MP 2012-04-23-021: Long-Pulse Low Rotation Plasma Investigation for ITER Applicability and Instability Characterization in KSTAR High Normalized Beta Plasmas

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Brief Run Summary

Presented to NSTX Research Team

December 3rd, 2012

PPPL

MP2012-04-23-02: expand KSTAR high β_N operating space, investigate instabilities, examine low ω_ϕ

- Motivation
  - Investigate plasma stability in regimes most relevant to ITER, while making connection with present tokamaks
    - Lower l_i, higher β_N, varied (lower) plasma rotation, ω_ϕ
    - New 2012 KSTAR capabilities will allow significant new results

- Overall Goals

✓
1. Approach n = 1 stability limit using 2nd NBI source
   - Key goal for KSTAR to demonstrate high stability performance to world community
2. Examine MHD mode stability vs. ω_ϕ by further demonstrating ω_ϕ reduction by non-resonant neoclassical toroidal viscosity (NTV)

   ½ done
   - Critical for direct applicability of KSTAR plasmas to ITER
   - Key precursor to rotation and active n = 1 mode control physics studies in KSTAR
3. Investigate physical elements of NTV that are presently not well established and are unique to KSTAR device capabilities

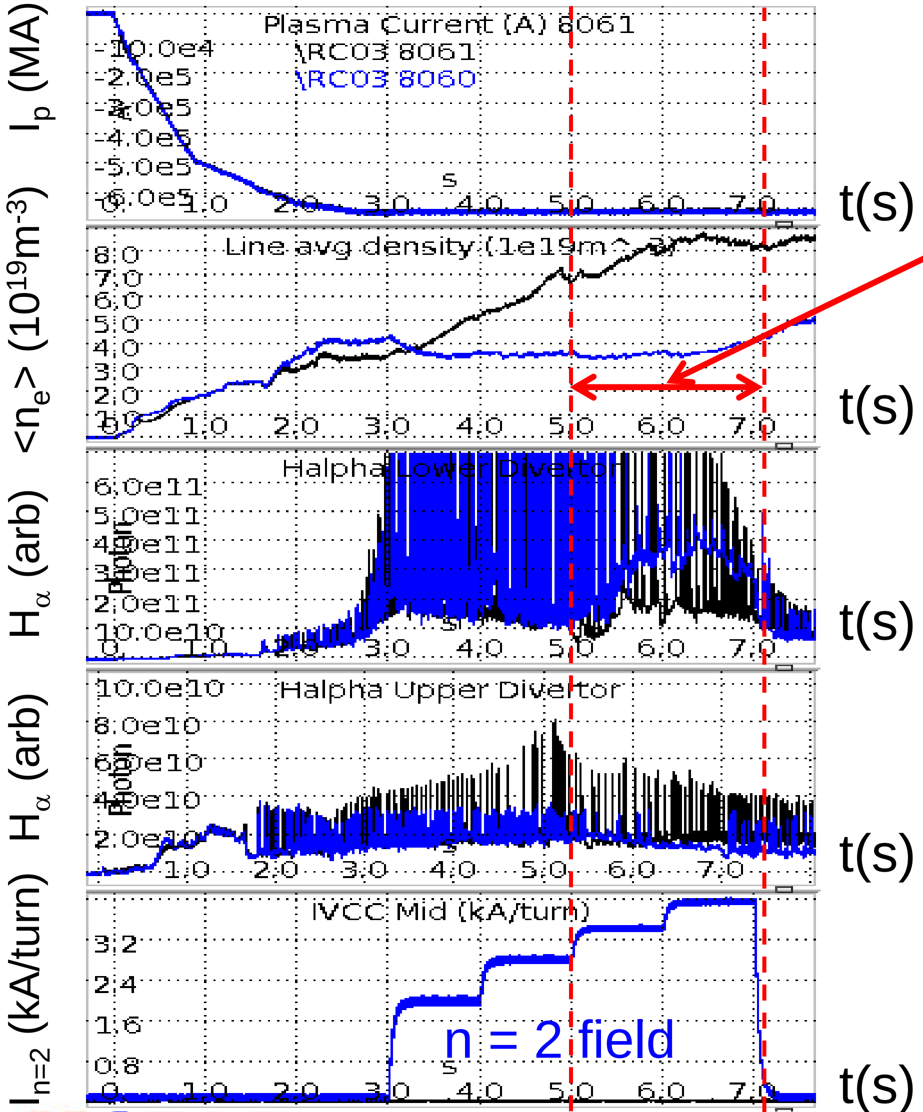
   ½ done
   - Examination of neoclassical steady-state rotation speed
   - Dependence of NTV torque on plasma collisionality (not done due to time)

← Incomplete due to lost run time, not an issue with physics

Even with an incomplete run, MP2012-04-23-021 generated important results so far

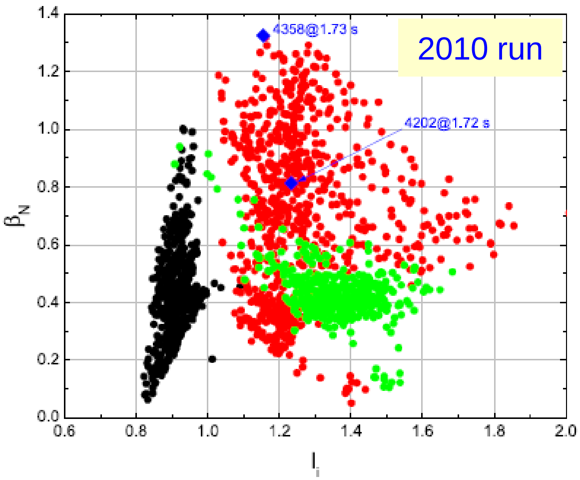
- Brief results summary
  1. ELM mitigation found using n = 2 fields with midplane IVCC alone
     - Challenges ELM stabilization hypotheses that require applied field that aligns with field line pitch (e.g. off-midplane coils)
  2. Plasmas have reached and surpassed the n = 1 ideal no-wall limit computed and published for KSTAR with H-mode profiles
     - High values of β_N up to 2.9, $\beta_N/l_i > 4$
     - Published n = 1 no-wall limit is $\beta_N = 2.5$ at $l_i = 0.7$ ($\beta_N/l_i = 3.57$)
  3. 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
     - Plan to run with top/bottom coils, and all coils not completed due to time
       - Two shots were taken with middle/bottom, and top/bottom (results were unexpected, but inconclusive)

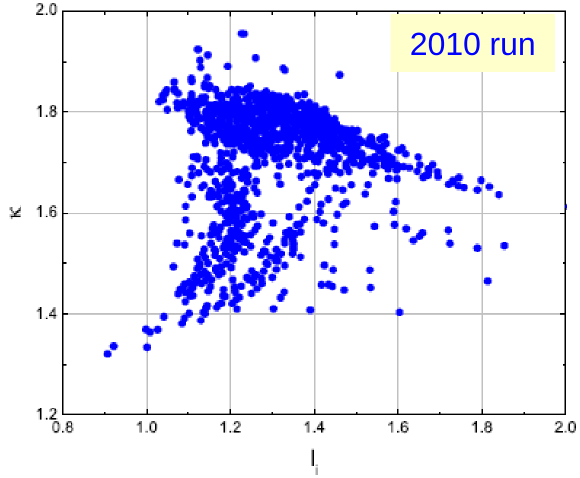
1. ELM mitigation found when using n = 2 field via middle IVCC only



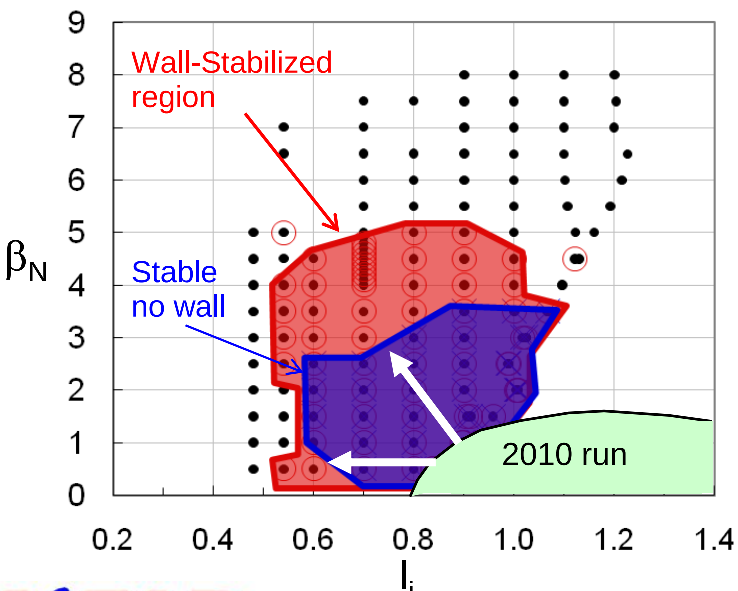
- Mitigation observed when sufficiently high n = 2 field is applied
  - I_{Ivcc} > 3 kA/turn
    - Note: not possible to see in 2011 due to 1.8 kA/turn limit
  - Reduction in density observed at start of n = 2 applied field
    - Need to verify validity of density evolution

Experiment to reach and surpass n = 1 no-wall limit in KSTAR planned since (at least) 2010 (from Muju meeting 2011)





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



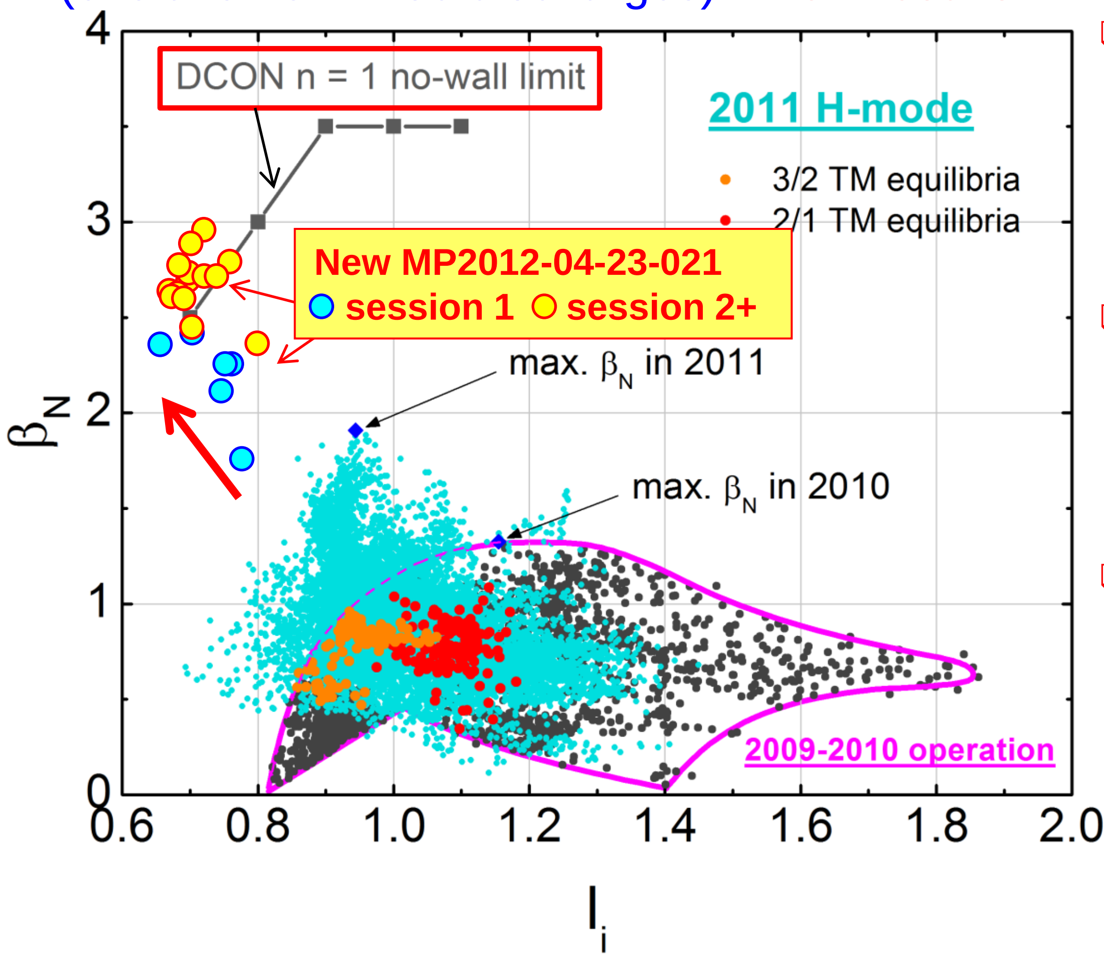
Projected n = 1 ideal stability for KSTAR H-mode plasmas (O. Katsuro-Hopkins, et al., NF **50** (2010) 025019)

- Highlights
  - Initial H-mode and NBI have reached β_N ~ 1.3, but…
  - …results reached at relatively high l_i
    - Ideal MHD (DCON) shows plasma to be stable to n = 1 mode
    - Ideal $\beta_N^{no-wall}$ ~ 2.5 at l_i ~ 0.7
    - High l_i is less stable to vertical instability
  - Key motivation to decrease l_i

2. Plasmas have passed the predicted "closest approach" to the n = 1 ideal no-wall stability limit: l_i = 0.7, β_N = 2.5

KSTAR equilibrium operating space 2009 – 2011

(evolution of > 130 discharges) + new results

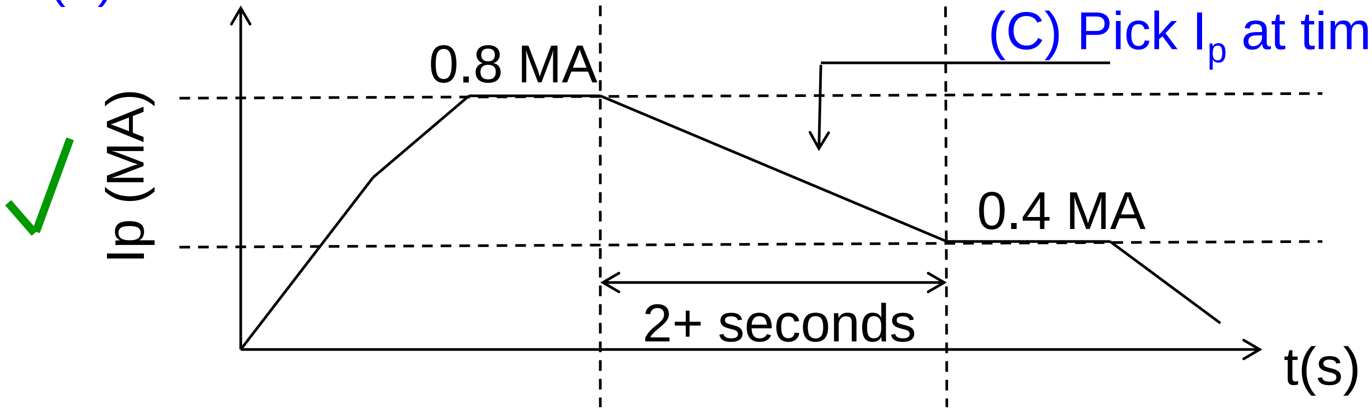


- Target plasma modified from YoungMu Jeon XP on 09-Nov-12
- I_p scan performed to determine "optimal" β_N vs. I_p
  - B_T in range 1.3 - 1.5T
  - β_N up to 2.9
- β_N/l_i = 4.1 (a 100% increase from 2011)
  - a high value for advanced tokamaks, e.g. for DIII-D
- Mode stability
  - Target plasma is at 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

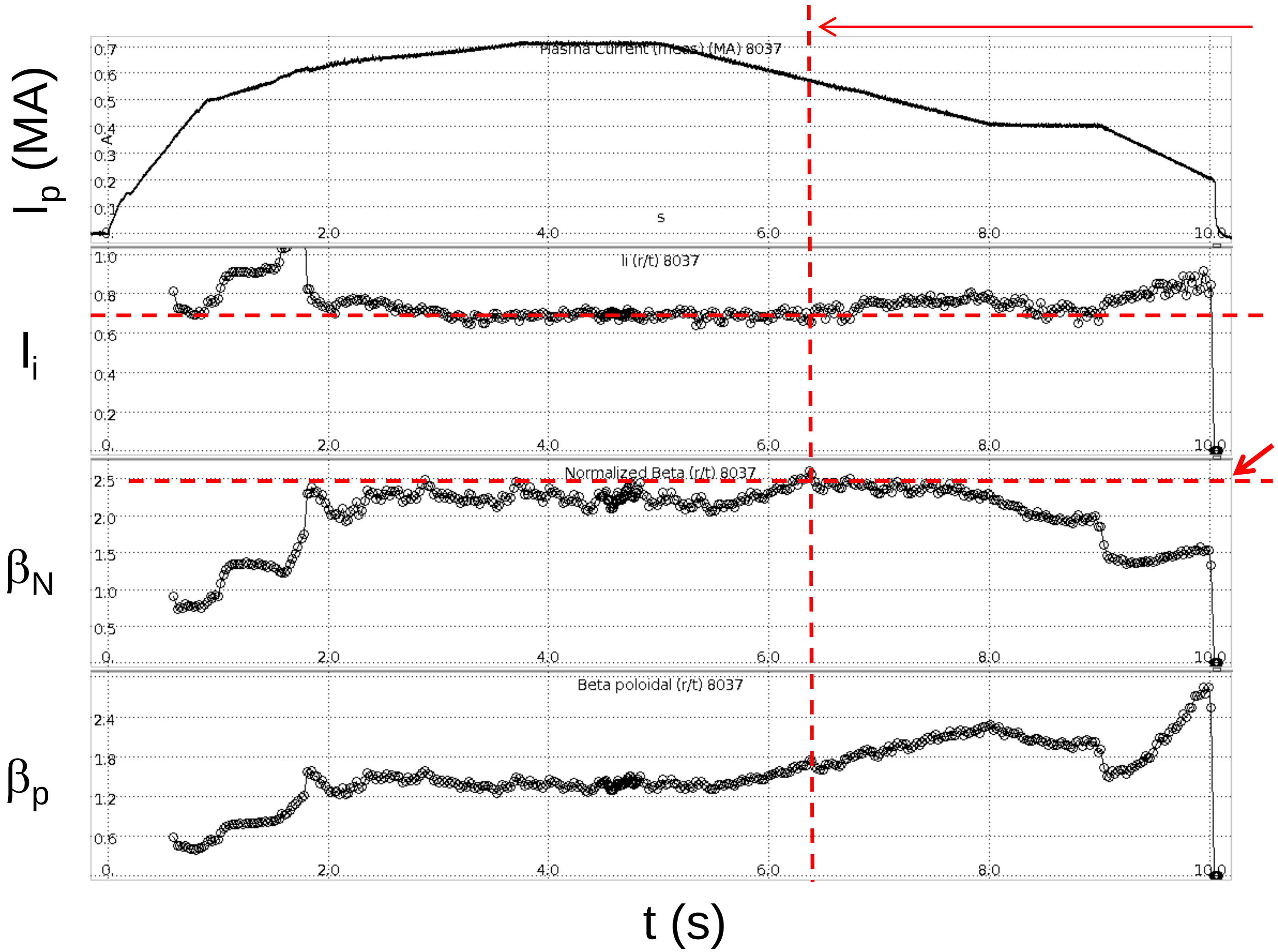
First step in MP04-23-021: Determine "optimal" I_p for β_N

1) Approach n = 1 ideal no-wall stability limit and characterize plasma instabilities
   (A) (NOTE: use Ip and NBI waveform as in shot 7966, Bt = 1.7T)
   (B)

(C) Pick I_p at time of maximum β_N

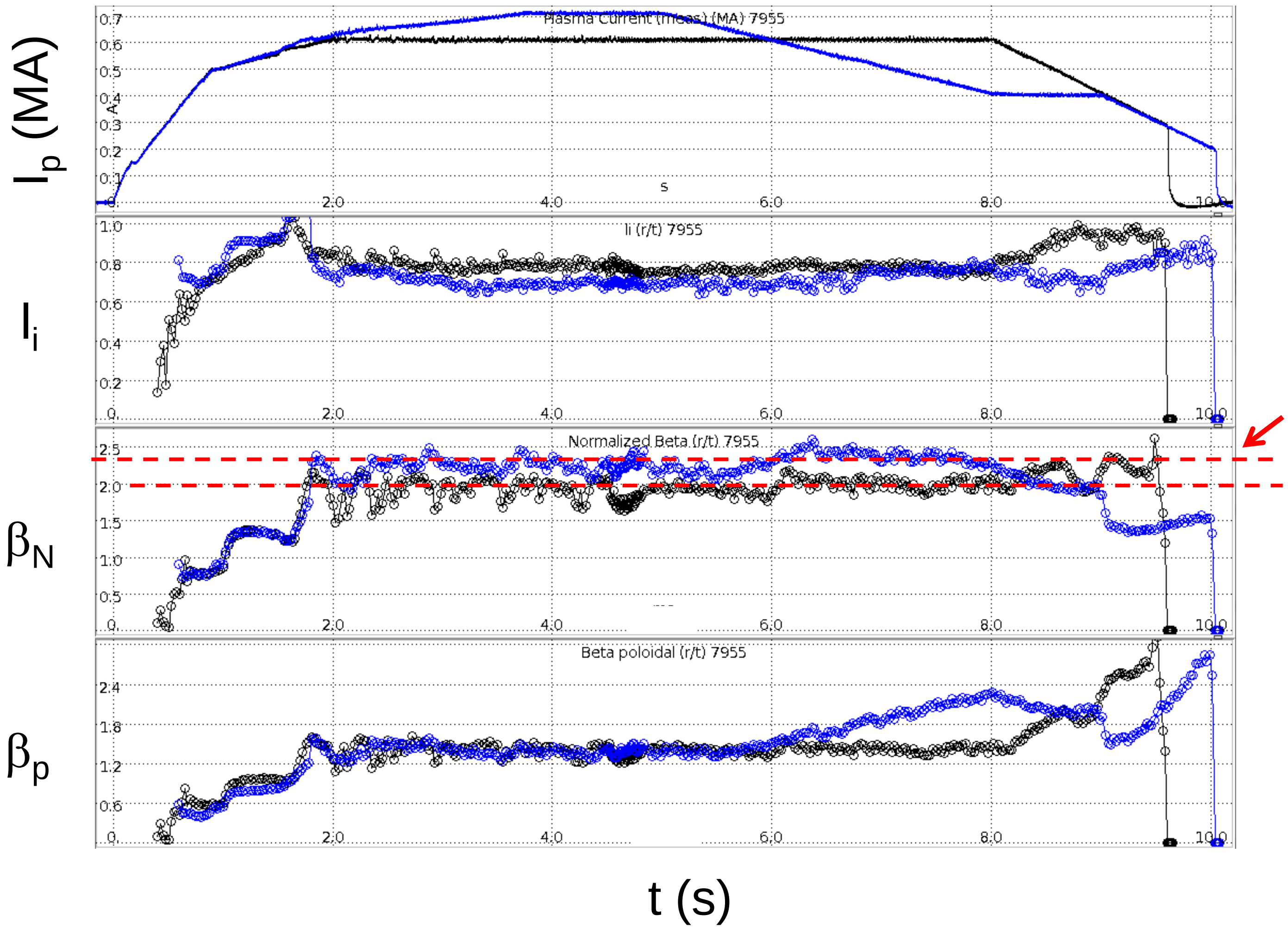


Weak dependence of β_N vs. I_p found in experiment



- "Optimal" I_p for maximum β_N is approximately 0.55 MA
  - But higher I_p has lower l_i
- Low l_i ~ 0.7 sustained
- Steady β_N, with max ~ 2.5
  - rtEFIT shown
  - Full KSTAR EFIT shows same value
  - Constant β_N expected for scaling $\tau_E \sim I_p$

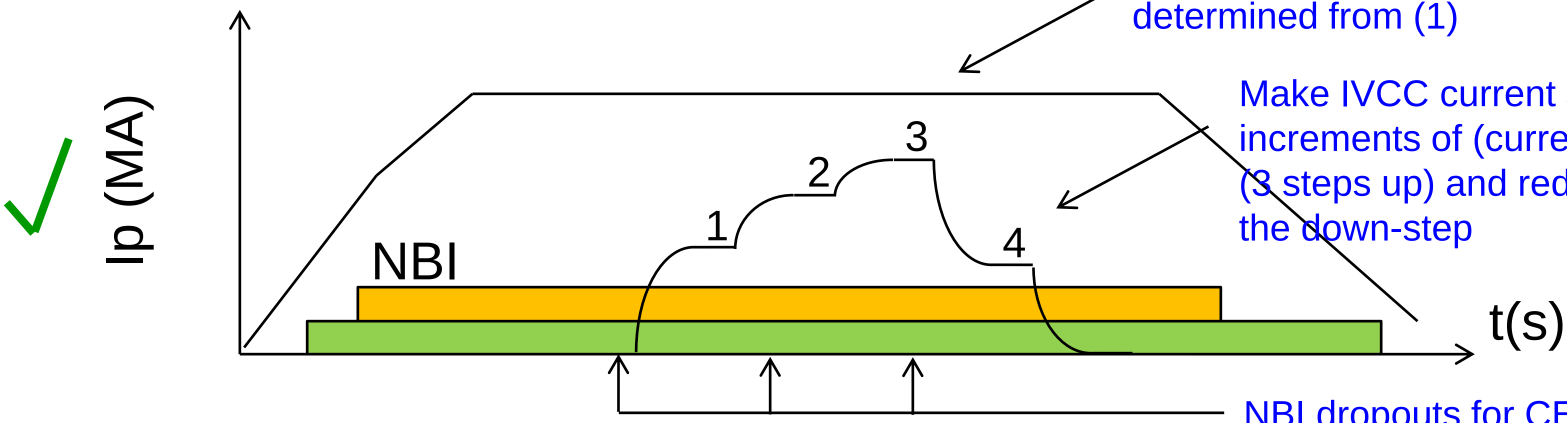
B_T scaling accounts for β_N increase



- Present shot 8037, B_T = 1.6T
- Comparison shot 7955, B_T = 1.8T
- Expected β_N = (1.27)*2.0 = 2.5
- Expected at B_T = 1.5T: β_N = 2.9
    - Gives β_N/l_i = 4

Step increases in n = 2 field used to alter $V_\phi(R)$ non-resonantly in MP04-23-021 with IVCC

2A) 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")

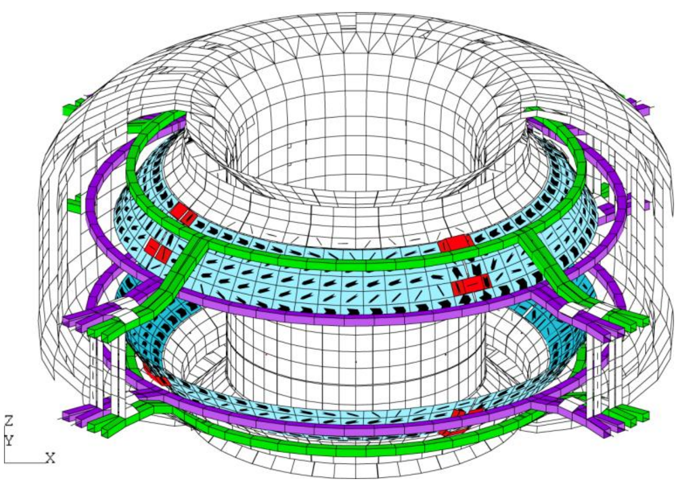
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\omega_\phi - \omega_{NC}) I_\lambda$$

$T_i^{5/2}$

Inverse aspect ratio

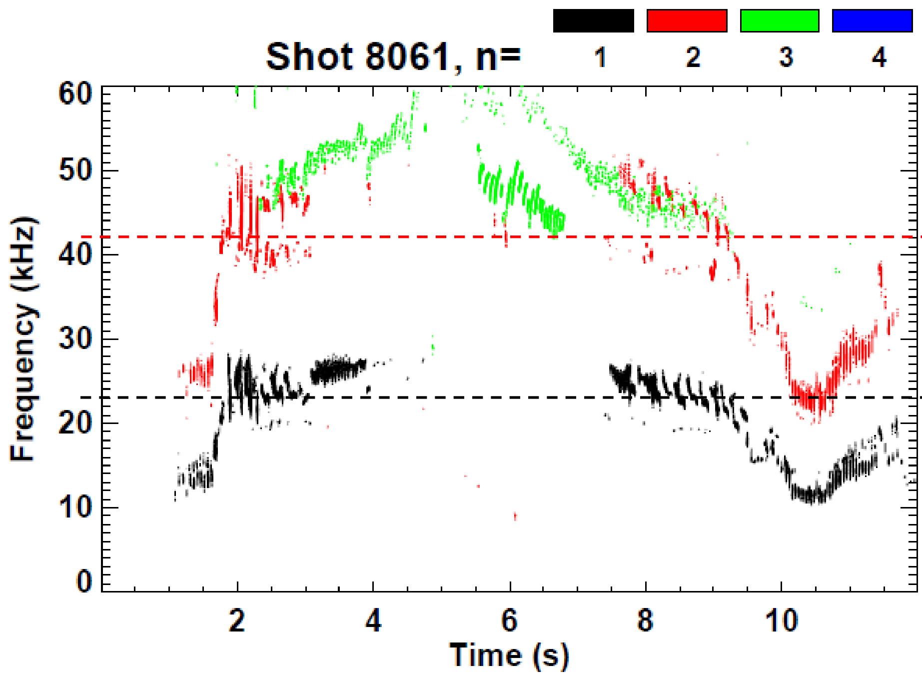
Steady-state velocity

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

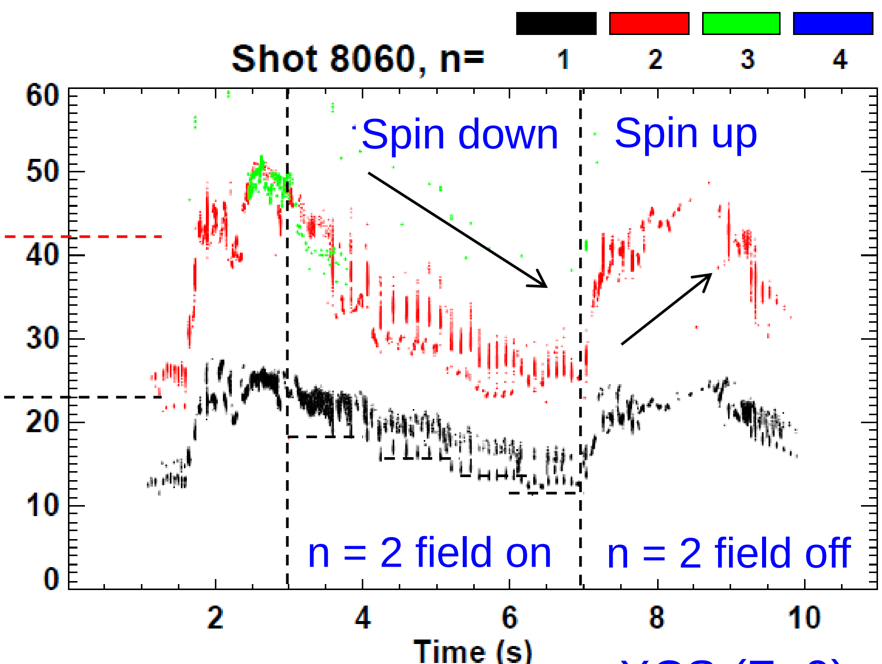


3. Effect of step increases in n = 2 IVCC current observed in mode frequency, XCS rotation data

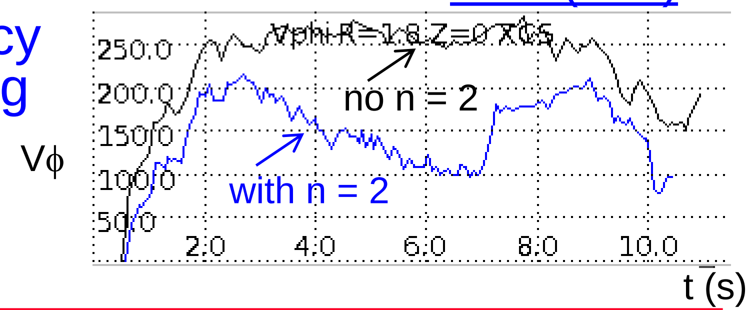
No IVCC n > 0 field



With IVCC n = 2 field



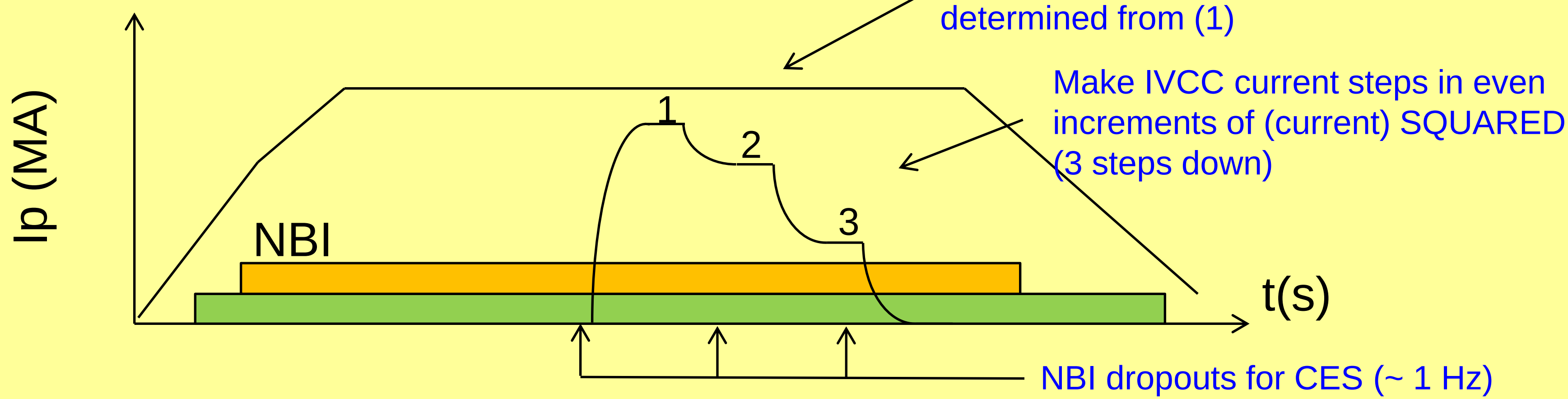
XCS (Z=0)



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

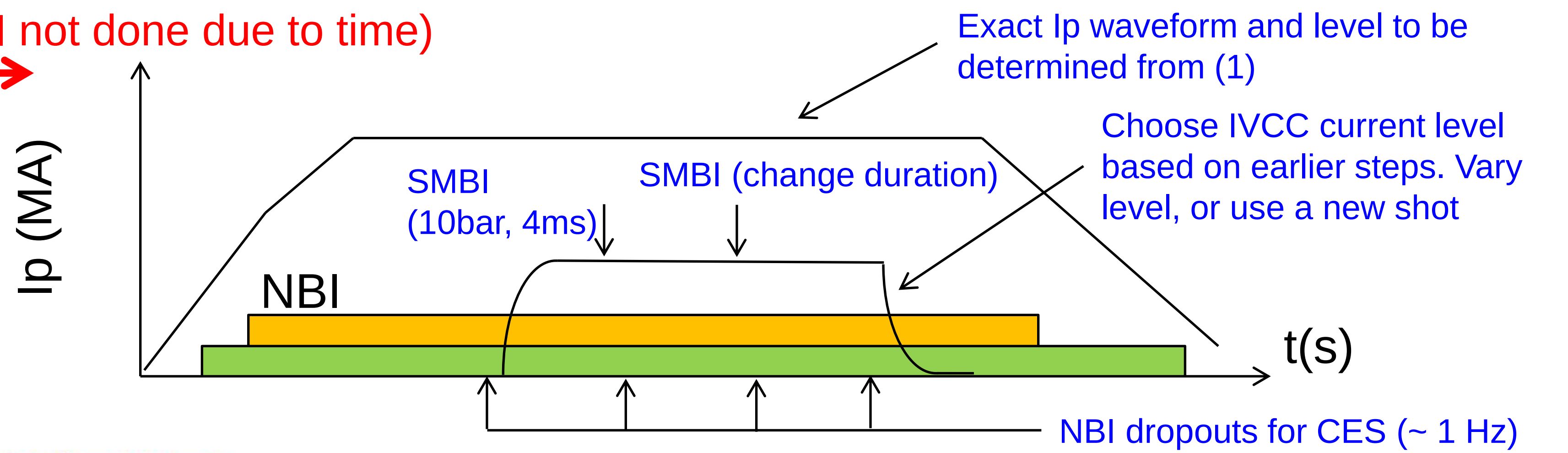
Schematic waveforms and timing - MP2012-04-23-021

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



4) Examine dependence of NTV on collisionality

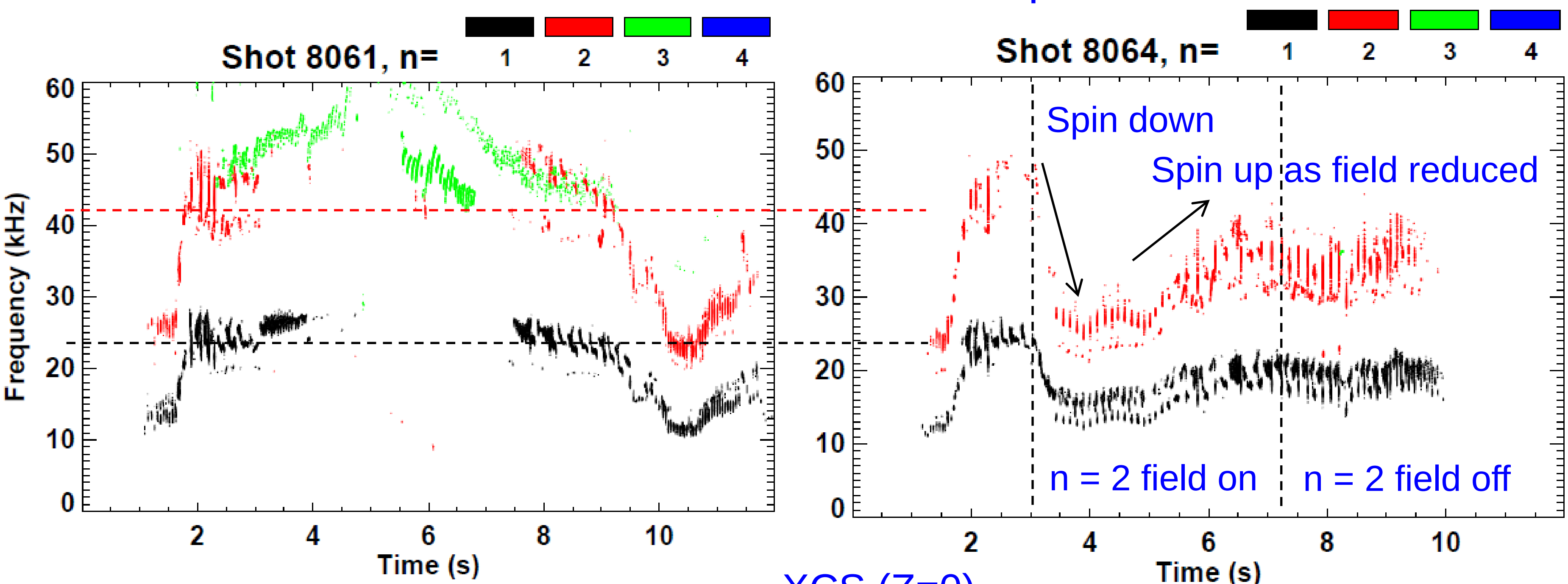
(SMBI not done due to time)



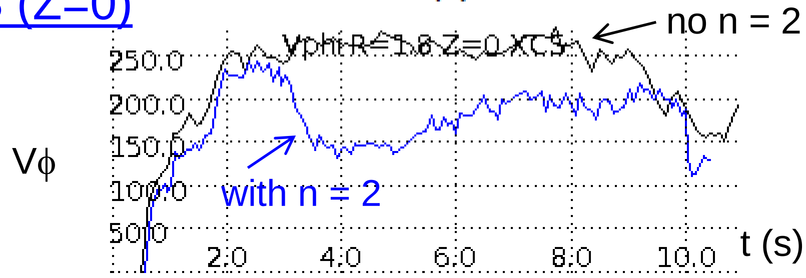
Effect of step increases in n = 2 IVCC current observed in mode frequency, XCS rotation data

No IVCC n > 0 field

With IVCC n = 2 field – large step first



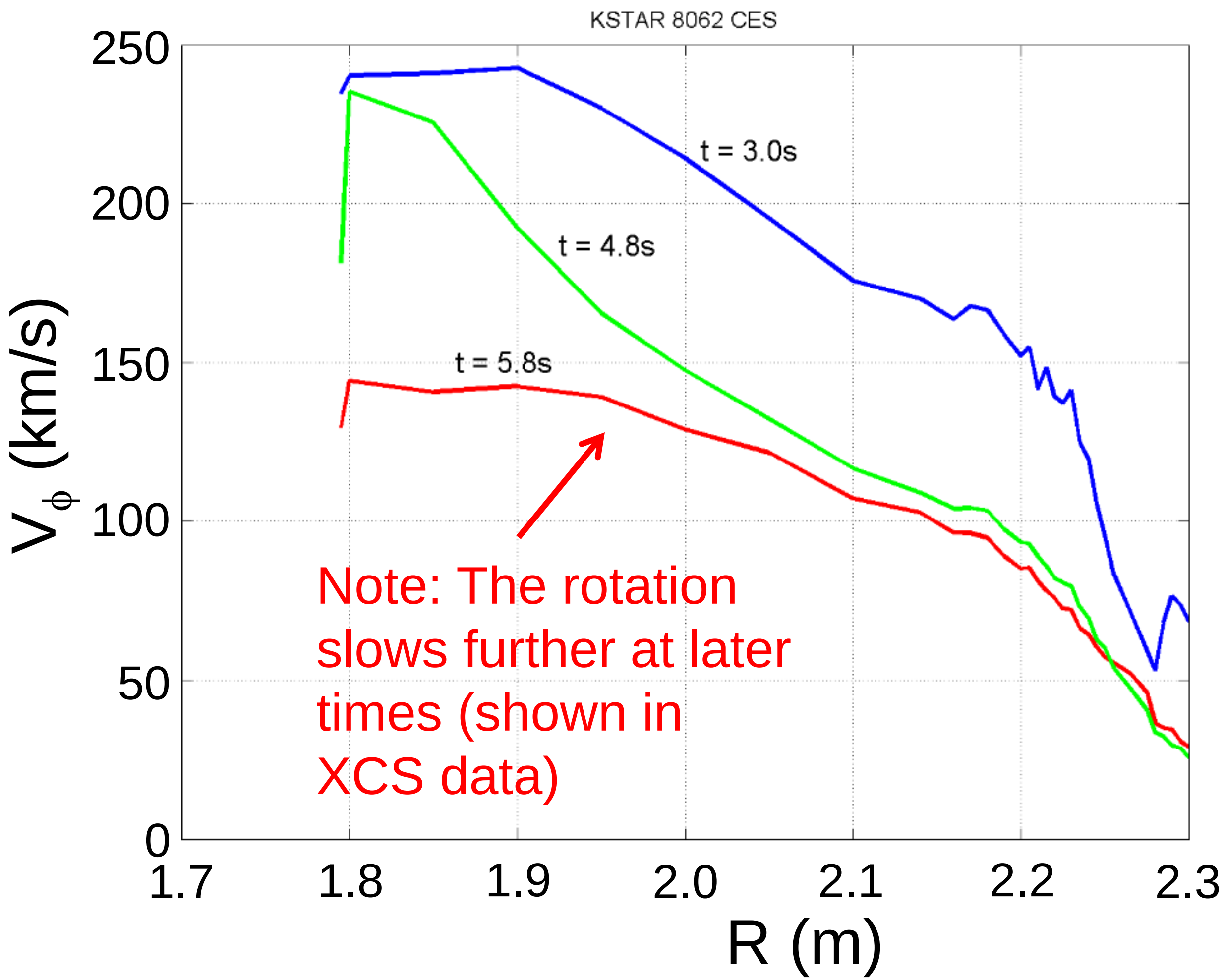
XCS (Z=0)



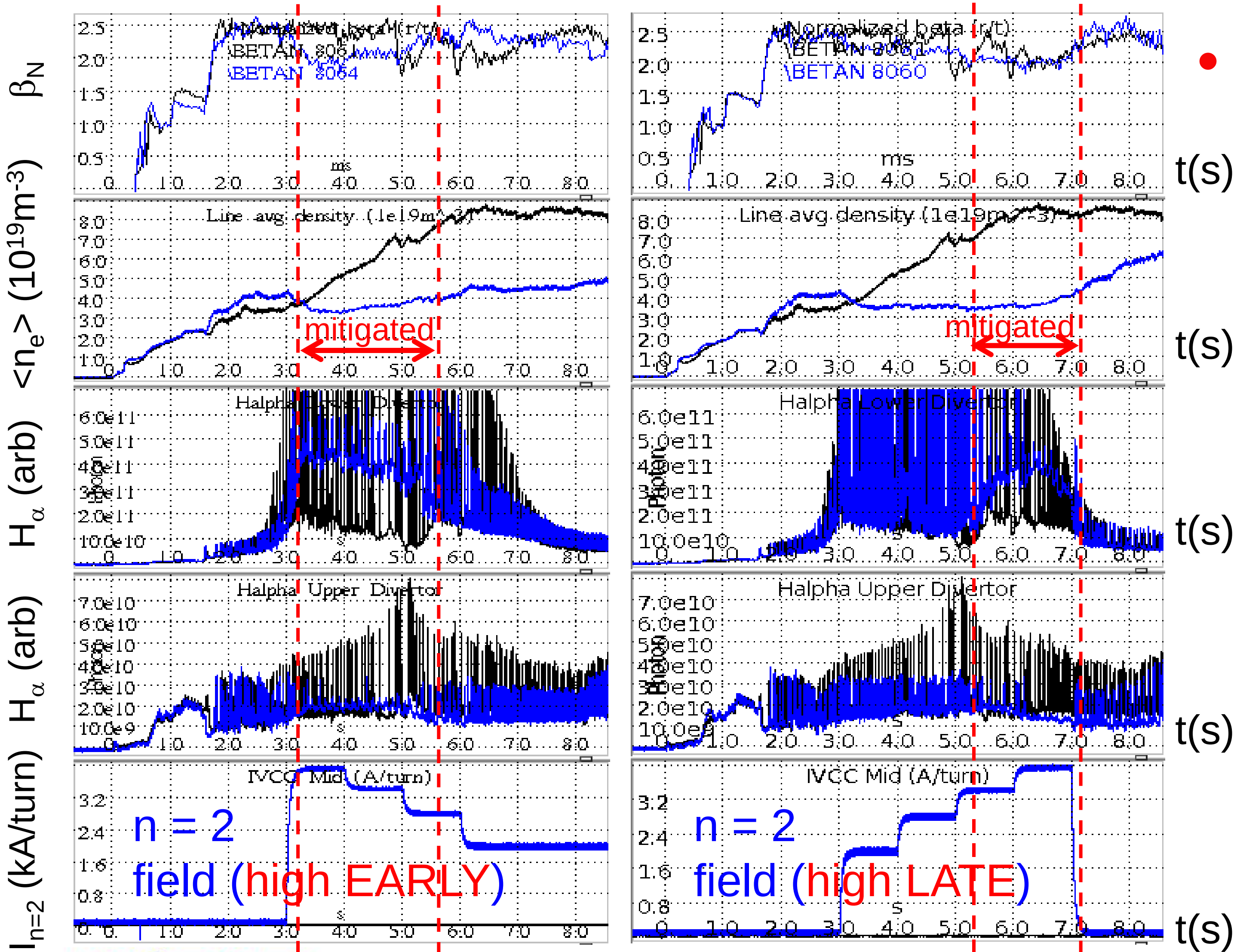
- Low frequency MHD mode rotation frequency decreased by 40 - 50% without mode locking

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

- Significant alteration of rotation profile using middle IVCC coil alone
- Further analysis of CES data required to determine if braking is primarily non-resonant
  - Any mode activity observed does not lock

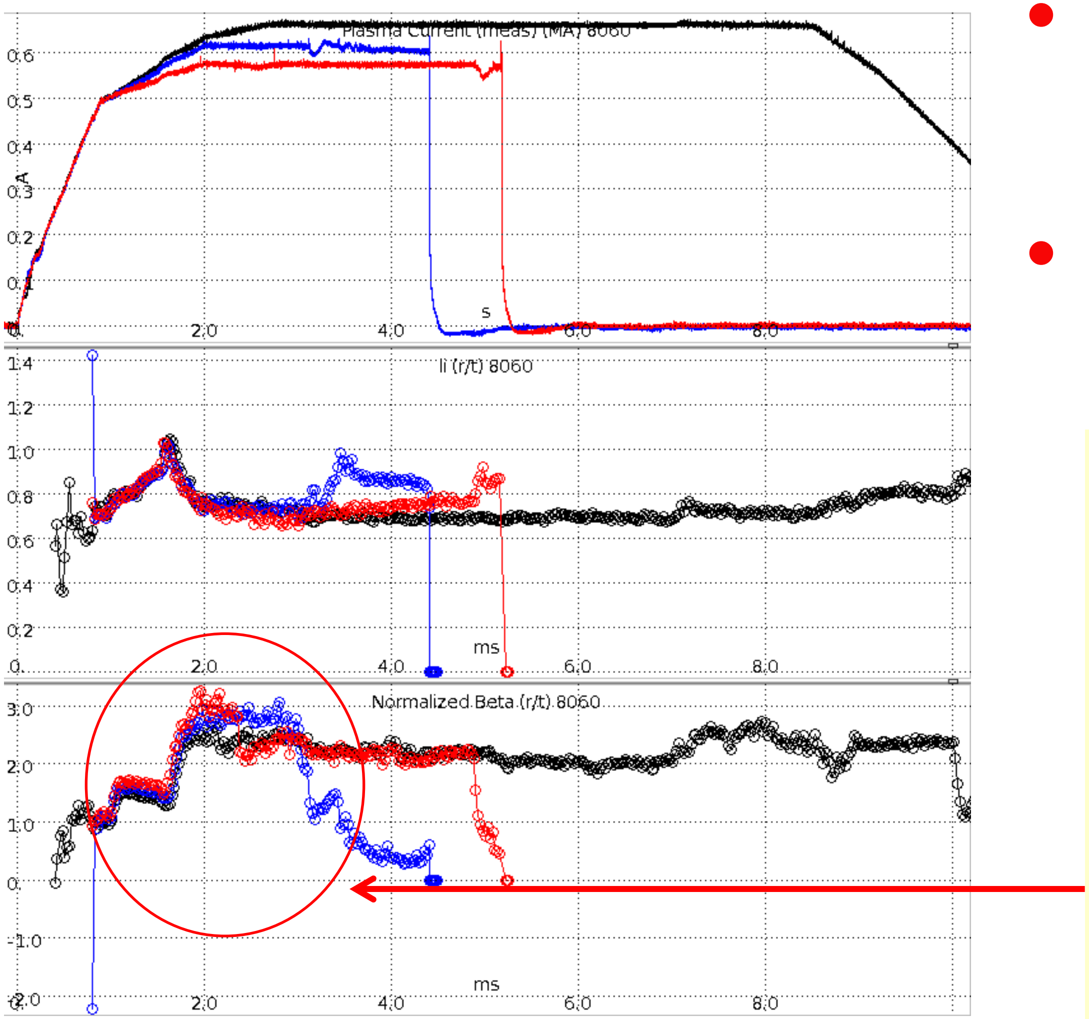


ELM mitigation found using n = 2 field, via middle IVCC only, correlates with field strength



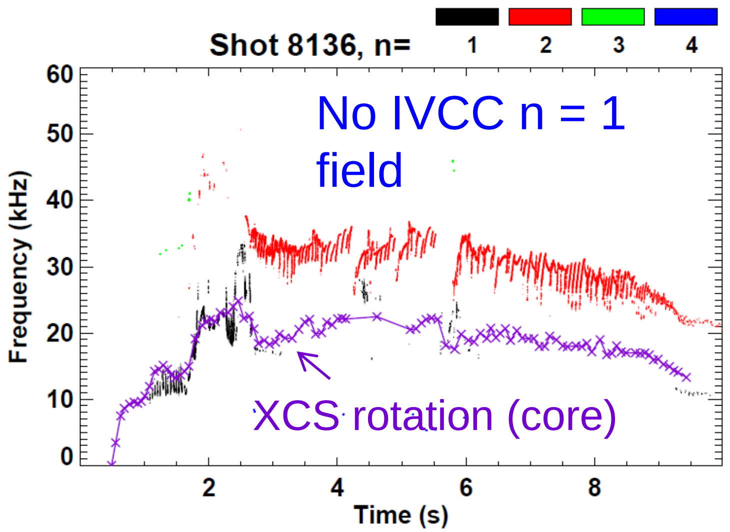
- Mitigation observed when sufficiently high n = 2 field is applied
  - Stored energy, β_N varies
  - However, shot that has continuous ELMing with no n = 2 field has same β_N variation

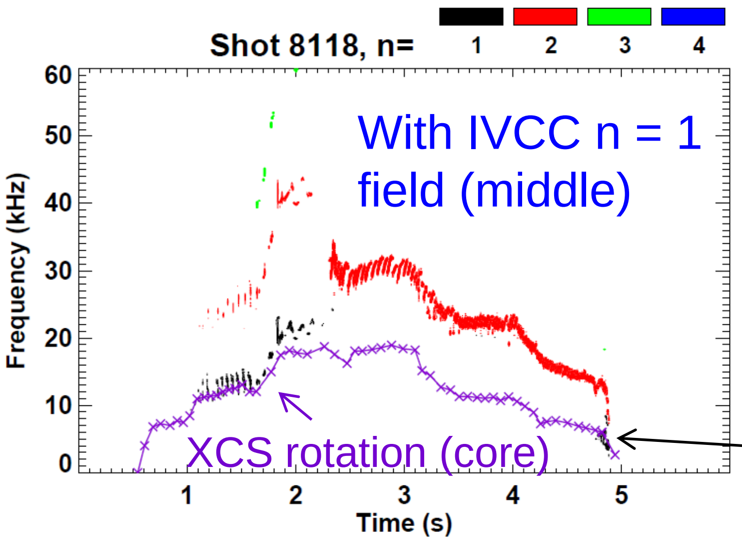
Extra 2 shots given to MP2012-04-23-021 on 11/19/12 (transiently) yielded yet higher β_N



- Toroidal field further reduced – plasmas started up successfully
- Only 2 shots, could not adjust to have them run long pulse
  - for KSTAR, these are "transient" results
  - rtEFIT values – DRAFT VALUES ONLY!
  - B_T = 1.4T, I_p = 0.6 MA
    - β_N = 2.96; β_N/l_i = 4.1
  - B_T = 1.3T, I_p = 0.563 MA
    - β_N = 3.2; β_N/l_i = 4.5
    - Shot sustained, not β_N

Final 4 shots given to MP2012-04-23-021 on 11/19-20/12 were very informative



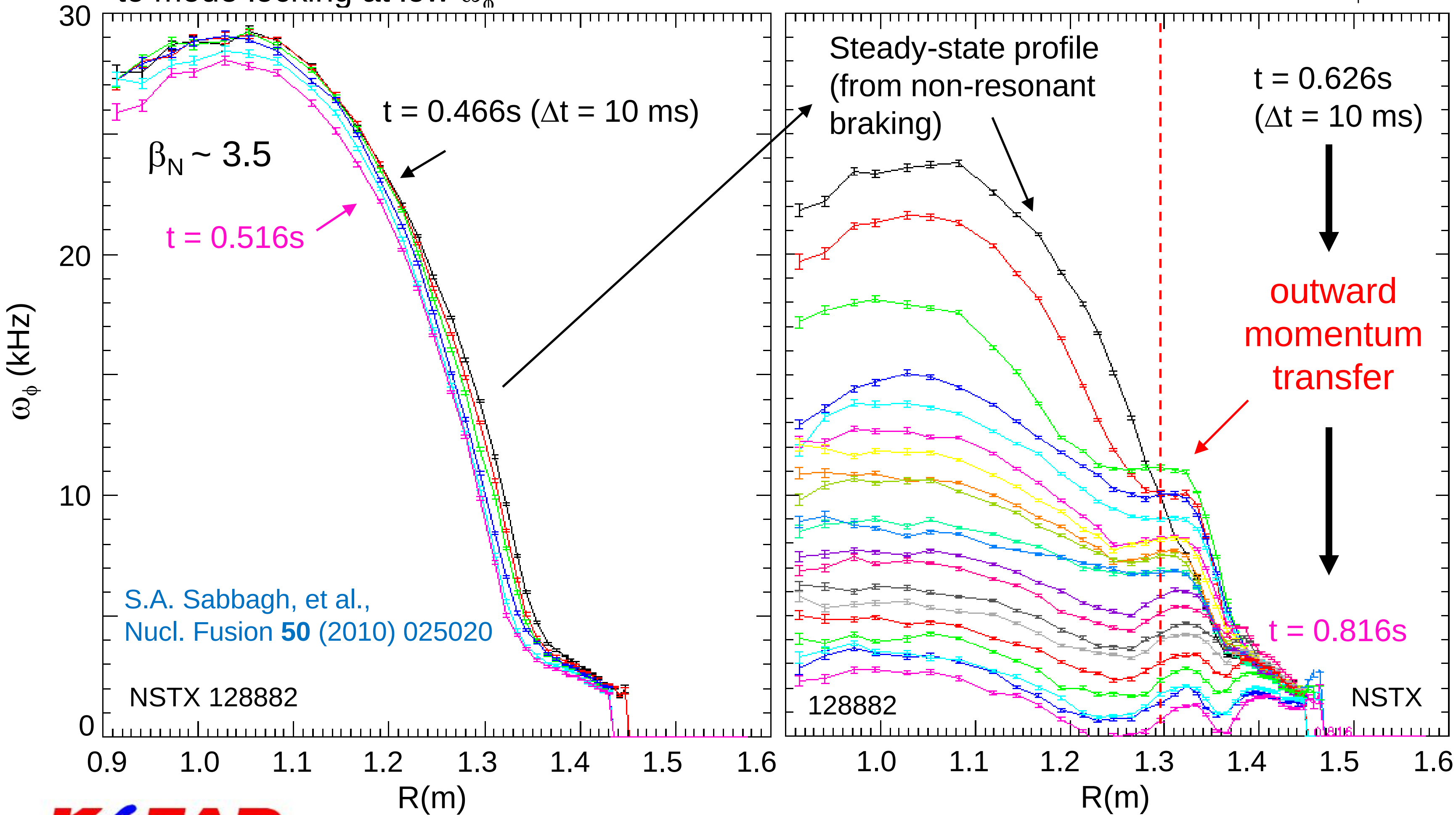


- Lowest B_T run
  - B_T = 1.3T, I_p = 0.563 MA
  - Fully converged KSTAR EFIT shows β_N ~ 2.9
    - Lower than expected β_N could be due to reduced τ_E or mode activity
    - Analysis continues
- Initial attempts with different IVCC fields:
  1. (Only) shot with n = 2 using IVCC top/bottom coils did not run as shots with n = 2 middle did - unexpected
  2. Shots with n = 1 applied field (middle) coil doesn't lock until n = 1 mode appears

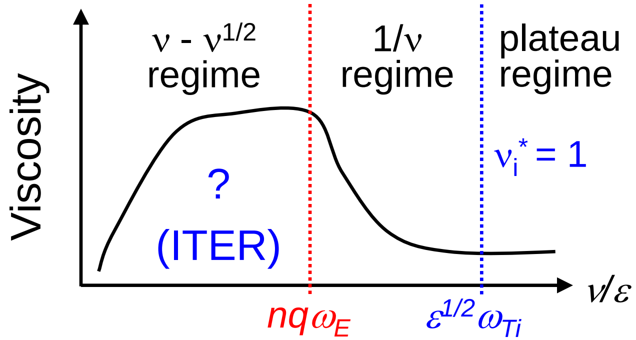
Supporting slides follow

NSTX data: n = 2 non-resonant rotation braking distinct from resonant

- Non-resonant braking:
  - Broad, self-similar reduction of profile
  - Shots not developing NTMs do not lead to mode locking at low ω_ϕ
- Resonant braking:
  - Momentum transfer across rational surface
  - Evolution toward rigid rotor core
  - Local surface locking at low ω_ϕ



Rotation control by NTV – A key physics to reach ITER-relevant operation regime in KSTAR



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

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

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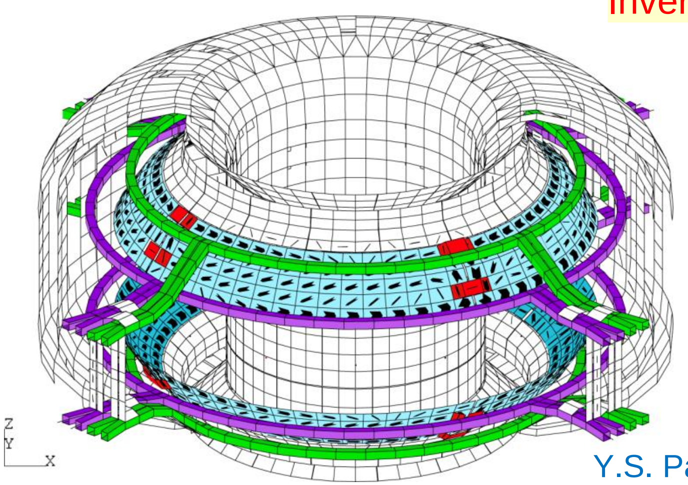
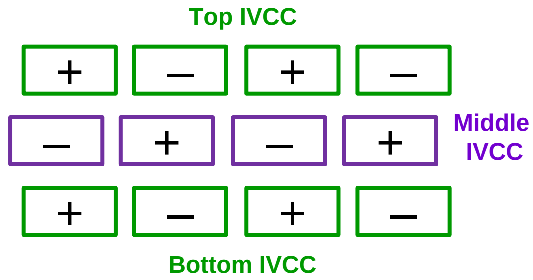
$T_i^{5/2}$

Steady-state velocity

Inverse aspect ratio





Applied n = 2 even parity config.
(view from outside of torus)

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

- Highlights (from proposal)
  - Plasma rotation and shear strongly effect MHD stability (NTMs, RWMs, etc.)
  - KSTAR (like NSTX) with co-injected NBI drives plasma rotation
    - Balanced NBI ≠ $\omega_\phi = 0$
  - NTV drag by n = 2 field can change ω_ϕ without mode locking/disruption
  - Several unanswered NTV physics questions KSTAR can address, e.g.
    - Neoclassical steady state (offset) velocity
      - DIII-D/NSTX different
    - Dependence of NTV drag with collisionality

Steady-state KSTAR non-resonant braking experiments can address key NTV physics

$$\tau = \tau_{non-resonant} + \tau_{resonant} \cong K \frac{p_i}{\nu_i}(\omega_\varphi - \omega_{NC})\delta B^2 + \frac{C}{\omega_\varphi}$$

Non-resonant torque weakens as ω_ϕ is reduced – allows good control

Resonant part leads to locking – keep this term small in experiment

Simple steady-state torque balance (assumes other torques are constant, δB finite) with resonant term = 0

$$\omega_\varphi = M(1/T_i^{5/2}\delta B_{n=2}^2) + \omega_{NC}$$

(i) Vary IVCC current (~ constant T_i):
(ii) Vary collisionality at constant IVCC current with SMBI

Fit data to:
(i) Check δB^2 scaling
(ii) Check $T_i^{5/2}$ scaling
(iii) Evaluate ω_{NC}

- This is in addition to the development of NTV alteration and control of rotation as a critical tool for use in KSTAR