MP 2015-05-23-001: Isolation of NTV torque profile: Dependence on plasma collisionality and NTV offset rotation – BRIEF summary

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Special thanks! (those marked in red)

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presented at the

NSTX-U Physics Meeting

PPPL

October 6th, 2015

Princeton, NJ

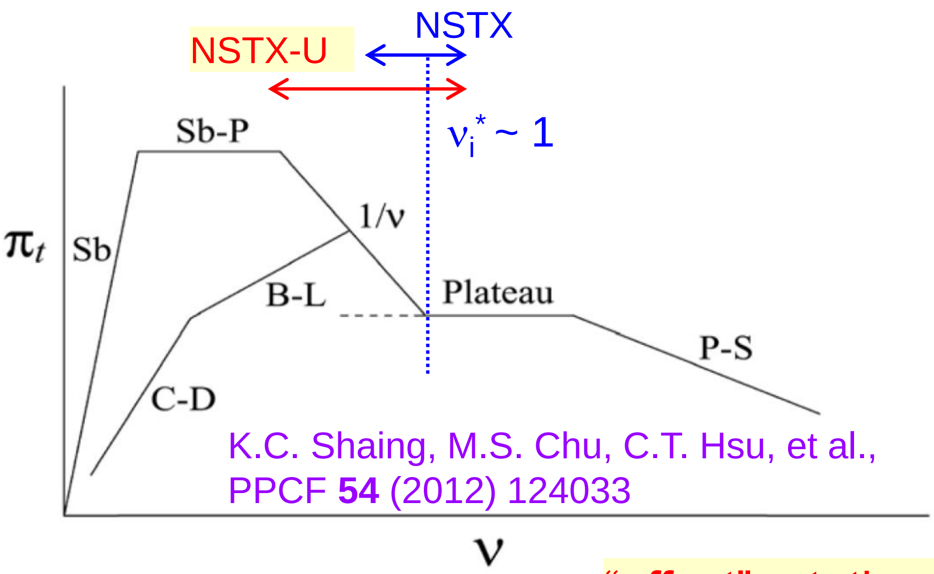
MP2014-05-02-007 aims to compute NTV profile accurately using IPS, also ν dependence, and offset

- Motivation
  - For the first time on KSTAR, the new IPS will allow the accurate isolation of the non-resonant NTV torque *profile*, with quantitative comparison of experiment to theory
  - Additional attention to NTV parameters:
    - Dependence of NTV profile on plasma collisionality and q variation
    - Measurement of NTV offset rotation
- Overall Goals (see full MP write-up for all detail)
  - Use KSTAR's new IPS power supply to perform an isolated measurement of the NTV torque profile for the first time ➔test multiple applied field spectra
  - Complete our long-standing proposal in KSTAR to determine the dependence of the isolated NTV torque profile on plasma collisionality
    - Use SMBI to maximize ν* variation in a unique way with the IPS
    - Compare this directly to past NSTX XPs, and new a joint NSTX-U experiment (NSTX-U XP1517 Sabbagh, et al.) as part of our international collaboration
  - Use an innovative technique to measure the NTV offset rotation on KSTAR for the first time

NSTX-U XP1517: Neoclassical toroidal viscosity at reduced collisionality "on deck" as joint experiment

- **Motivation**
  - Experimentally, the dependence of neoclassical toroidal viscosity (NTV) at low collisionality needs further study
  - Understanding important for NSTX-U V_ϕ control, other tokamaks, future devices
- **Goals / Approach**
  - Examine the dependence of NTV on ion collisionality
    - expected to increase with decreasing ν_i from present experiments, and theory
  - Determine if superbanana plateau increase of NTV depends on ν_i
  - Operate with pre-programmed n = 2, 3 applied fields for V_ϕ feedback control testing at reduced ν_i
- **Addresses**
  - NSTX Milestones R(15-3), closed-loop rotation control with 3D fields
  - Joint experiment with KSTAR

NTV strength varies with plasma collisionality ν, δB^2, rotation



K.C. Shaing, M.S. Chu, C.T. Hsu, et al., PPCF **54** (2012) 124033

NTV force in "1/ν" collisionality regime

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

"offset" rotation

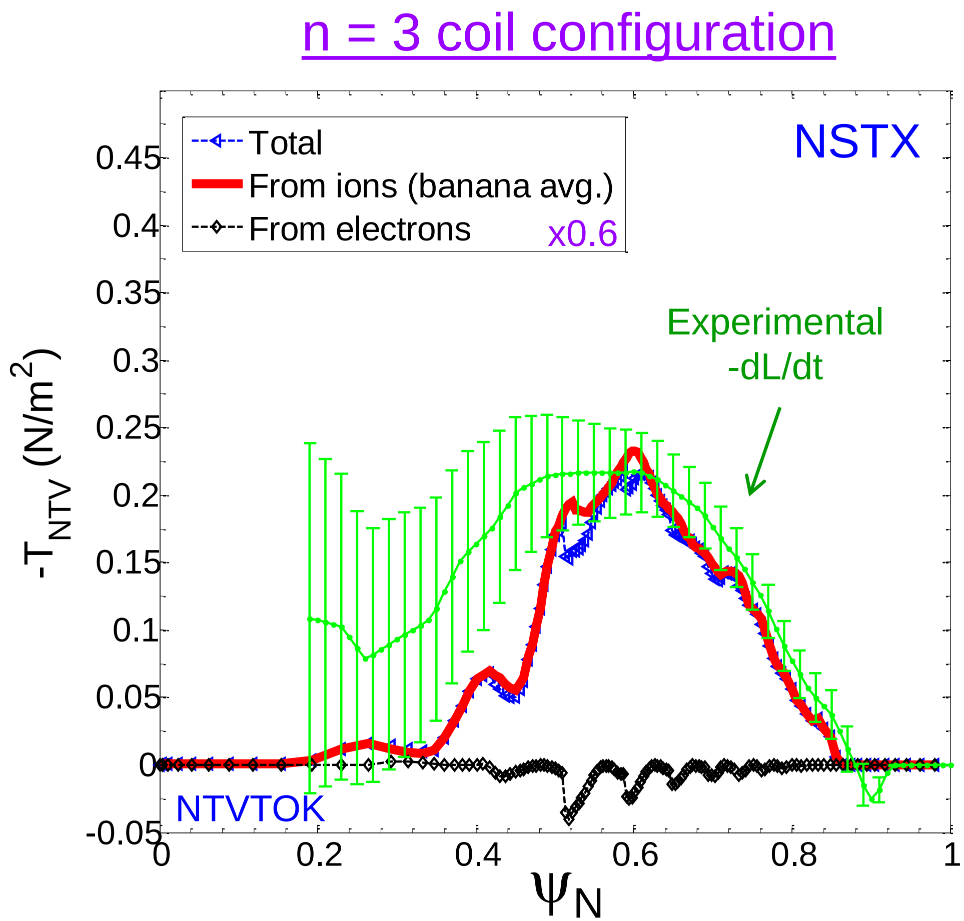
$T_i^{5/2}$

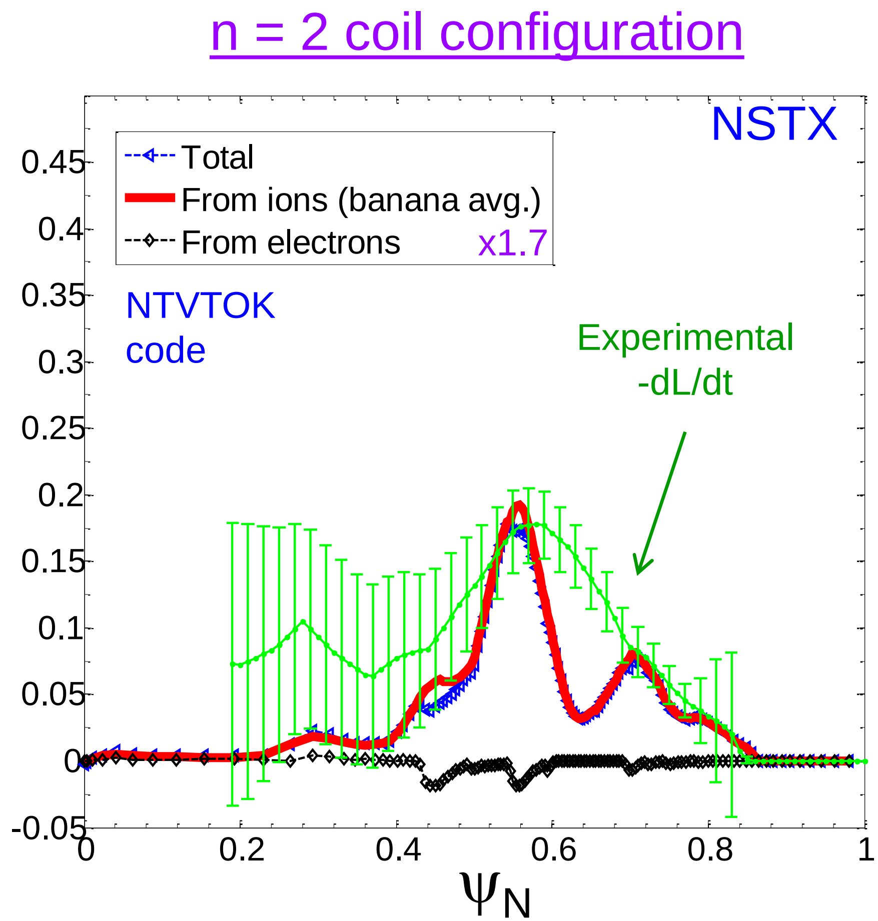
plasma rotation

1/aspect ratio (compare to KSTAR)

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

KSTAR experiment to be compared to experiments on NSTX/NSTX-U, part of our international collaboration



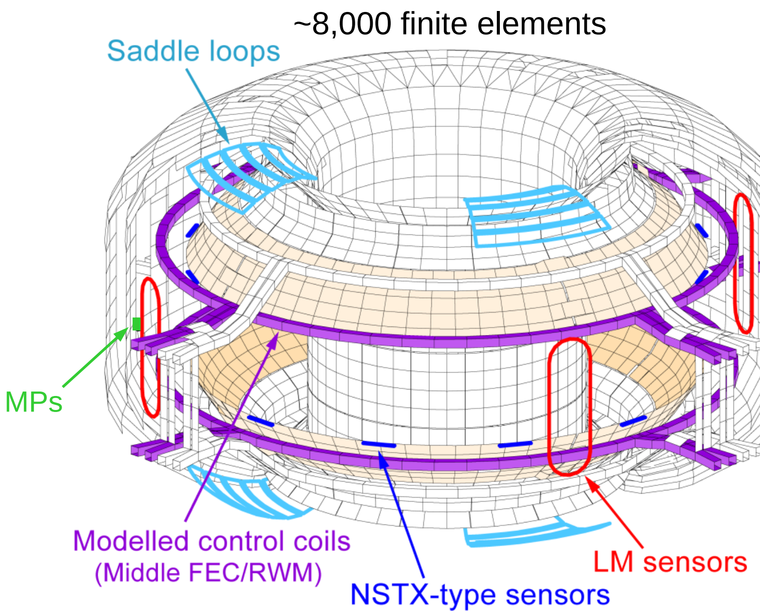


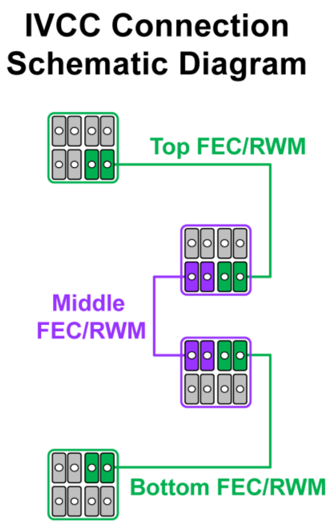
(S.A. Sabbagh, R.E. Bell, T.E. Evans, et al., IAEA FEC 2014 paper EX/1-04)

- Utilize technique similar to pioneering NSTX experiments, most recent validated analysis, using full Shaing theory

KSTAR In-Vessel Control Coil (IVCC) + new power supply in 2015 enabled this experiment

KSTAR IVCC, vessel, sensors (VALEN model)





- New high bandwidth power supply (IPS) for 2015
  - 4 SPAs for 3D field control; 1 SPA for n = 0 control
  - Each SPA can deliver 5 kA current (~ coil rating); 500V
  - DC to 1 kHz bandwidth
  - Can run steady-state
  - PCS control
  - Physics / engineering design strongly guided by Columbia U. / PPPL collaboration

KSTAR IVCC and the IPS: Subset of the patch panels set up for 2015

Coil Arrays

	(1)STD-N2				(2)STD-N1				(4) STD-N12				(6) STD-N1A				(7) STD-N1B			
TOP	+	−	+	−	+	−	−	+	−	−	+	+	+	−	−	+	+	−	−	+
MIDDLE	−	+	−	+	+	+	−	−	−	−	−	−	+	+	−	−	−	+	+	−
BOTTOM	+	−	+	−	−	+	+	−	−	−	+	+	−	+	+	−	+	−	−	+

	(8) STD-N1C				(9) STD-N1D				(10) STD-N1E				(11) MXD-121A				(13) MXD-121C				
TOP	+	+	−	−	−	+	+	−					+	−	−	+	+	−	−	+	n = 1
MIDDLE	−	+	+	−	−	−	+	+	−	−	+	+	−	+	−	+	−	+	−	+	n = 2 or 1
BOTTOM	−	−	+	+					+	−	−	+	−	−	+	+	−	+	+	−	n = 1

This patch panel was used

(applied 6 different spectra including n = 1 pitch-aligned and non-pitch-aligned)

MP 2015-05-23-001: Isolation of NTV torque profile: Brief summary

- 20 "clean" shots with ~ 20s pulse duration taken in total
  - Gives 20 x 9 x 2 = 360 opportunities to measure the isolated NTV torque profile
  - Rotating MHD not apparent, so resonant braking by modes not an issue
  - Could be the most comprehensive NTV database – still, we almost, but did not fully complete shot list (due to time constraint)
  - Data / analysis could compete for an IAEA 2016 oral presentation
- Significant variation of key parameters
  - ($\delta B_{3D}/B$), q_{95} (from 5.0 - 8.2), collisionality (T_i altered significantly), V_ϕ
  - Six 3D field spectra run (n = 2 and n = 1 pitch-aligned/non-pitch-aligned)
- Key diagnostics – with some pleasant (significant) surprises!
  - CES (absolutely required); also MSE and Thomson available

MP2014-05-02-007 Isolation of NTV torque profile, plasma collisionality and offset rotation: shot plan

Task	Number of Shots
1) Use KSTAR's new IPS power supply to perform an isolated measurement of the NTV torque profile	
(Target: Bt = 2.0T ➔ 13300), 13300 (INCREASE Bt = 2.6T), 13300 (DECREASE Bt = ~~1.5~~T); MXD-121C patch panel)	
A) Generate H-mode target plasma at Bt = 2.6T (reload shot 13300)	1
B) Reload 13308 (increasing IVCC steps, separate spectra) run at Bt = 2.6	1
C) Reload 13299 (decreasing IVCC steps, separate spectra) run at Bt = 2.6	1
D) Reload 13303 (increasing IVCC steps, combined spectra) run at Bt = 2.6	1
E) Reload 13304 (decreasing IVCC steps, combined spectra) run at Bt = 2.6	1
(With Bt = 2.6T, GO TO step 2 first, then: F) Repeat steps A) – E) with B_T = ~~1.5~~T	5

1.7 T (2 shots only)

Task	Number of Shots
2) Determine the dependence of the isolated NTV torque profile on plasma collisionality, using SMBI	
(use target plasma established from above step)	
A) Reload 13305, (set Bt = 2.6T) use divertor gas puffing to increase density	1
B) Reload 13305, (set Bt = 2.6T) but move SMBI timing back to 120 ms before the IVCC pulse	1
C) Repeat steps (2A) and (2B) at Bt = 2.0T and ~~1.5~~T ← 1.7 T	4
(NOTE: These shots will have CONSTANT IVCC current step levels determined by step (1C) above; also rerun steps (1D and 1E) with CONSTANT IVCC current step levels, but at a different IVCC current value)	

Not needed

Task	Number of Shots
3) Use an innovative technique to measure the NTV offset rotation on KSTAR for the first time	
A) Generate control shot that will start up with OH and ECH only (targets: 13379, 13412)	1
B) Control shot using specific ECH and NBI waveforms, no 3D applied field	1
C) Vary 3D applied field (one IVCC level per shot is expected) – HIGHEST IVCC current first	3

(not enough time to run)

MP2014-05-02-007 Isolation of NTV torque profile: Considerations for run (illustration of SMBI + 3D field)

- Setting up varied 3D field spectra (MXD-121C patch panel)
  - δB/B variation with IVCC current steps
  - Vary the spectrum in each group of steps
  - Take shots with combined non-resonant spectra

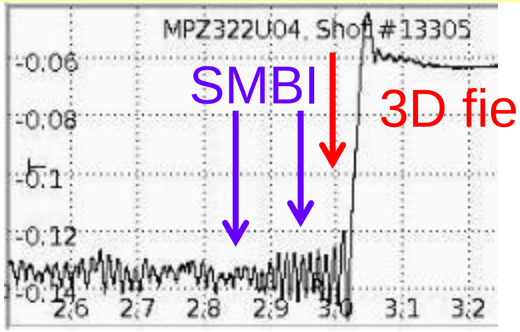
Accomplished (q_{95} ~ 5.0, 6.2, 8.2)

Still to do (in red)

- Varying collisionality
  - B_T, I_p variation; natural density evolution
  - SMBI (cold); divertor gas puffing
- NTV offset rotation – target plasma
  - 2015 shots: 13379, 13412

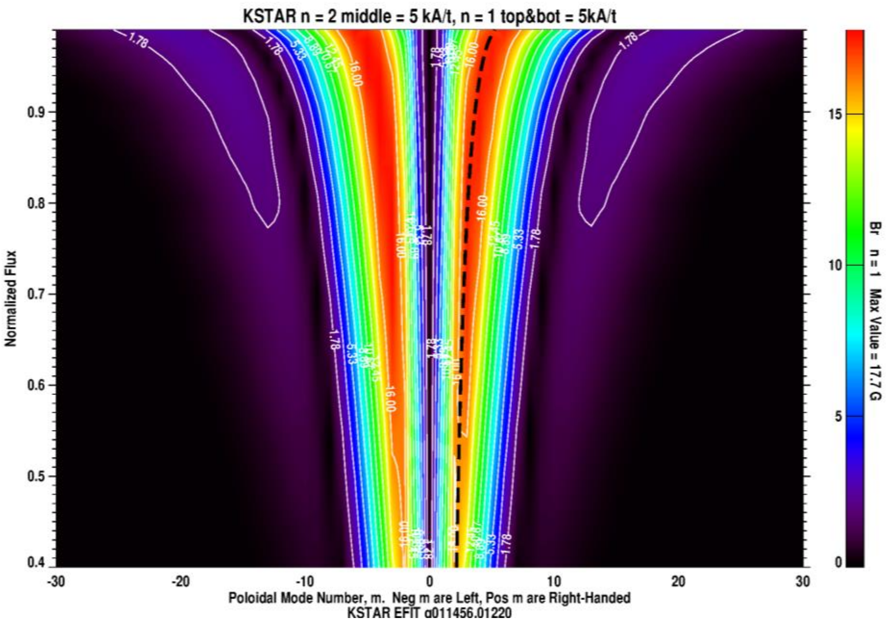
SMBI delivery successful, increased small mode, then 3D field applied 40ms later apparently leads to mode lock

dB/dt from one of the new (2015) RWM sensors



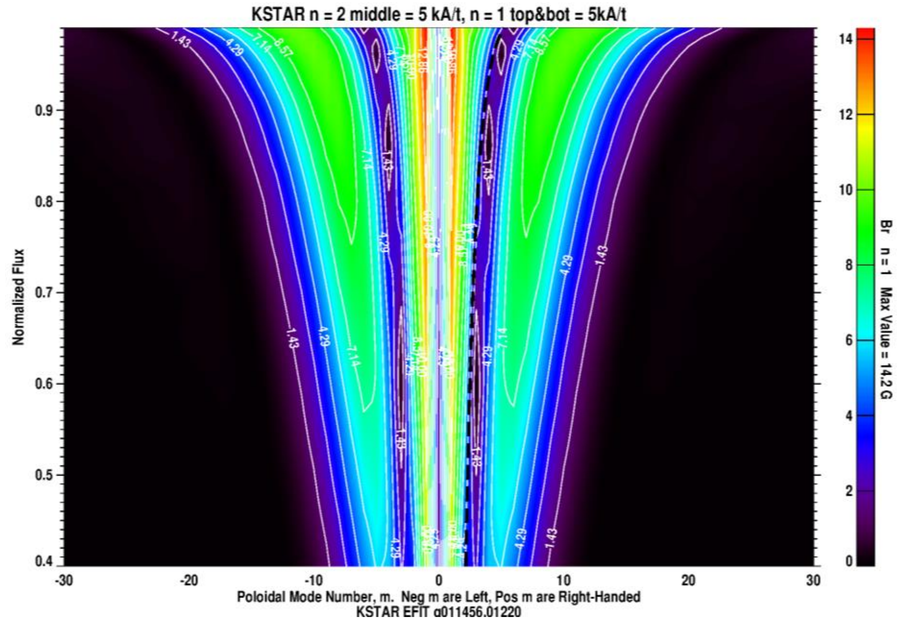
MXD-121C patch panel chosen to allow wide investigation of 3D field spectra, including relative alignment to 2D field pitch

Combined n = 2 + 1
"Field pitch aligned" (+180deg phasing)



n = 1	T	+	+	–	–
n = 2	M	+	–	+	–
n = 1	B	–	–	+	+

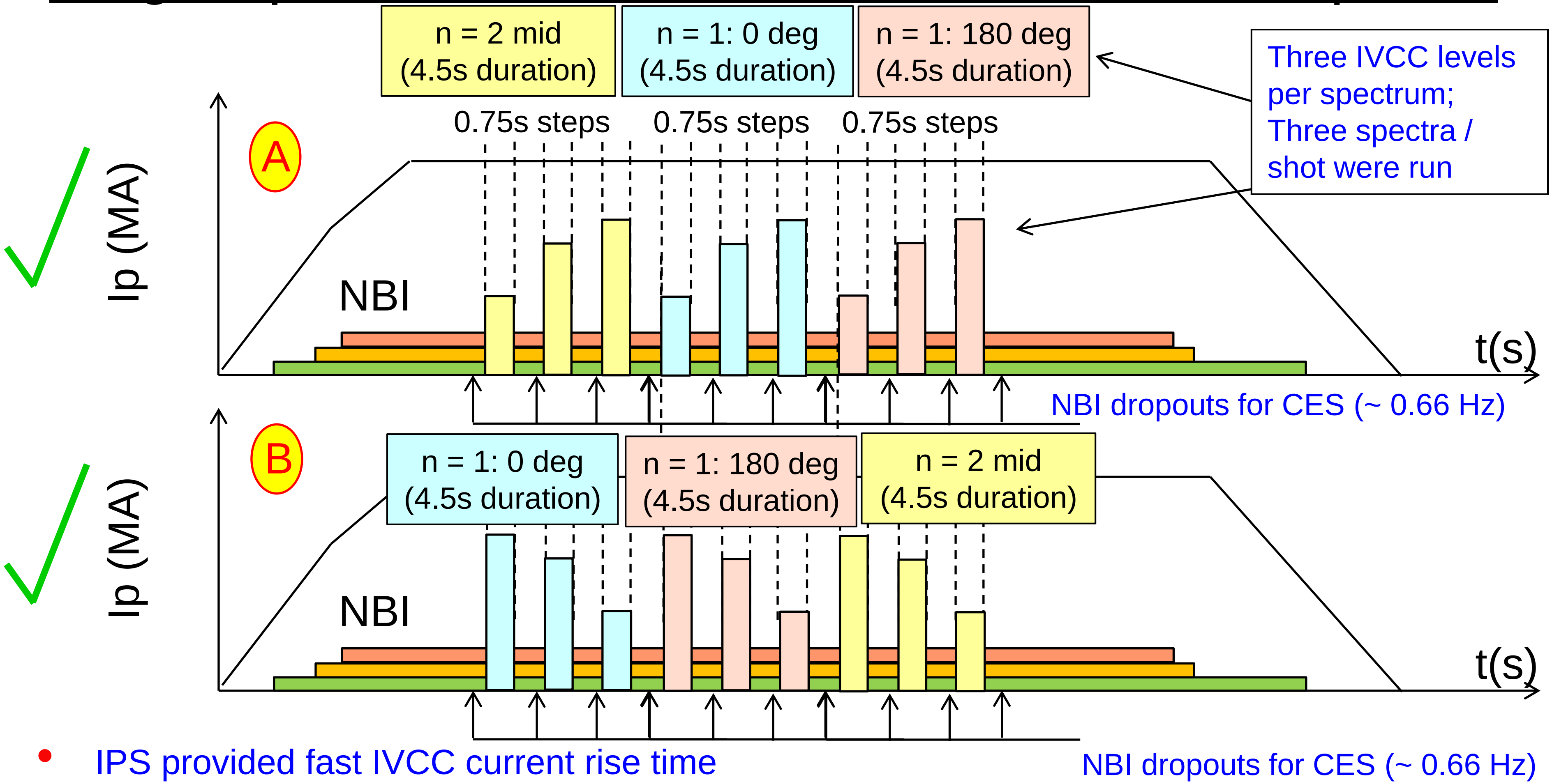
Combined n = 2 + 1
"Field pitch non-aligned" (0 deg phasing)



T	+	+	–	–
M	+	–	+	–
B	+	+	–	–

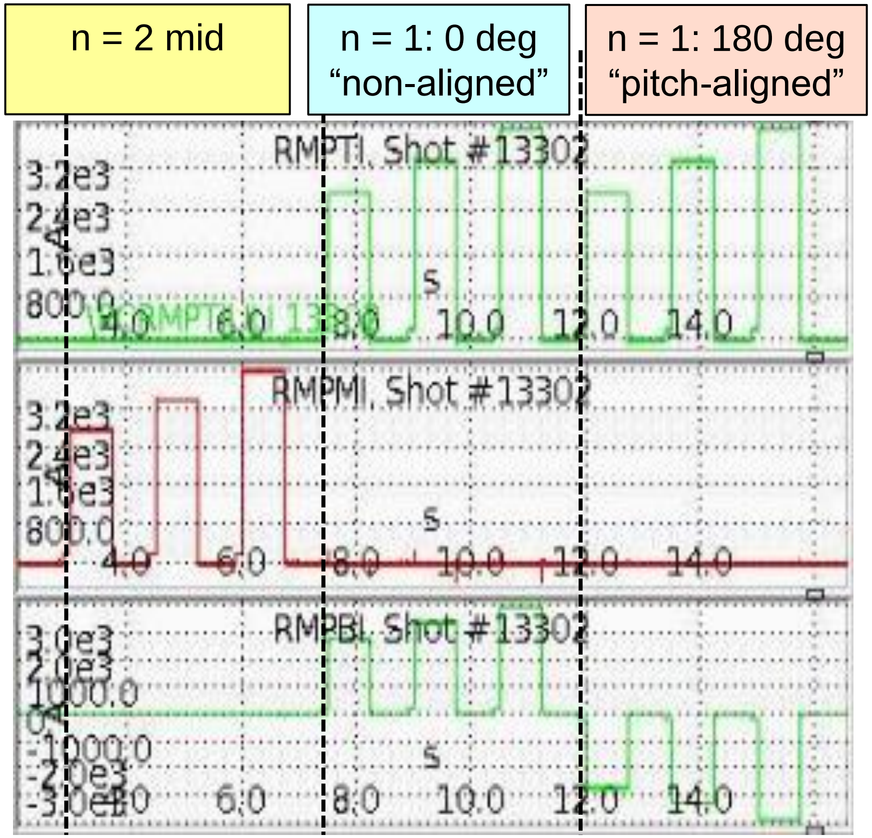
- Non-pitch aligned has lower Br n = 1 field overall, broad region ~ 10G

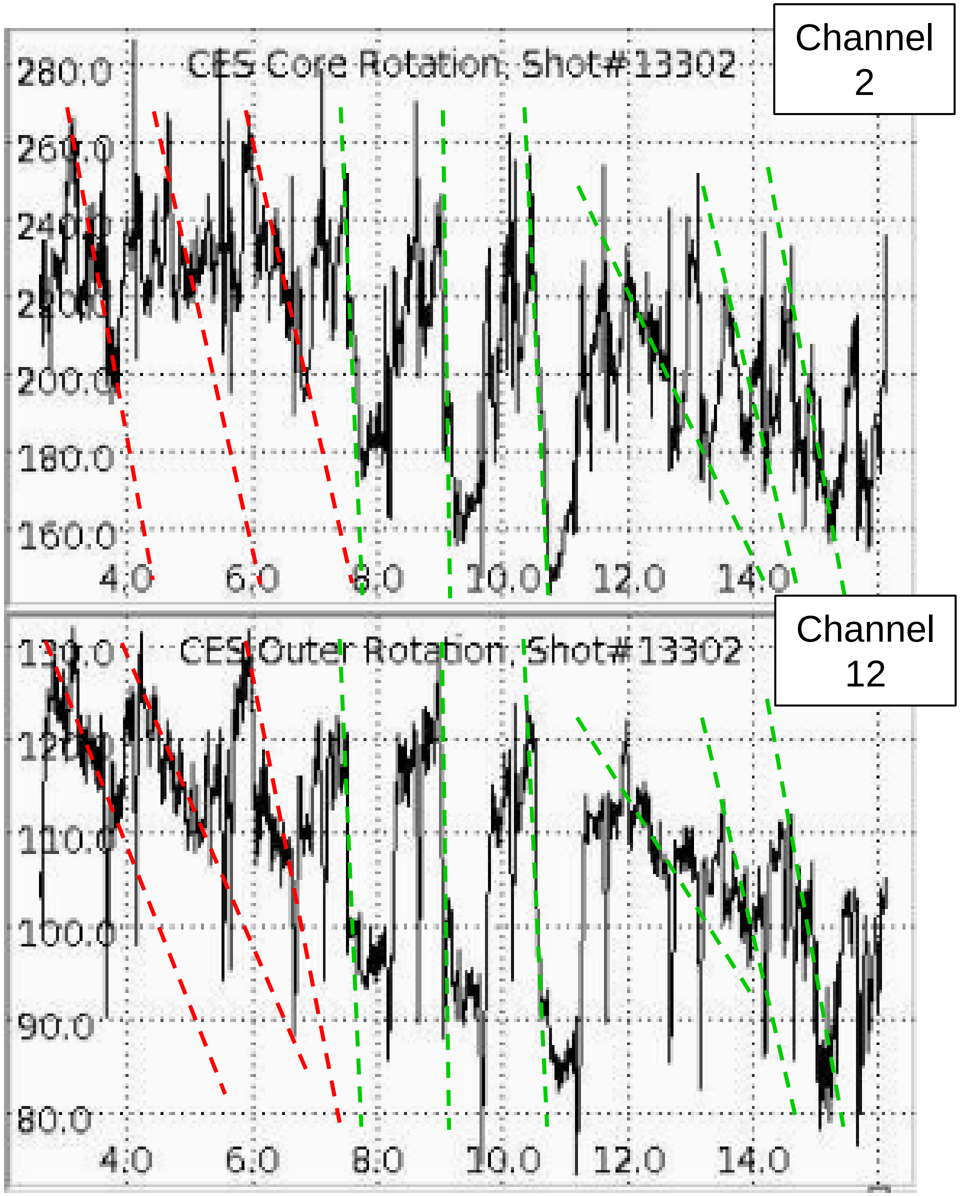
Single spectrum waveforms run to isolate NTV profile



- IPS provided fast IVCC current rise time
  - ~ 3 ms to maximum current << momentum diffusion time
- Step the IVCC as many times as plasma pulse length allows
  - (A) Vary applied field magnitude and spectrum (2 or three steps using n = 2 midplane; n = 1 non-pitch-aligned; n = 1 pitch-aligned ➔ ALL in one shot if possible)
  - (B) Take second shot, changing the order of the IVCC current steps

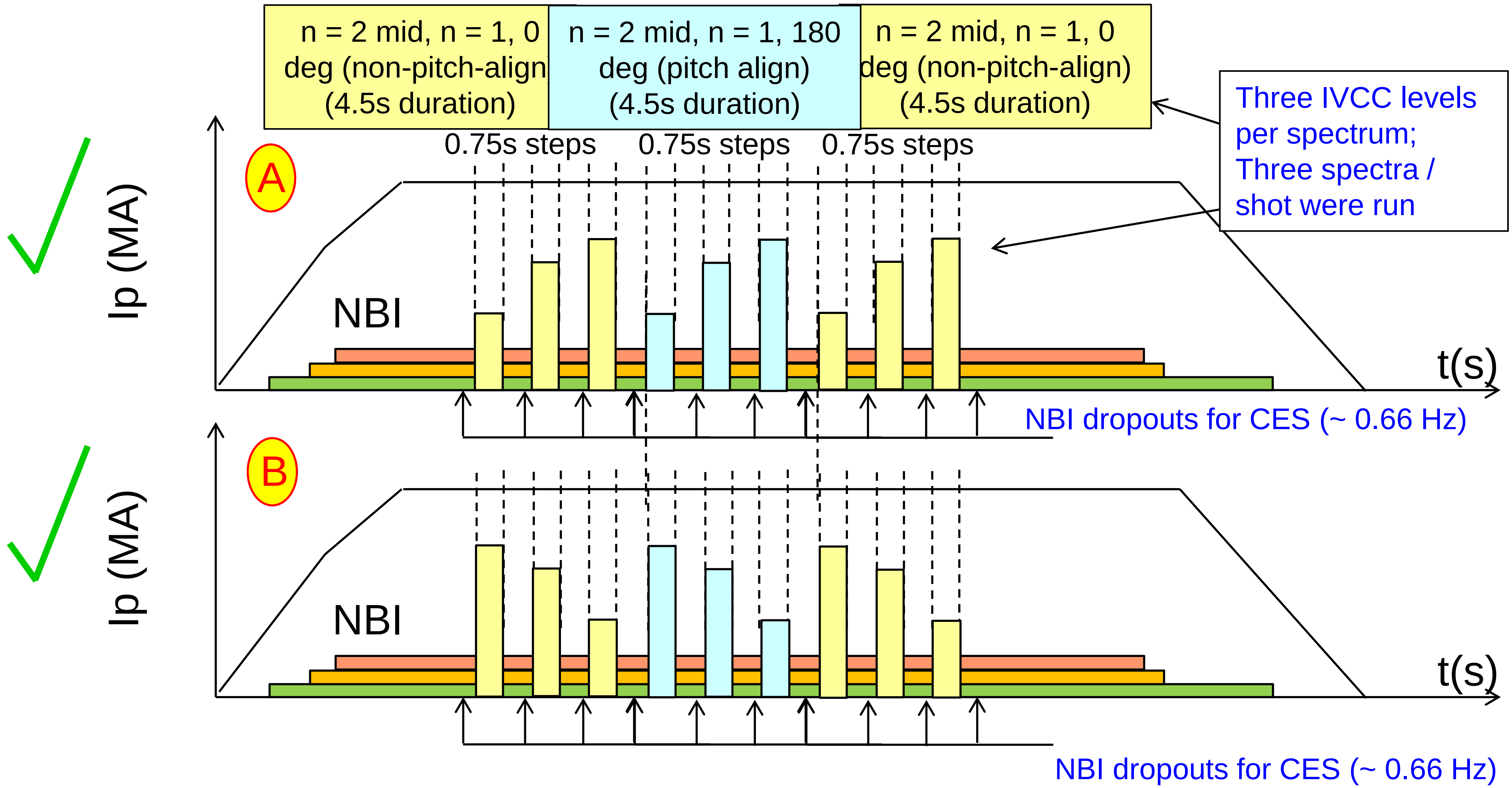
NTV effect has been successfully isolated with the new IPS!





- Increasing field strength = stronger NTV
  - Shown by change in |dVp/dt|
  - |dVp/dt| changes vs. R – NTV PROFILE
- Altered field spectrum alters NTV
- "Non-pitch-aligned" n = 1 field apparently provides stronger braking (!)

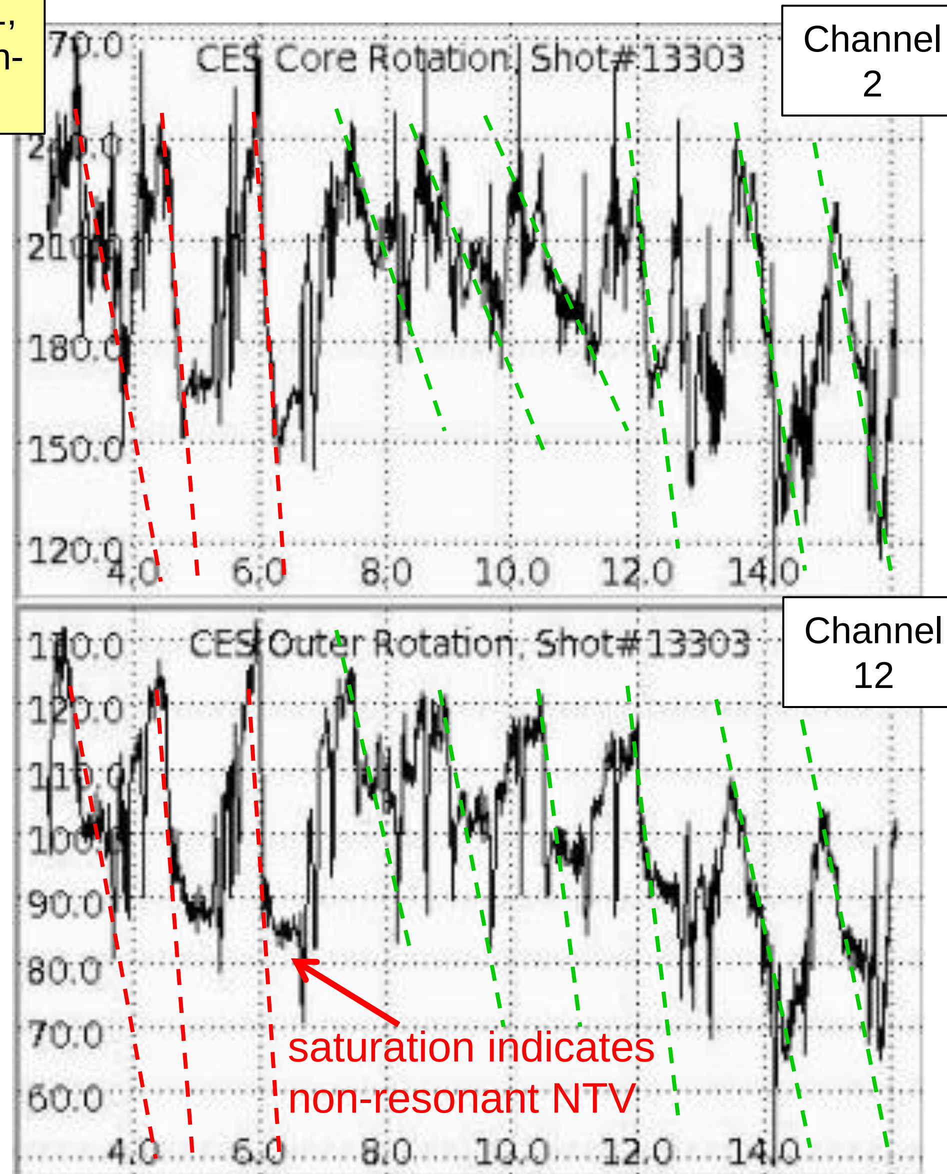
Combined spectrum waveforms run: isolate NTV profile



- Shots with COMBINED non-resonant field spectra (n = 2 + n =1 non-pitch-aligned
  - (A) Vary applied field magnitude fixed combined spectrum (n = 2 midplane; n = 1 non-pitch-aligned: ➔ ALL in one shot if possible)
  - (B) Take second shot, changing the order of the IVCC current steps

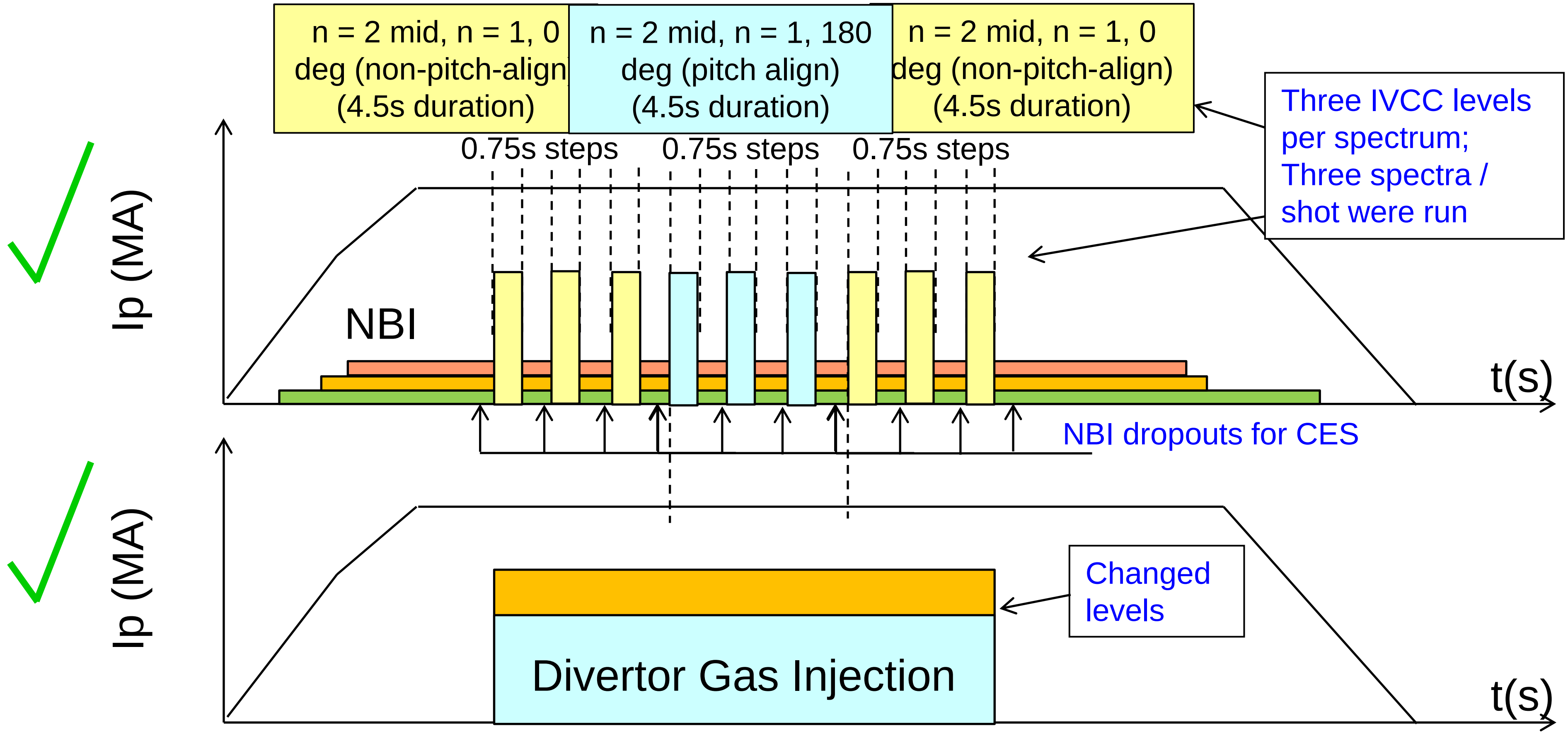
NTV successfully isolated for COMBINED n = 2 + n = 1 spectra

n = 2 mid, n = 1, 0 deg (non-pitch-aligned)	n = 2 mid, n = 1, 180 deg (pitch aligned)	n = 2 mid, n = 1, 0 deg (non-pitch-aligned)



- Increasing field strength = stronger NTV
  - Shown by change in |dVp/dt|
  - |dVp/dt| changes vs. R – NTV PROFILE
- Altered field spectrum alters NTV
- Again, "non-pitch-aligned" n = 1 field apparently provides stronger braking

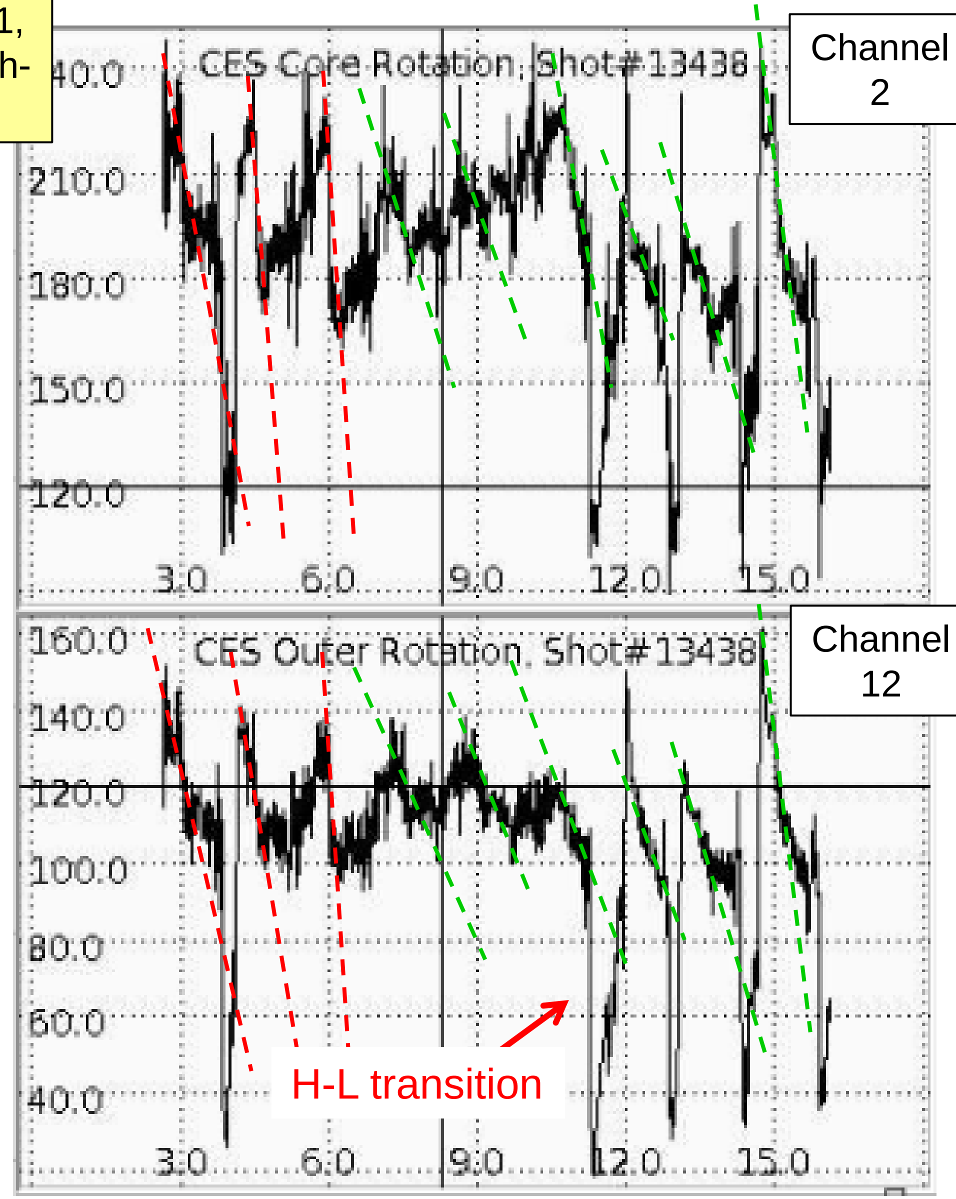
Isolate NTV torque profile: collisionality scan waveforms



- Shots with COMBINED non-resonant field spectra (n = 2 + n =1 non-pitch-aligned)
  - Varied collisionality through director gas puffing
  - Varied profiles with H-L transitions

NTV for COMBINED n = 2 + n = 1 spectra, q_{95}=8.2, NO gas puff

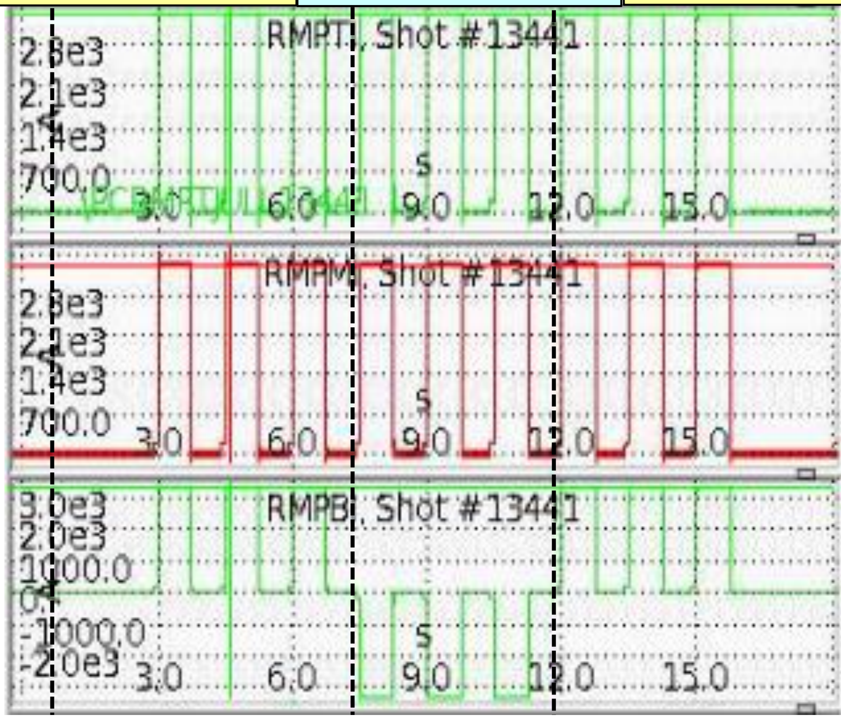
n = 2 mid, n = 1, 0 deg (non-pitch-aligned)	n = 2 mid, n = 1, 180 deg (pitch aligned)	n = 2 mid, n = 1, 0 deg (non-pitch-aligned)

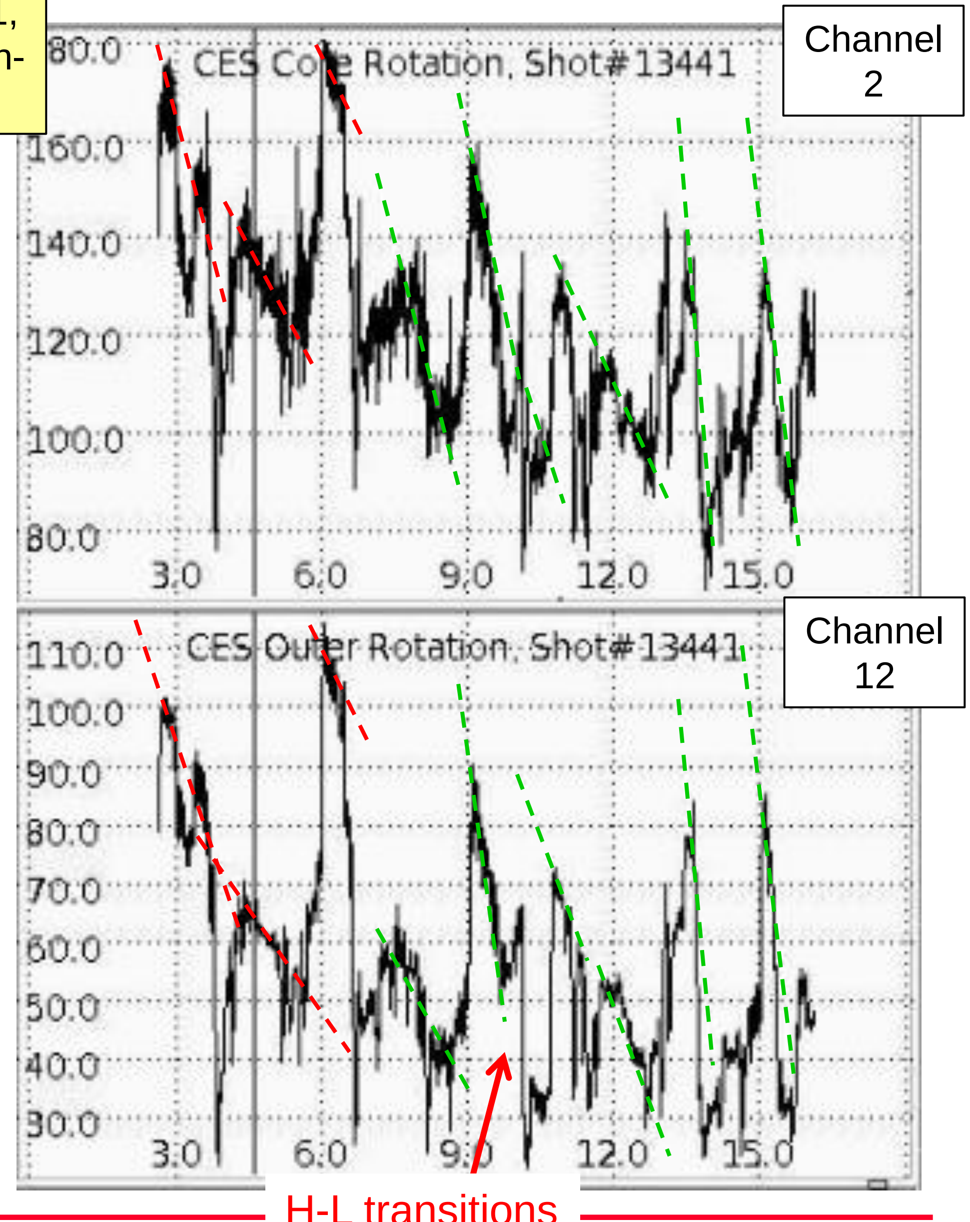


- Increasing field strength = stronger NTV
- Altered field spectrum alters NTV
- Some H-L transitions – can take NTV before, and sometimes after transition
- Again, “non-pitch-aligned” n = 1 field apparently provides stronger braking

NTV for COMBINED n = 2 + n = 1 spectra, q_{95}=8.2, w/gas puff

n = 2 mid, n = 1, 0 deg (non-pitch-aligned)	n = 2 mid, n = 1, 180 deg (pitch aligned)	n = 2 mid, n = 1, 0 deg (non-pitch-aligned)



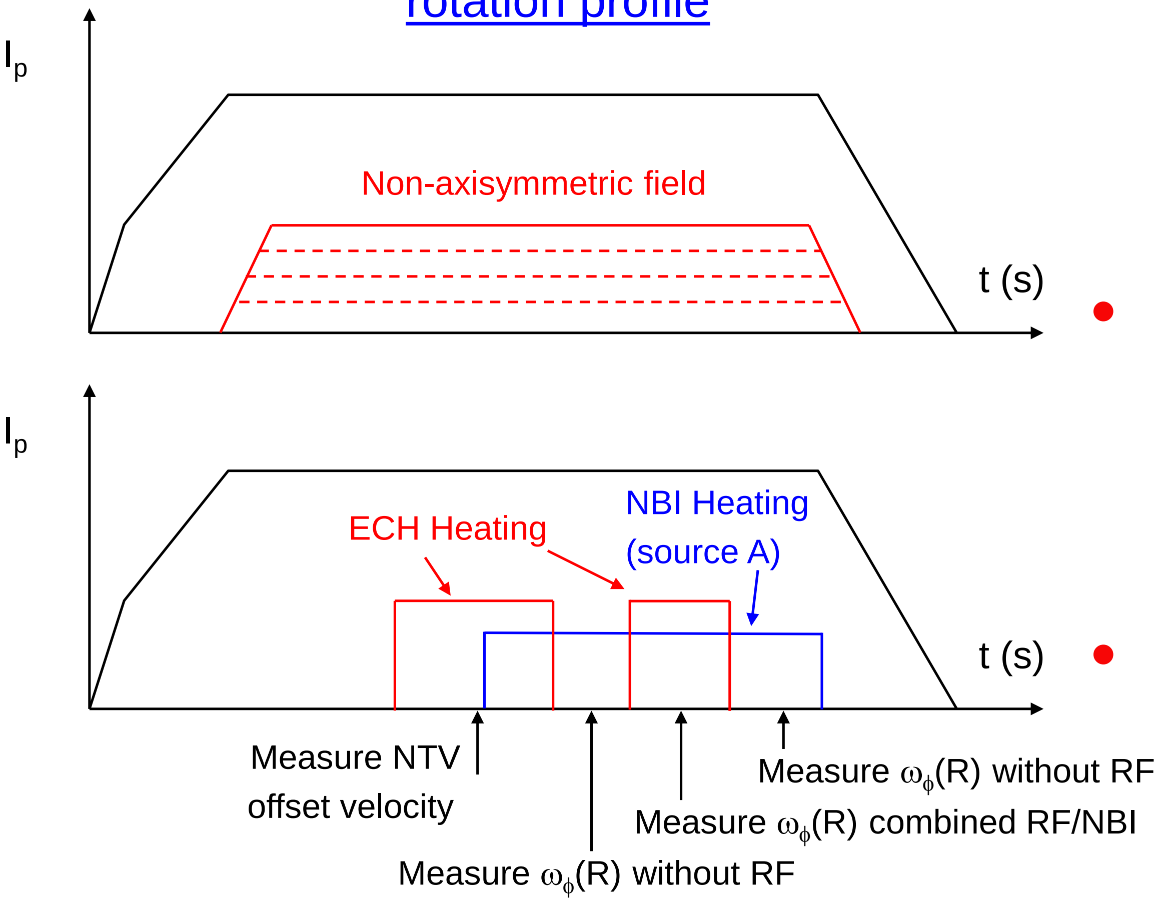


- Increasing field strength = stronger NTV
- Altered field spectrum alters NTV
- Some H-L transitions – can take NTV before, and sometimes after transition
- Generally effect of gas puff is noticeable in NTV braking (need further analysis)

Innovative technique to measure the NTV offset rotation on KSTAR for the first time - waveforms

(time did not allow us to run this)

Schematic of approach to measure NTV offset rotation profile



- Determine NTV offset velocity profile using an innovative approach with ECH and NBI
  - Also, to be compared to an experiment proposed on NSTX-U (2016)
- Run with two 3D field spectra and compare
  - Run n = 2 field at midplane
  - Run n = 1 non-pitch-aligned off-midplane
- Target plasmas
  - 2015 shots: 13379, 13412

Brief summary of "control room" observations and hypotheses

- KSTAR NTV as observed in these new, isolated NTV shots
  - Initial observation: strong resonant MHD modes have been avoided
  - Initial observation: pitch aligned 3D field does not have stronger NTV
  - Observation indicates no strong amplification due to kink response
  - Observation: NTV profile is global, non-resonant, no huge variations
  - Initial observation: NTV profile of combined spectra might be understood by simple superposition of applied field (analysis needed)
  - Working Hypothesis: NTV depends primarily on $|\delta B|$, ν, not on resonant effects, particulars of resonances, or alignment with 2D field
- Experience from NSTX (theory/experiment verification 10 years old!)
  - Non-resonant NTV is robust, not strongly dependent on profile details
  - No strong resonant effects – unless strong resonant MHD is present

Essential plan to complete this data was (nearly) completed! Great data! Further detailed comparison to past dedicated NSTX, and new joint NSTX-U NTV experiments, will yield further understanding of NTV in tokamaks

MP 2015-05-23-001: Isolation of NTV torque profile – Diagnostics

- Required diagnostics / capabilities
  - ✓ ❑ Equilibrium magnetics, ECH, full NBI power
  - ✓ ❑ IVCC coils in Mixed 1/2/1C patch panel (n = 2 (mid), n = 1 (top/bot))
  - ✓ ❑ Toroidal rotation measurement (CES, X-ray crystal)
  - ✓ ❑ Ion temperature (CES)
  - ✓ ❑ Toroidal Mirnov array / between-shots spectrogram with toroidal mode number analysis
  - ✓ ❑ SMBI (cold)
  - ✓ ❑ ECE, ECEI

Acquired. Density profile will help provide a reasonably accurate NTV profile calculation

- Desired diagnostics / capabilities
  - ✓ ❑ Thomson scattering (T_e, n_e); MSE
  - ✓ ❑ Interferometer (line avg. n_e evolution)
  - ✓ ❑ Locked mode detectors (all positions)
  - ✓ ❑ fast camera

MSE acquired for all shots taken

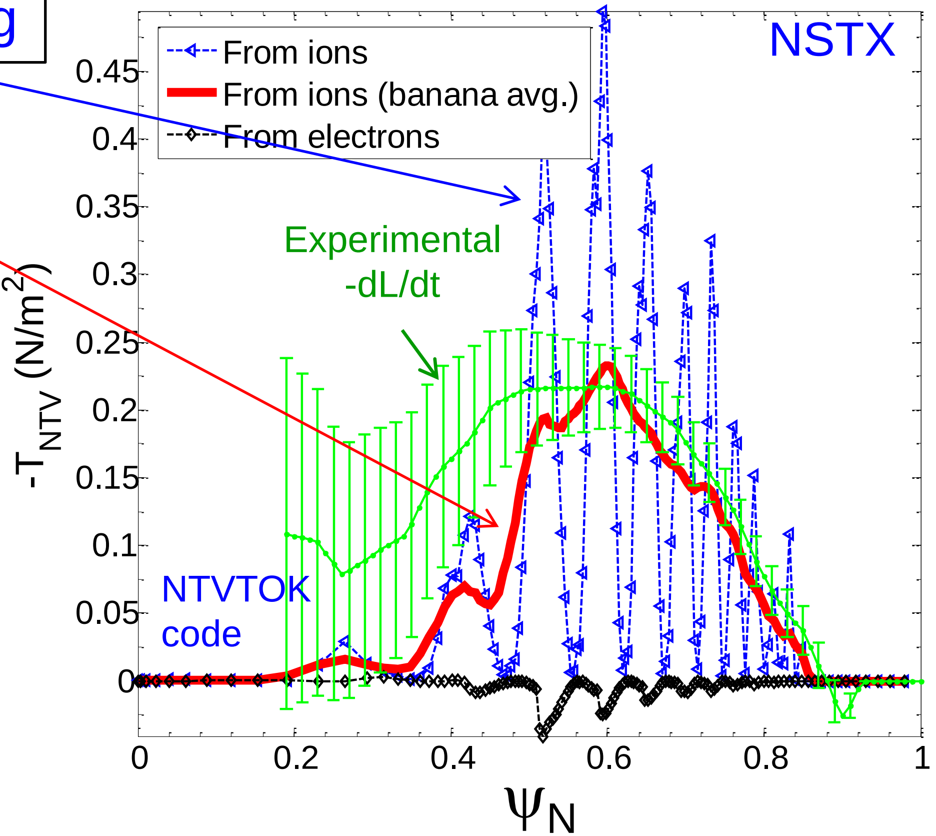
Supporting Slides Follow

Resonant effects, hypothesized in some publications, are not observed in NSTX – due to finite gryo-radius/banana width

Theory without banana-width averaging

with banana-width averaging

n = 3 coil configuration



- Published in Sabbagh, et al., IAEA FEC 2014 paper EX/1-4
- Can explain why strong resonances are not observed
- Further analysis of KSTAR data from this experiment should provide further support, or different understanding
  - Present “control room” analysis seems to support non-resonant nature of NTV

- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor ($(dL/dt)/T_{NTV}$) = 0.6 (for case shown above) – O(1) agreement
  - NO plasma amplification of 3D field in these calculations