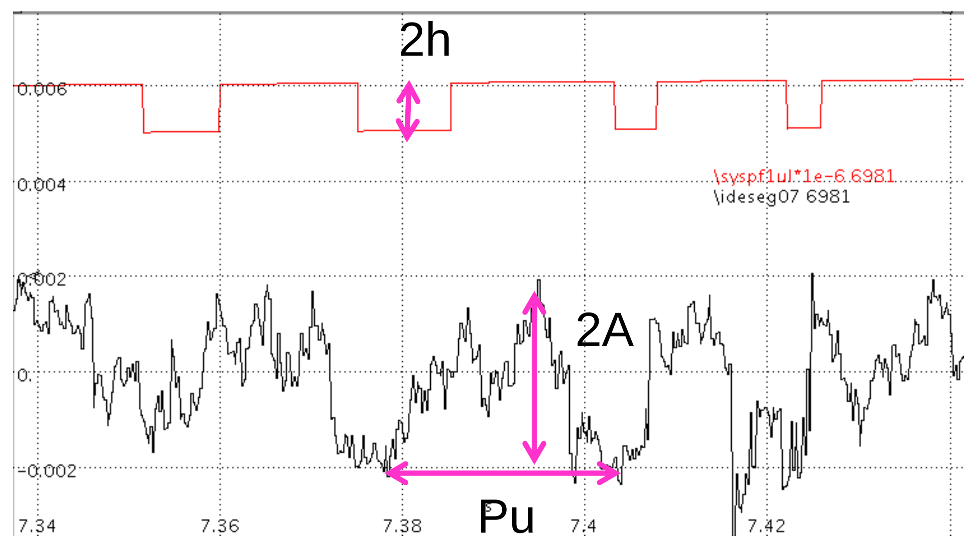
- Sysmain category: if relay feedback's turned on for a coil, the coil current demands will oscillate like the picture, invoking responses on the PID loop
  - The method gave a direct, optimized set of gains for Ip & segment PID
  - Gives also the Rule of Thumb for ratio of Gp / Gi



$[P,I,D]=4h/(\pi A)*[0.6,\ 2/P_u,\ P_u/8]$

$$\frac{G_p(SEG07)}{G_i(SEG07)} = 0.3 * P_u$$

#6981: PF1UL → SEG07 (inboard gap)

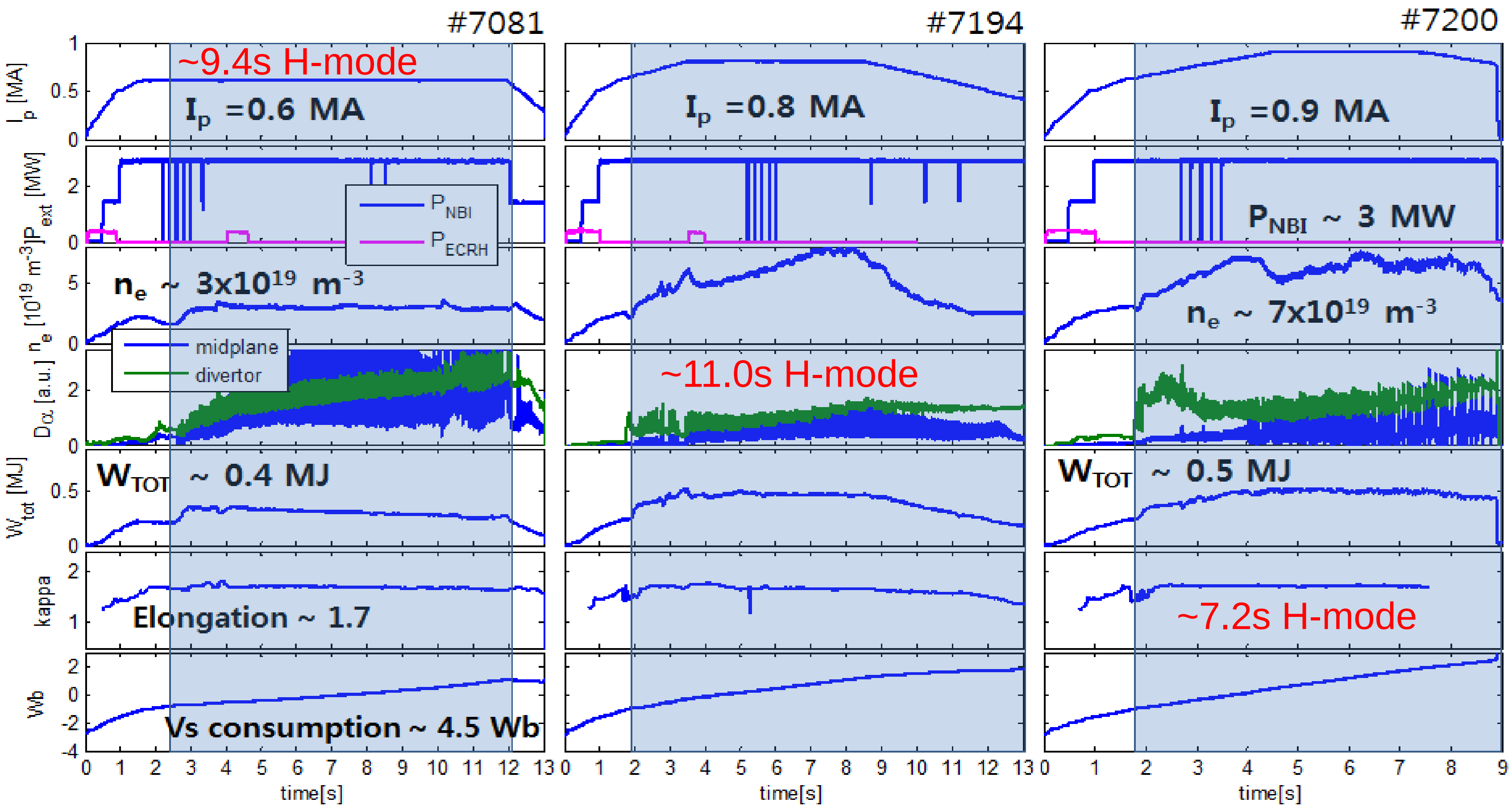


E. Kolemen (PPPL)

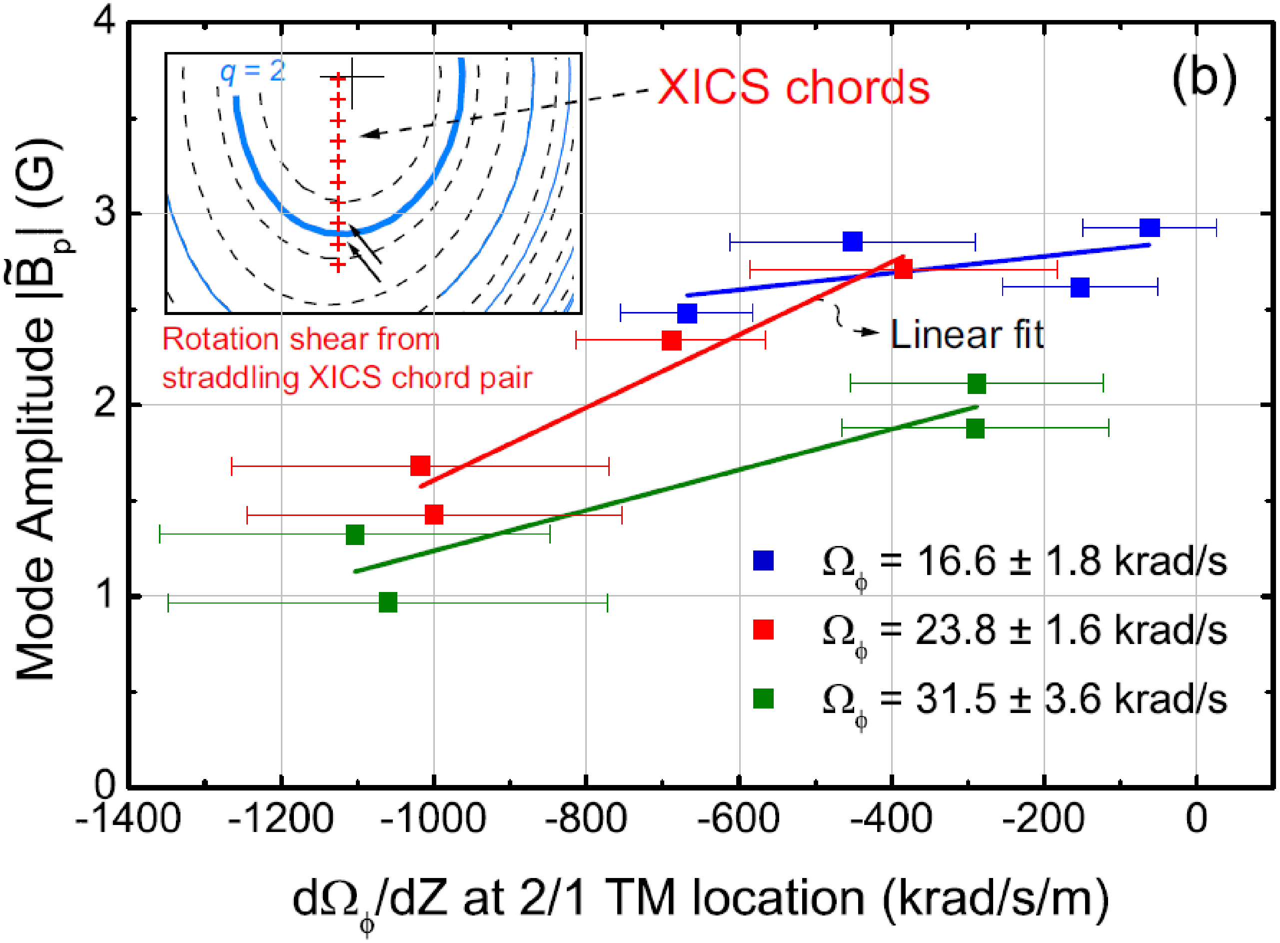
The new improved control development helped enable increase of plasma current and duration of H-mode (11 seconds)

- Expanded the operation regime of the plasmas
  - I_p up to 0.9 MA with 3 MW beams
  - Stored energy (W_{tot}) ~ 0.4 MJ

E. Kolemen (PPPL)



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

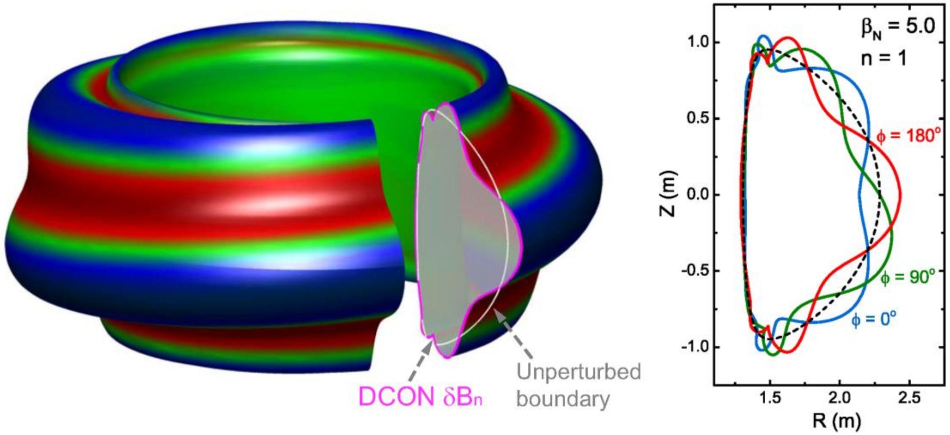


- Mode identification from ECE, ECEI systems
- Observed increase of TM amplitude vs. Ω_ϕ shear decreases at reduced Ω_ϕ

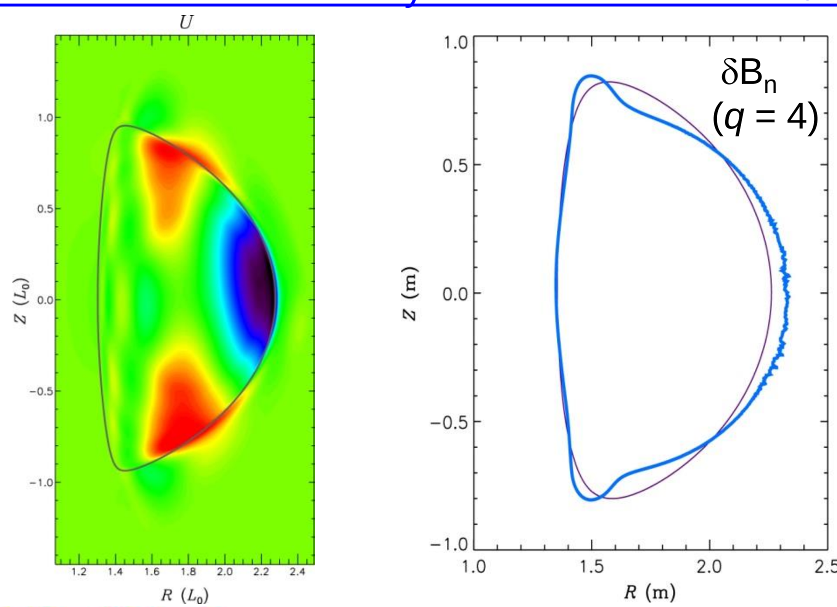
Y.S. Park, S.A. Sabbagh, J.M. Bialek, et al. Nucl. Fusion **53** (2013) 083029

M3D-C¹ MHD code being run for KSTAR, compared to DCON

KSTAR DCON n = 1 unstable mode eigenfunction



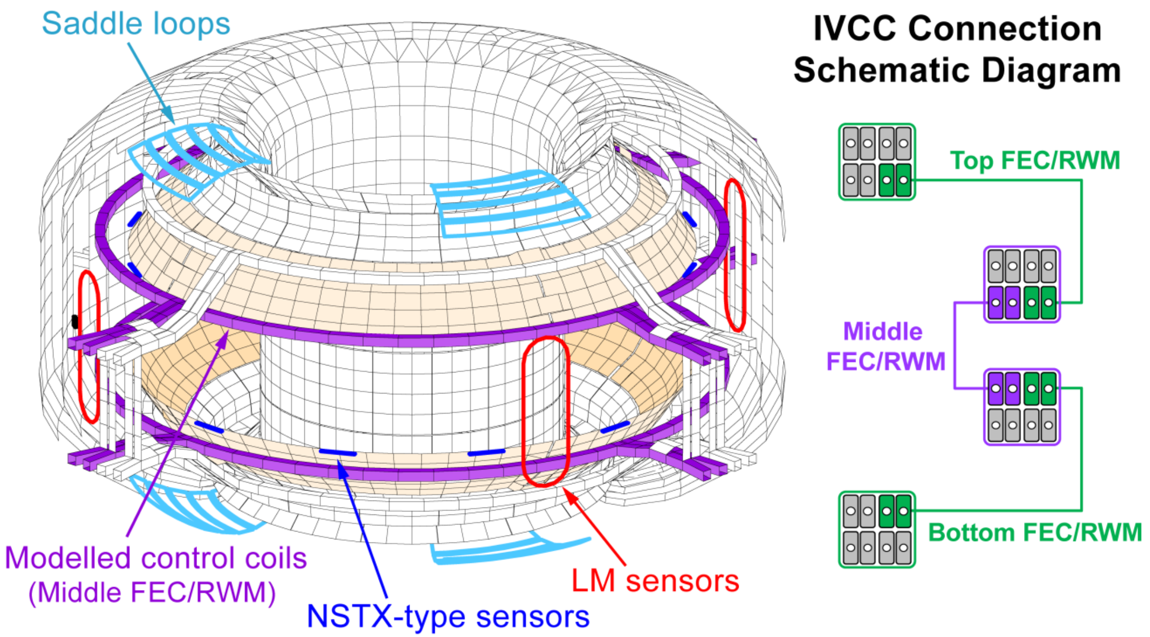
M3D-C¹ unstable mode velocity stream function and δB_n



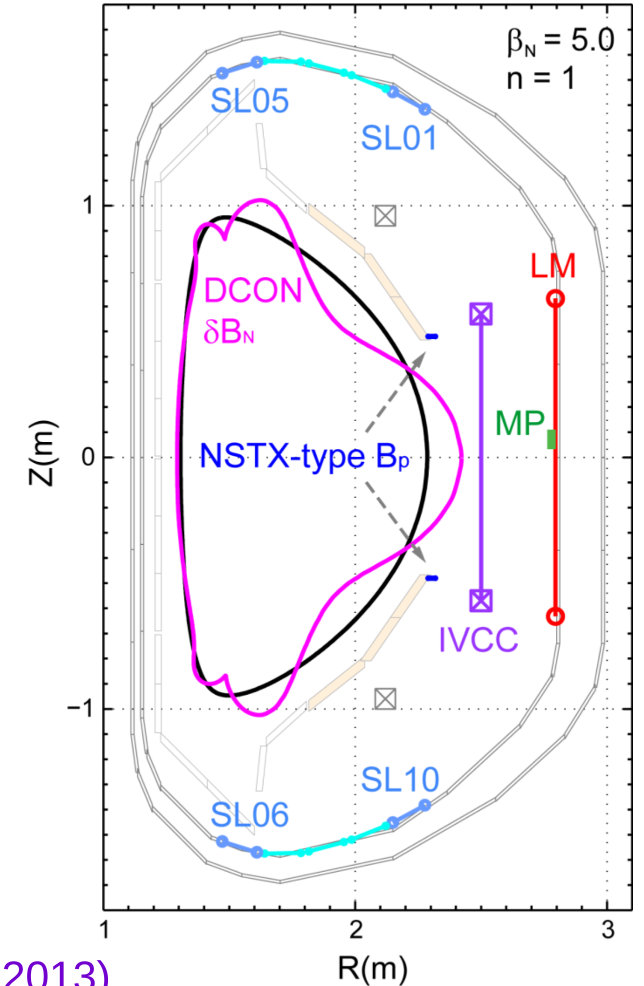
- Linear stability analysis using M3D-C¹ code (collaboration S. Jardin)
  - Extended MHD code solving full two-fluid MHD equations in 3D geometry
  - Non-linear code, presently being used in linear mode for initial runs
- Ideal n = 1 stability limit from DCON and M3D-C¹ compare well
  - For the same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

Y.S. Park, et al.

Active n = 1 RWM control performance determined with 3D sensors



Sensor location and n = 1 DCON eigenmode



- Study considered different sensors
  - Sensors presently available: (i) LM, (ii) SL, (iii) MP,
  - Possible new sensors: (iv) "NSTX-type B_P" sensors
  - (NOTE): Need more toroidal sensor positions to track n = 1 mode rotation

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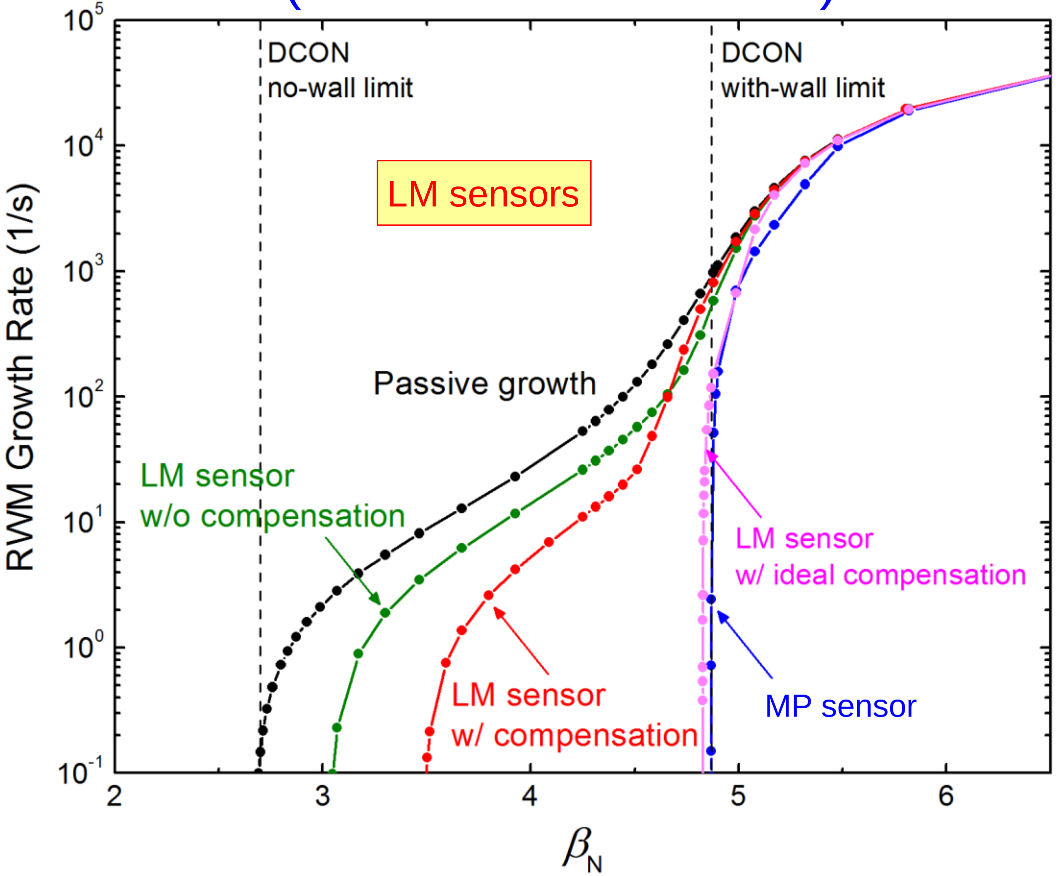
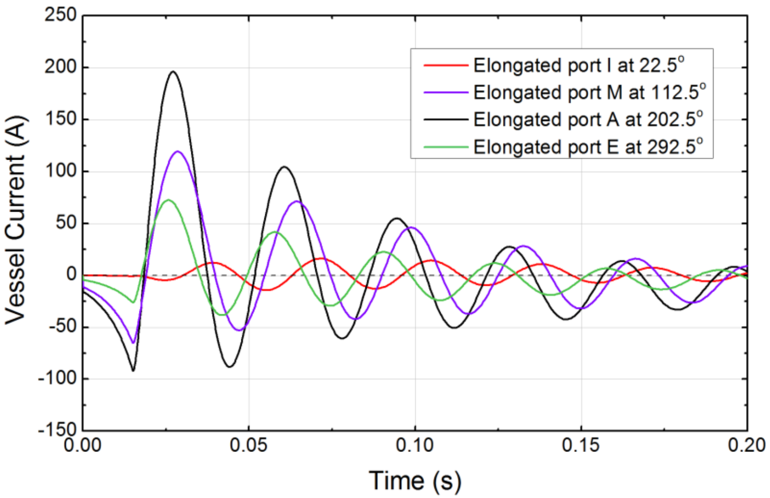
Active n = 1 RWM control performance determined for present "LM" 3D sensors

RWM growth rate vs. β_N
(no kinetic stabilization)

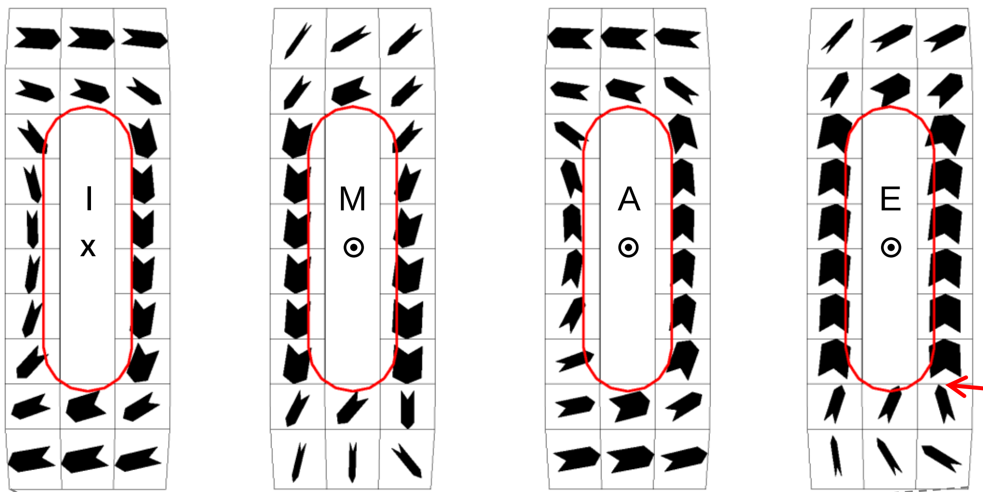


Vessel currents around ports



- Performance strongly affected by vessel currents around ports

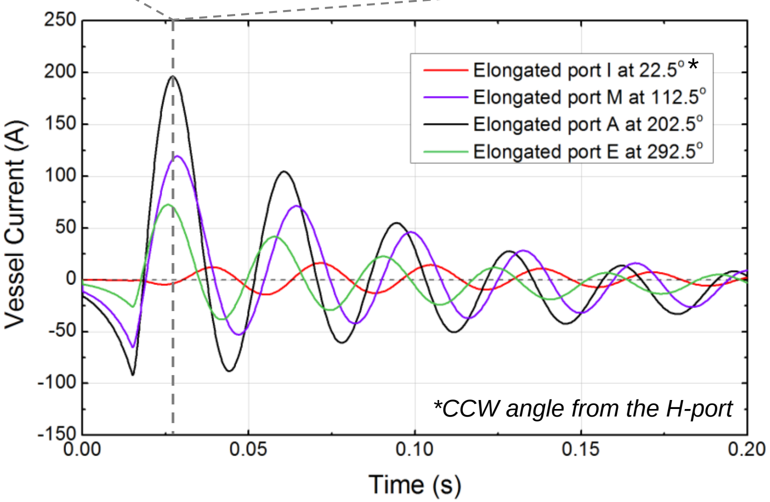
Control coil-induced vessel current significantly limits performance of the LM sensors

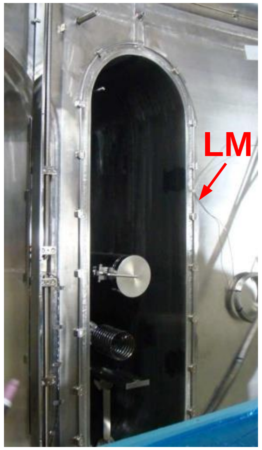


VALEN3D computation of induced vessel current during successful n = 1 feedback

Induced current in vessel around ports

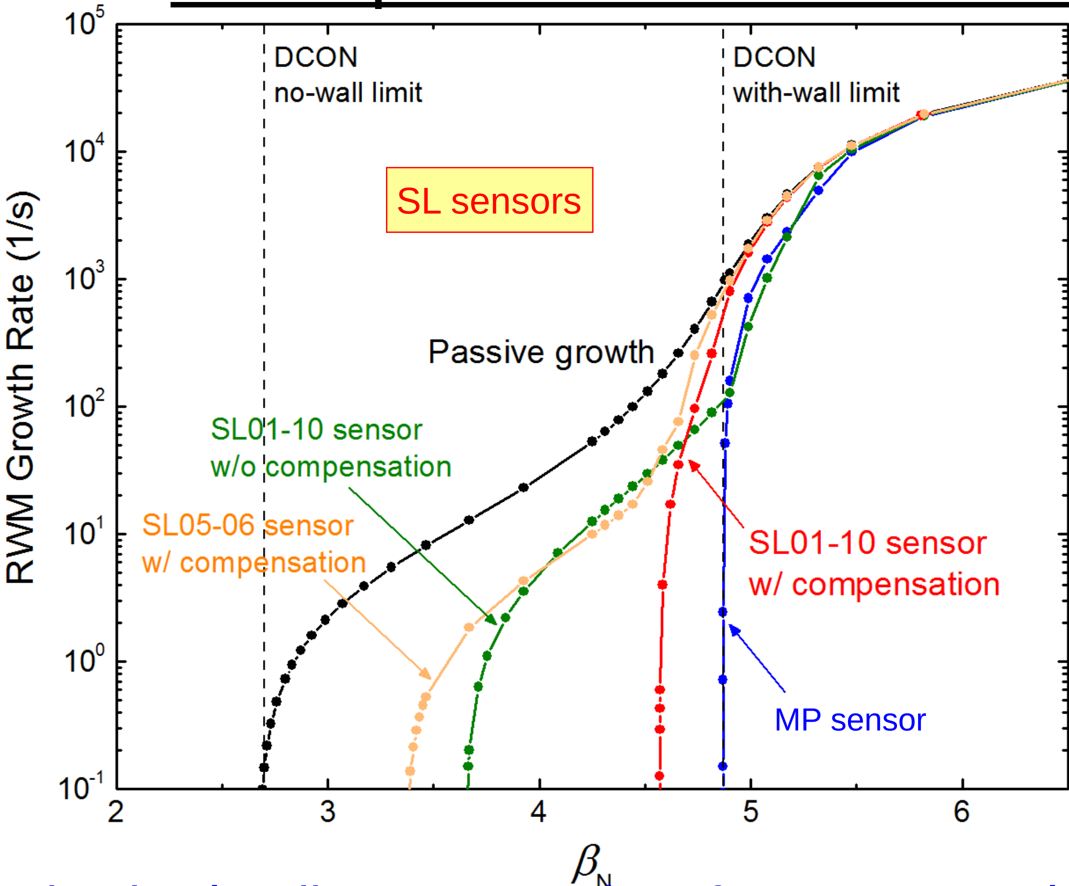
LM sensors

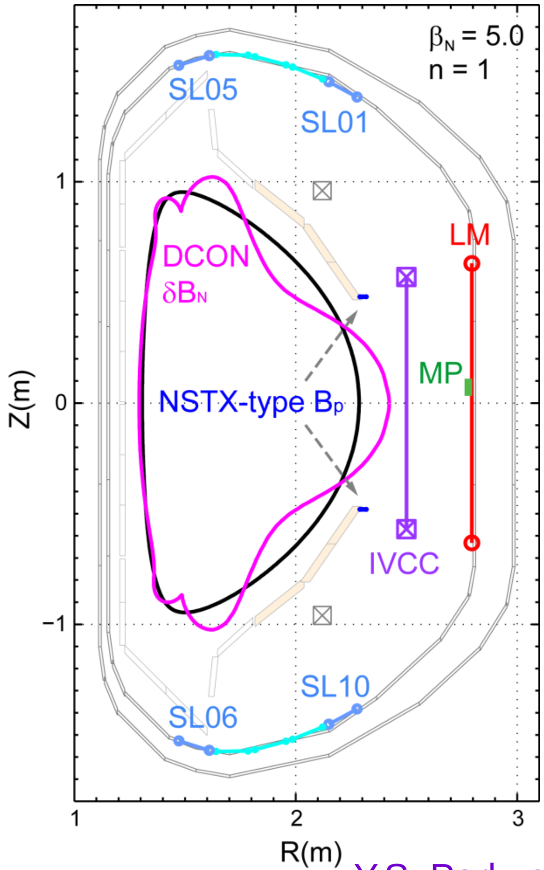




- Control performance with LM sensors
  - limited by control coil-induced vessel currents circulating around the elongated port
  - Induced vessel currents significantly alters the measured mode phase

Active n = 1 RWM control performance improved when present "SL" 3D sensors are used





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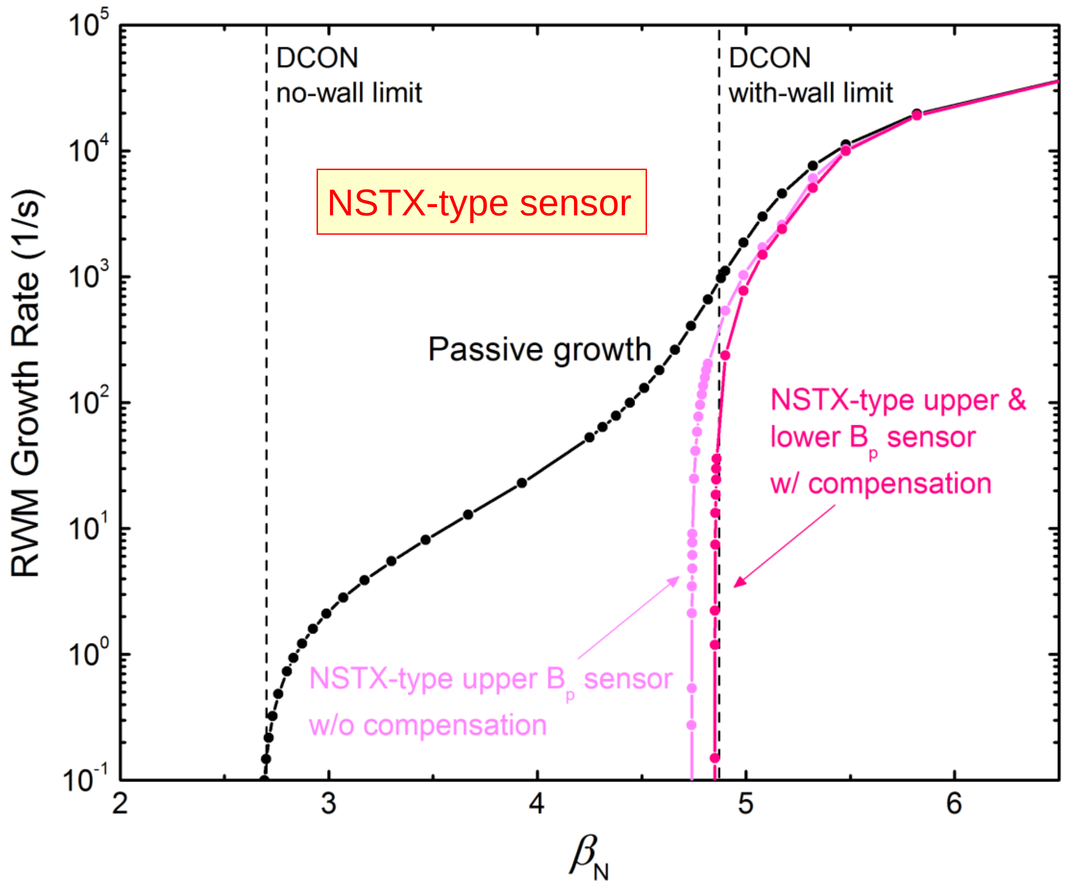
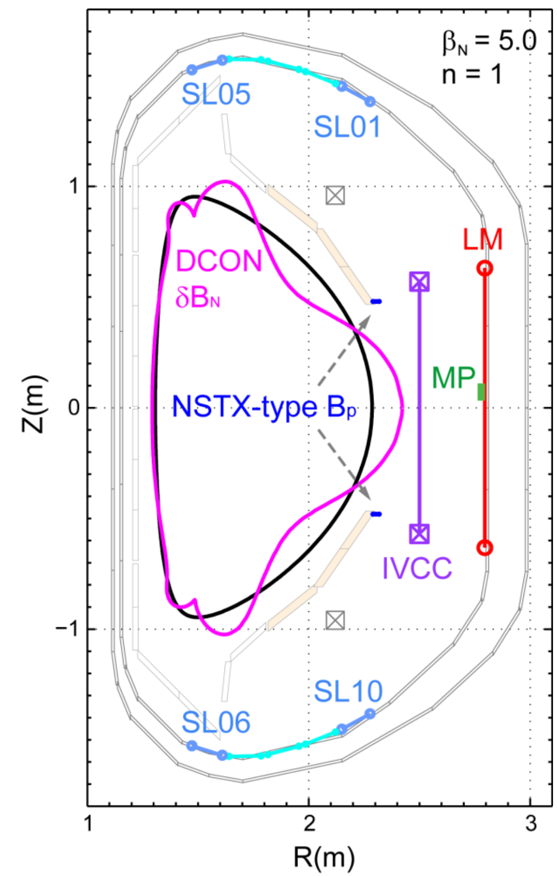
- Physics leading to control performance results
  - SL sensor performance mostly set by interference due to passive plates (SL01-10 with applied field compensated perform best)
  - MP sensors have lowest coupling to vessel/plates: but only 3 toroidal positions, small effective area

Active n = 1 RWM control performance determined for "optimized", realistic 3D sensors





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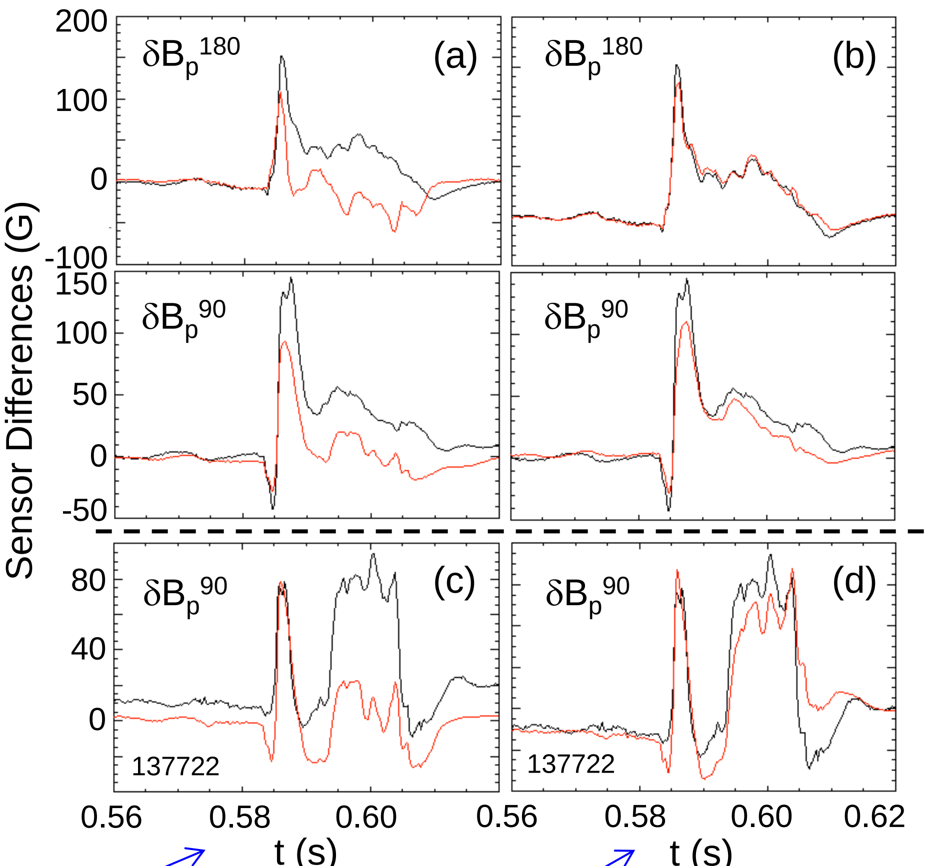
- Physics leading to control performance results
  - "NSTX-type B_p" sensor performance only weakly affected by vessel and passive plate currents

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

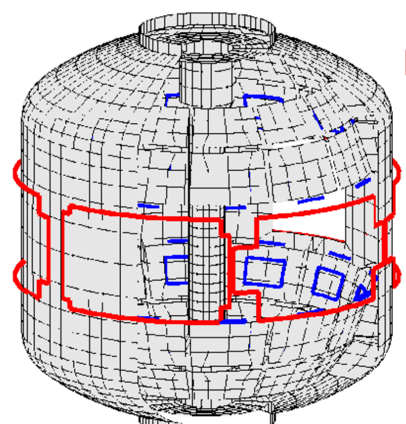
NSTX: RWM Upper B_p Sensor Differences (G)

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



- NSTX software written to be transportable, e.g. to KSTAR
  - Discussed implementation on KSTAR

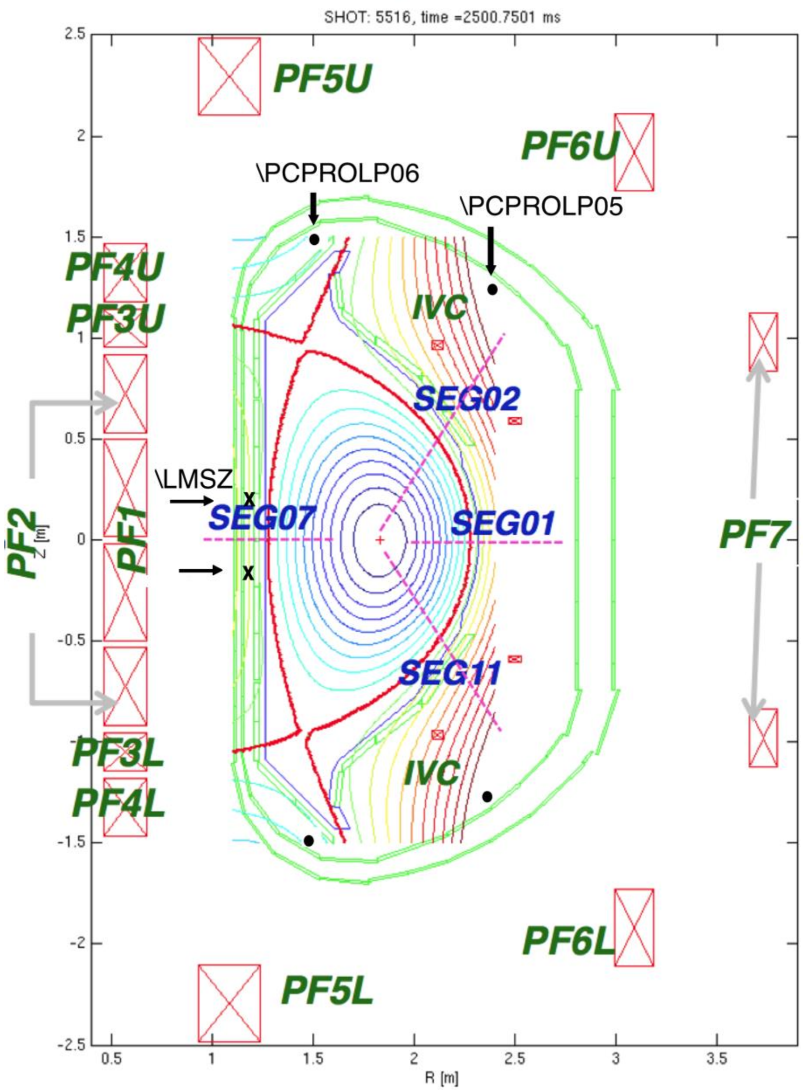
S.A. Sabbagh, et al., Nuclear Fusion **53** (2013) 104007

US-Korea collaboration on KSTAR on high beta and 3D plasma stability research having continued success

- Plasmas have reached and exceeded the n = 1 ideal no-wall limit for H-mode profiles for first time in KSTAR
- Open-loop rotation profile control has been demonstrated via n = 2 field application, and +ECH without mode locking
  - Aim toward future closed loop control, active research on NSTX-U
- ELM mitigation shown with n = 2 field using "middle" coil alone
- RWM control calculations indicate reasonable performance with compensated SL sensors
  - Improvements by using new sensor positions / state space controller
- Analysis continues, is expanding (e.g. TRANSP, M3D-C[1])
- Research plan includes higher β_N, lower V_ϕ (for ITER), stability and NTV understanding at long pulse in 2014 experiment

Supporting slides follow

Loop voltage differences - better, faster dz/dt signal

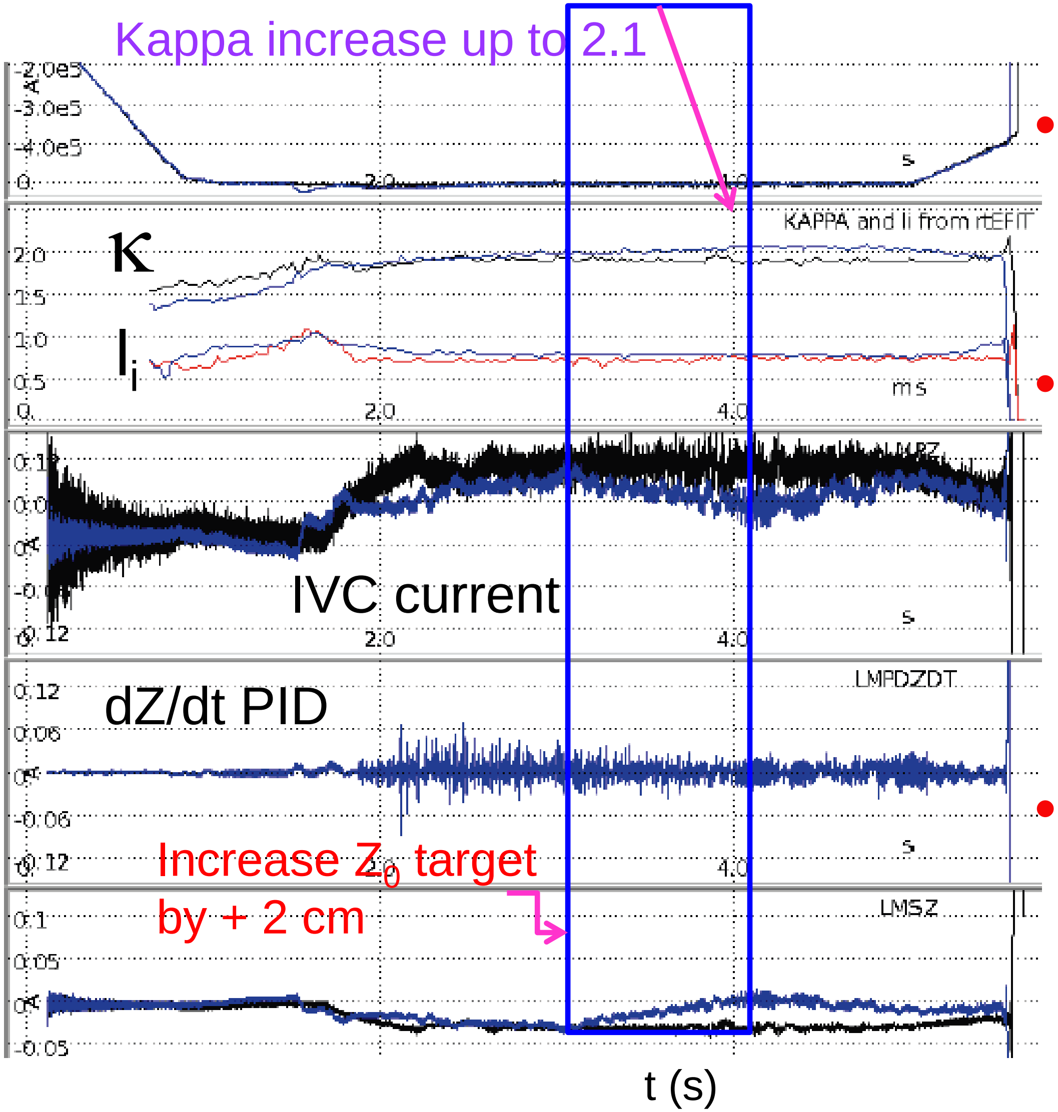


- The In-vessel Vertical Control (IVC) coil is used for fast control (~20 ms)
- Presently the fast z estimate (\LMSZ) is based on 2 magnetic probe sensors
  - On centerstack, near midplane
  - Shielded from plasma by passive plates
  - Integrated signals, similar in size, small difference
- Loop voltage differences provides reasonable dz/dt signals
  - Large in size, better signal to noise
  - May allow use of derivative-only term for IVC, reducing DC-offsets
  - Caveat: picks up poloidal fields and/or IVC itself
    - \PCPROLP05 must be compensated for IVC, for -06 it is not so important
    - pickup of SC coils is present, but is small compared to plasma motion for each pair
    - Noise spikes on some shots, must be resolved

D. Mueller (PPPL), S.H. Hahn (NFRI)

New dZ/dt control increased available kappa with suitable Z_0 target

Black = accomplishment in 2013
Blue = future work suggested



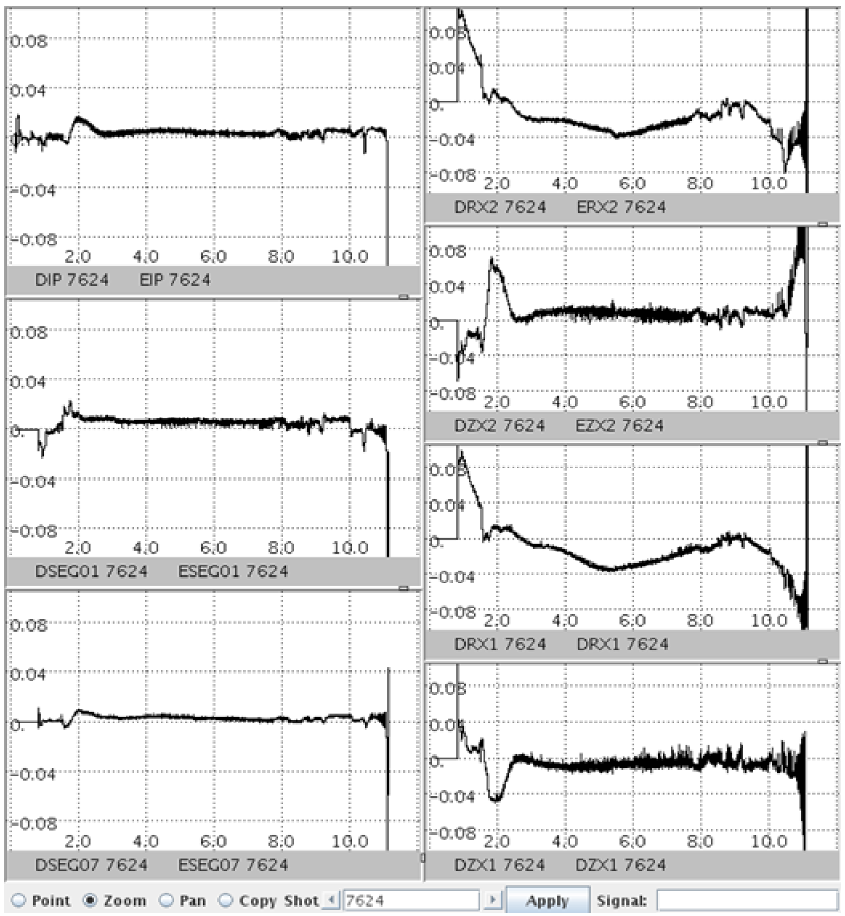
- Made a dZ/dt signal estimator with reasonable corrections
  - Need to validate against 2013 EFIT / SXR core information
- Implemented an experimental algorithm for using both Z and dZ/dt at the PCS
  - Need to deal with spike pickups, which origin is not clarified
  - Baseline noise (~20mVpp) needs to be removed
- Application of the algorithm enhanced available kappa
  - Z position control at faster CPU is inconsistent with isoflux (slower)
  - Need to modify PCS next year

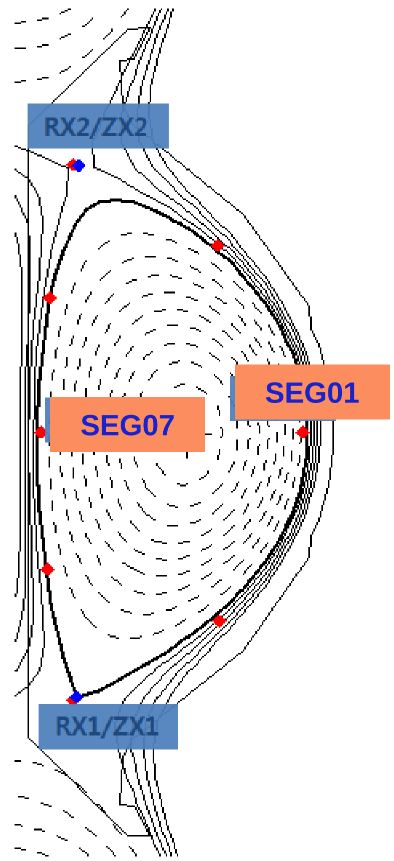
D. Mueller (PPPL), S.H. Hahn (NFRI)

Double-null shape is controlled only with control points

8-s of successful steady controls by the tuned control set:

Gains for plasma current (DIP), in- & out- board gaps (seg07, seg01) are tuned by relay feedback algorithm

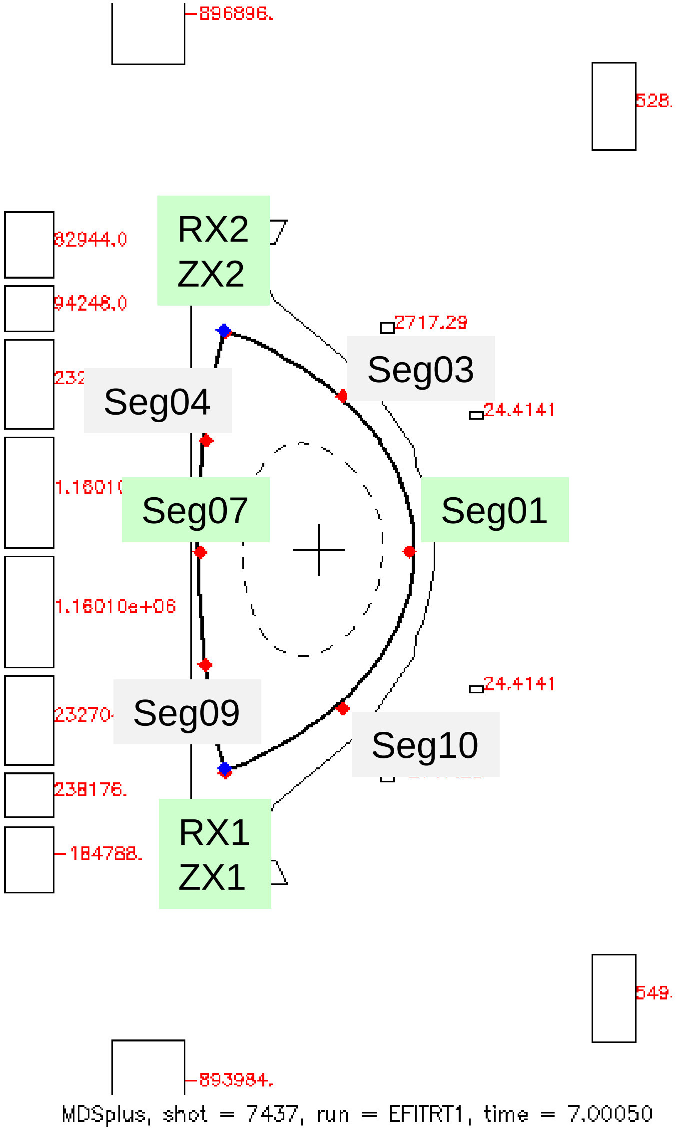




7624, run = EFITRT1, time = 3.55150

E. Kolemen (PPPL)

SISO configurations used for double-null shape [isodnull]



ISODNULL

Basic set:

all -> Plasma current (all coils)

PF3/4 or 3-4/4-5 -> RX/ZX for X-point positions

PF1/2 -> SEG07 (inboard gap)

PF6/7 -> SEG01 (outboard gap)

Optional: for drSep

PF6 -> Seg03/10 (75/285 deg)

PF3 -> Seg04-09

E. Kolemen (PPPL)

Vertical Control Summary

- Voltage loop differences successfully used in the fast vertical control loop (IVC)
  - Some evidence that higher Kappa was achieved
  - Run time limited ability to quantify the improvement
- Inconsistency in Z_0 between fast data and rtEFIT
  - Probable cause of vertical control oscillations below the stability limit
  - Resolving discrepancy reduces demand on IVC (and likely the control induced oscillations)
- Did not have time to attempt using only dz/dt feedback control for IVC
- Noise spikes are too short to be due to plasma motion, suspect noise from crates with ground shared with filter scopes

D. Mueller (PPPL), S.H. Hahn (NFRI)

Experiment MP2012-04-23-021 accomplished three key results

- Results Summary

A. Plasmas have reached and surpassed the n = 1 ideal no-wall limit computed and published for KSTAR with H-mode profiles

- High values of β_N up to 3, β_N/l_i > 3.8
- Published n = 1 no-wall limit is β_N = 2.5 at l_i = 0.7 (β_N/l_i = 3.57)

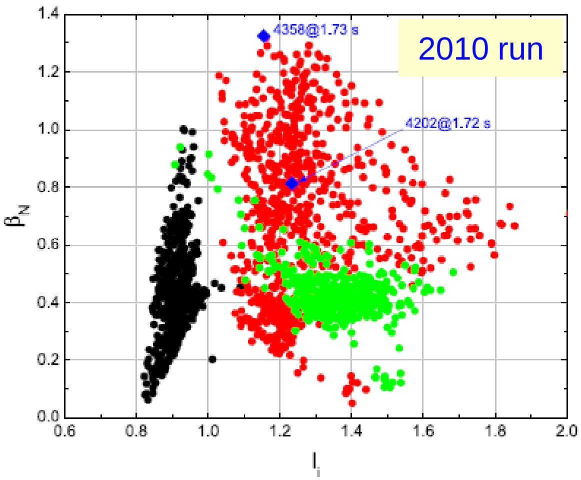
B. Plasma rotation has been significantly altered in a controlled manner with n = 2 applied 3D field

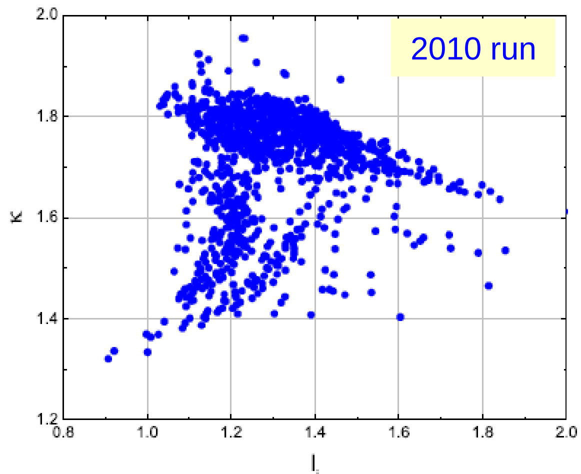
- Key for mode stability studies, and access to ITER-relevant rotation
- Utilized middle IVCC only (so far); ~ 50% reduction in core rotation
- H-mode rotation profile shape is altered by n = 2 field

C. ELM mitigation found using n = 2 fields with midplane IVCC alone

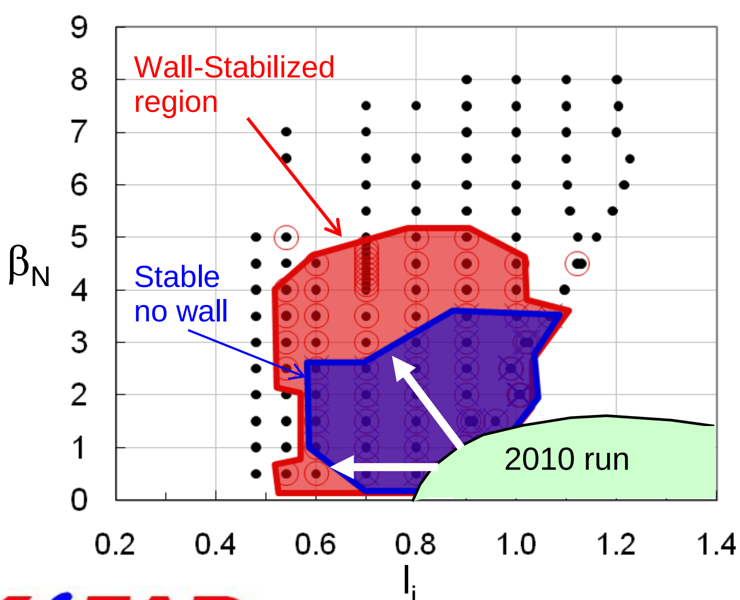
- Challenges ELM stabilization hypotheses that require applied field that aligns with field line pitch (e.g. off-midplane coils)

Experiment to reach and surpass n = 1 no-wall limit in KSTAR planned since (at least) 2010



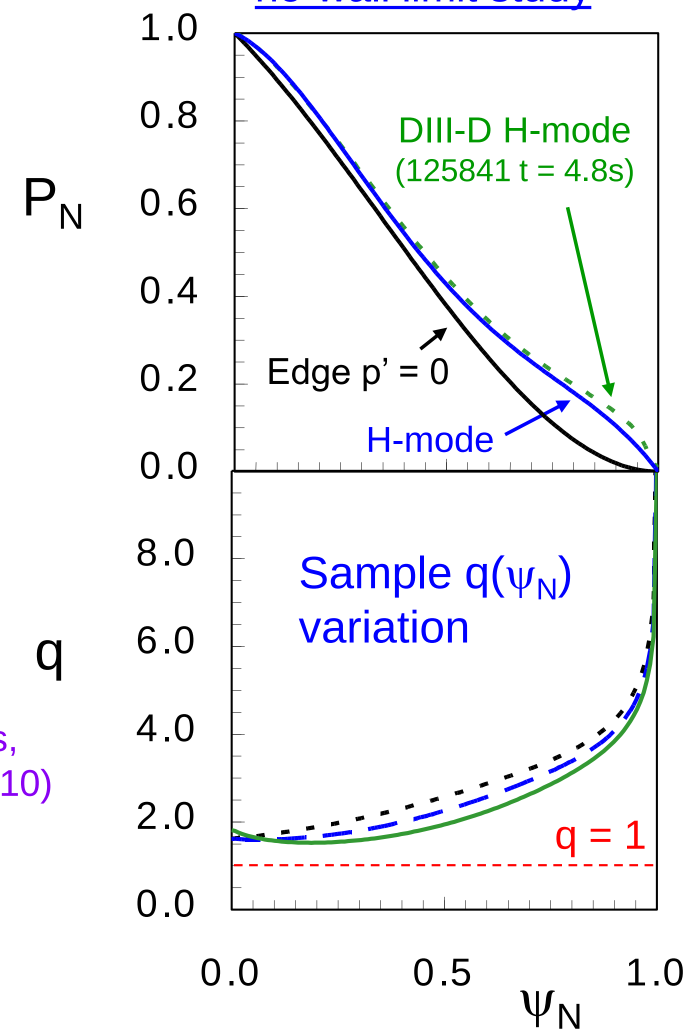


Y.S. Park, et al., Nucl. Fusion **51** (2011) 053001



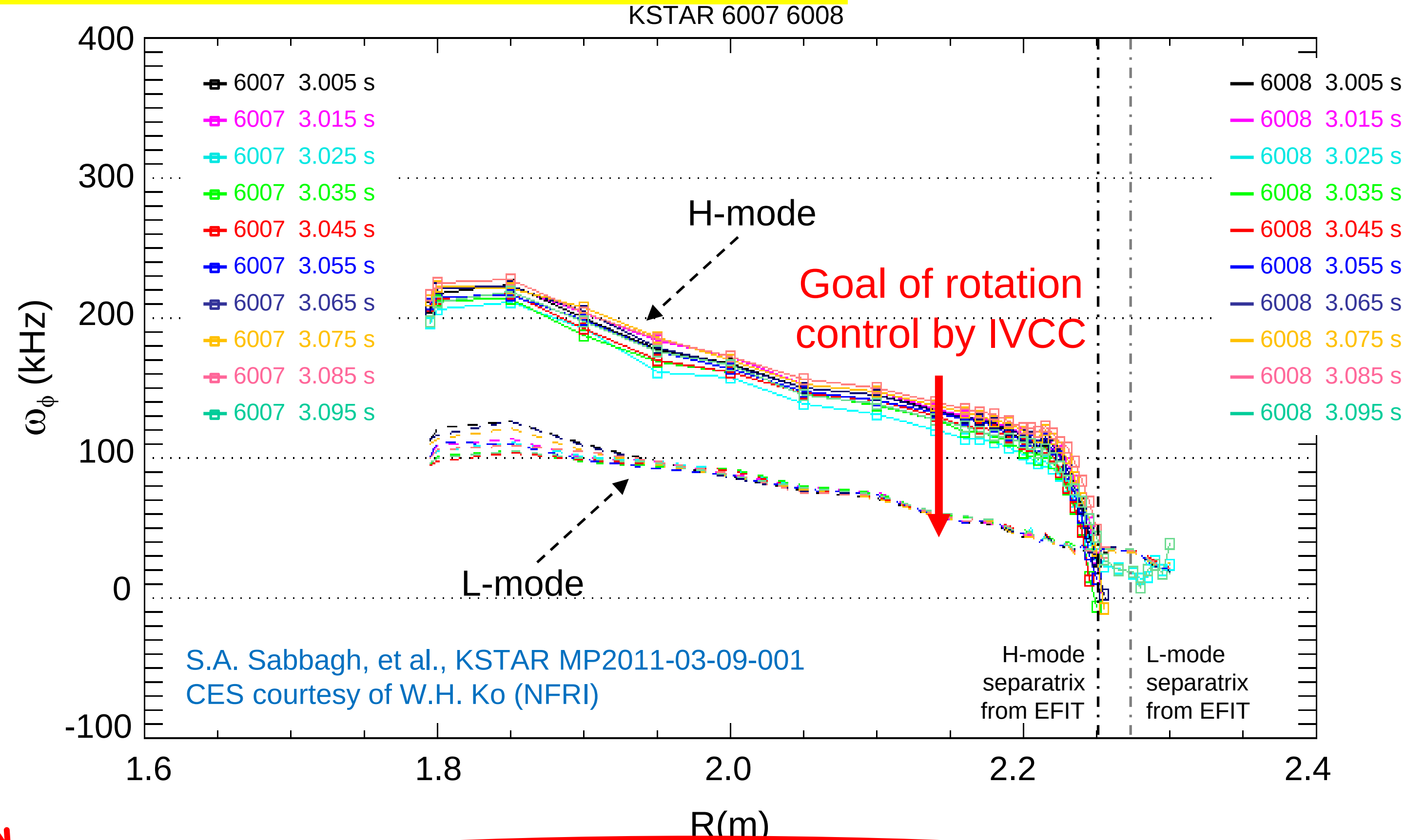
Projected n = 1 ideal stability for KSTAR H-mode plasmas (O. Katsuro-Hopkins, et al., NF **50** (2010) 025019

Profiles used in ideal MHD no-wall limit study



H-mode / L-mode rotation profiles considerably different in KSTAR – a positive characteristic for physics studies

Slide from 2012 KSTAR Conference (Muju)

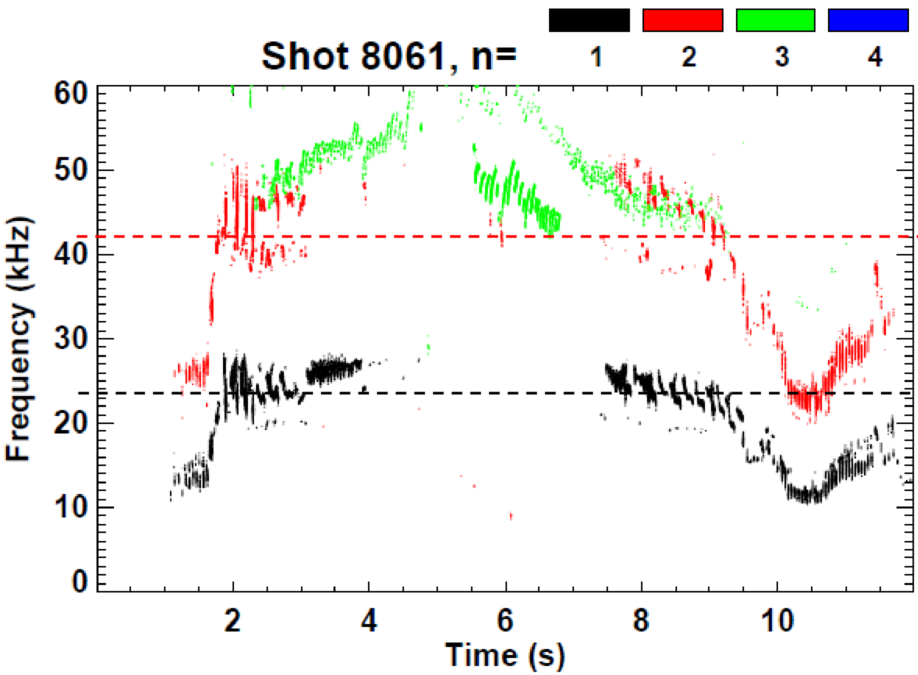


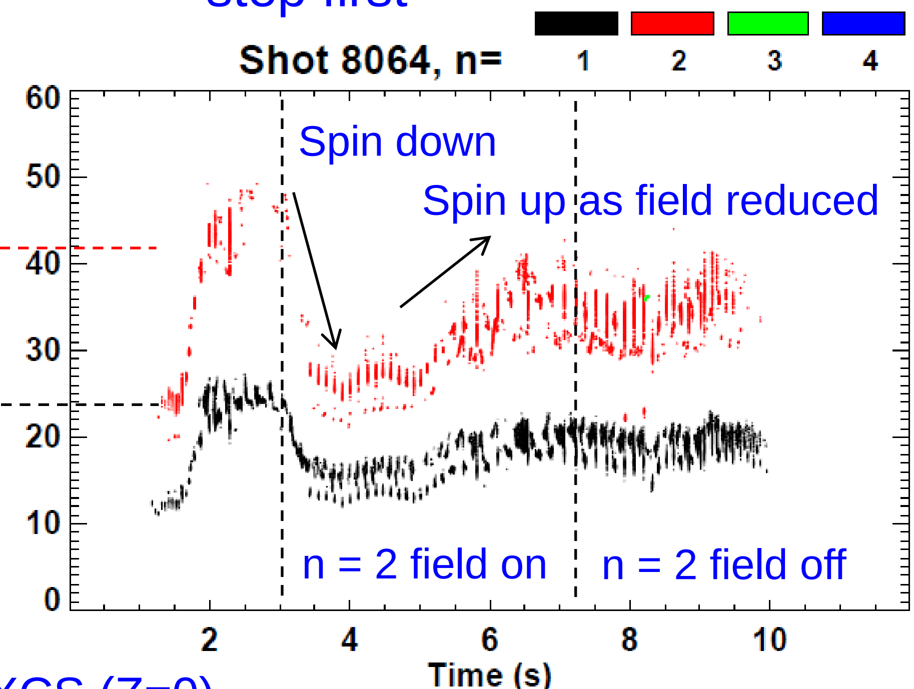
- Develop a method to change rotation profile from H-mode to L-mode like shape (NTV type non-resonant braking) by applied field from IVC

Open-loop rotation control with n = 2 IVCC current produced: V_ϕ decreased, then increased

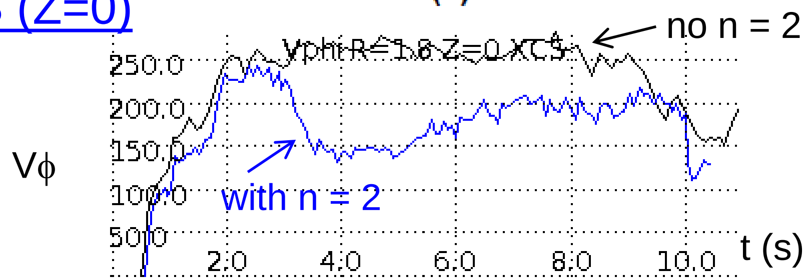
No IVCC n > 0 field

With IVCC n = 2 field – large step first





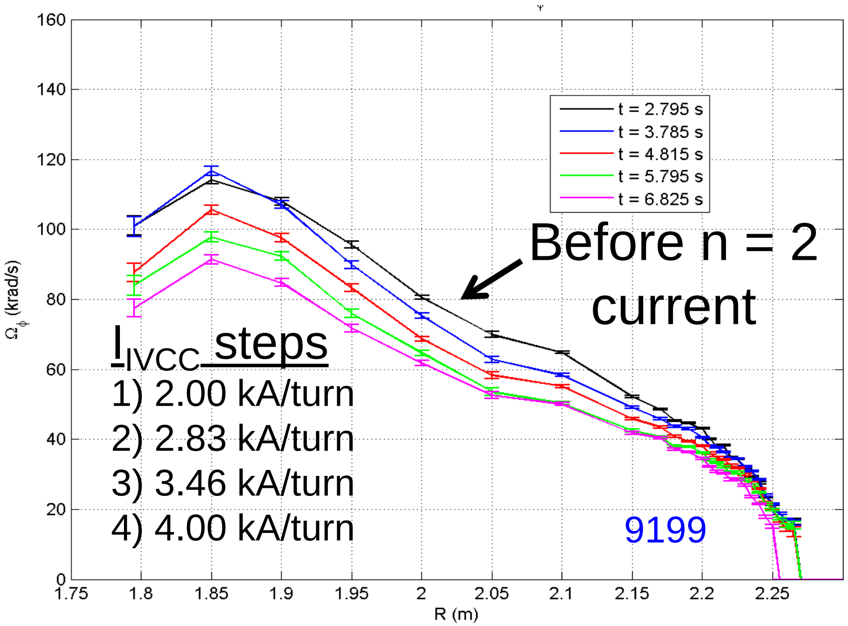
XCS (Z=0)



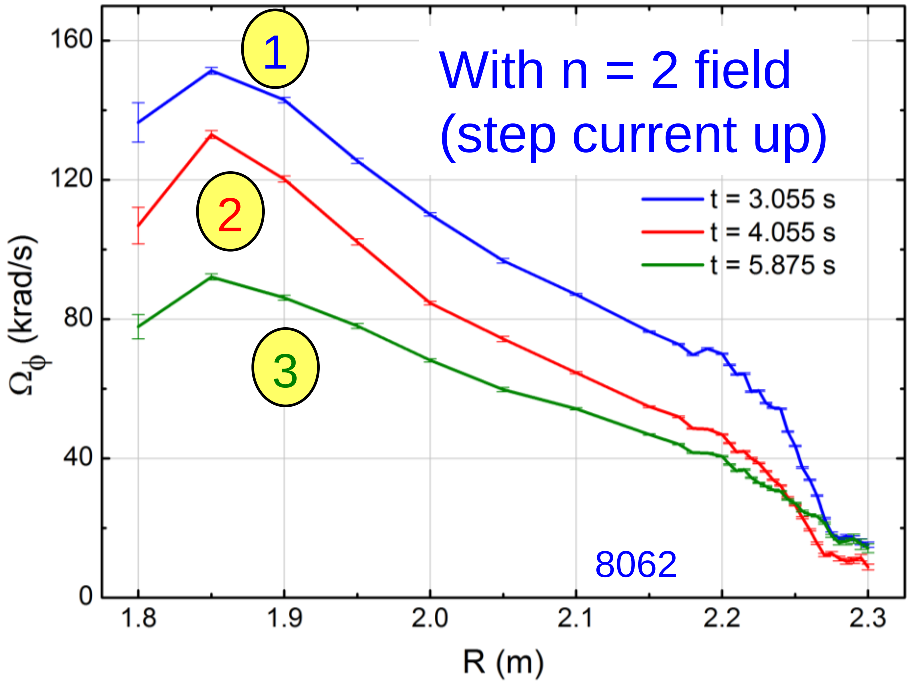
- Low frequency MHD mode rotation frequency decreased by 40 - 50% without mode locking

Percentage reduction on V_ϕ apparently larger in 2012 experiment

Toroidal rotation profile evolution (middle IVCC (n = 2)): 2013



Toroidal rotation profile evolution (middle IVCC (n = 2)): 2012



- Might be explained by a lower stored energy (lower Ti) in present experiments
  - This is one of the experimental objectives, further analysis will determine this

Experiments MP2013-05-03-003; MP2012-04-23-021