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Macroscopic Stability TSG 2010 Mini Results Review

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NSTX Macroscopic Stability Topical Science Group

NSTX Mini Results Review

September 30th, 2010
Princeton Plasma Physics Laboratory

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v1.1

MHD XPs guided by Milestones, ReNeW ST, and ITPA needs

- NSTX R10-1 Milestone
  - *Assess sustainable beta and disruptivity near and above the ideal no-wall limit*
- Priorities (summarized in two lines)
  - *Understand active and passive mode stabilization physics to improve mode control and assess sustainable beta and disruptivity near and above the ideal no-wall limit (Milestone R10-1)*
  - *Study mode-induced disruption physics and mitigation, including halo current generation and the properties of the thermal quench, and 3-D field effects including plasma viscosity*
- All XPs serve NSTX Milestones, ReNeW Thrust 16, ITPA joint XPs, ITER support
  - 7 MHD ITPA tasks addressed (see http://nstx-forum-2010.pppl.gov/macroscopic_stability.html)
  - Cross-cutting tasks outside MHD ITPA also addressed by MHD TSG

Macroscopic MHD TSG 2010 XPs – Status 9/30/10

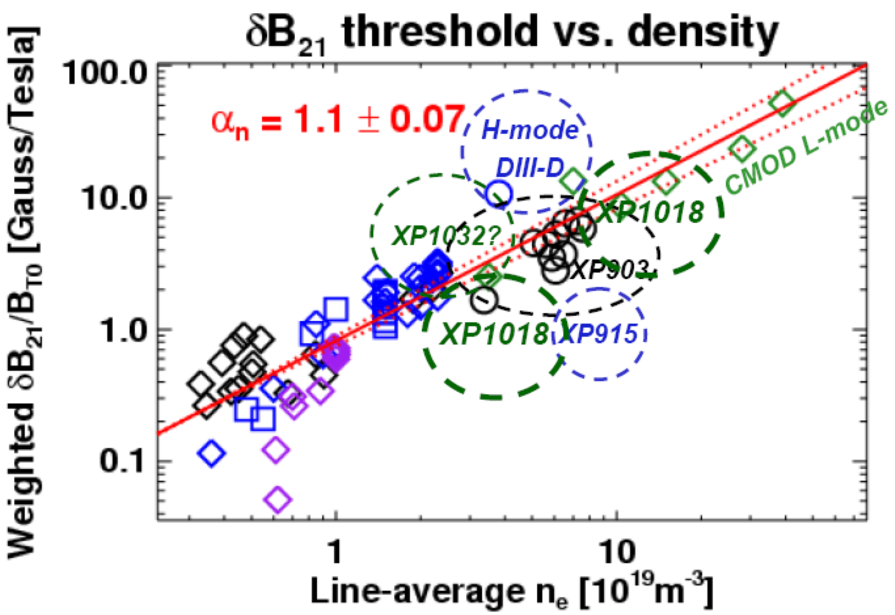
Author	Proposal Title	NSTX Forum Allocations / Priority			XP / Status
J. Park	Error field threshold study at high-beta - reduced torque	1.0	1	0.50	XP1018
Menard	Effects of non-res. fields on low/moderate beta locking threshold	1.0	1	0.50	
Buttery	Error field threshold scaling in H mode - next step devices	1.0	1	0.50	XP1032
Gerhardt	Optimization of beta-control - disruptivity	1.0	1	0.50	XP1019
Berkery	Determination of, navigation through weak RWM stability Vf(psi)	1.0	1	1.00	XP1020
Reimerdes	Measuring resonance frequencies relevant for RWM stabilization	1.0	1	-	
McLean/Gerhardt	Halo current study w/ extended diagnostic capability + LLD	1.0	1	1.00	XP1021
Y-S. Park	RWM state-space control in NSTX	1.0	1	1.00	XP1022
Sabbagh	Optimized RWM feedback for high <bN>pulse at low n and li	1.0	1	1.00	XP1023
Gerhardt	Comparison of RFA suppression using different sensors	1.0	2	1.00	XP1060
Buttery	2/1 NTM stability (and EF sensitivity) vs q profile	1.0	2	0.50	XP1061
Sabbagh	NTV physics: low collisionality and maximum variation of wE	1.0	2	0.50	XP1062
Berkery	RWM stabilization by energetic particles	1.0	3	1.00	
J. Park	Resonant Field Amplification of n=2 and n=3 applied fields	1.0	3	1.00	
La Haye	Effect of rotation on amplitude of 3/2 NTMs	1.0	3	1.00	
Y. Park	Passive/active stability of kink,RWM, Vf control: KSTAR Joint	1.0	3	1.00	
Sabbagh	Global MHD / ELM stability vs edge current, n*qped, edge nu	1.5	ITER	0.50	XP1031
Sontag	Peeling-ballooning stability and access to QH-mode in NSTX	1.5	ITER	0.50	XP1063
Gerhardt	Optimization of beta-control XMP	0.5	CCE	0.50	XMP65
Menard	Influence of LLD-induced collisionality, profile on ST stability	1.5	CCE	1.50	XP1055 (team)
Goldston	RF Amplification of EHOs in Lithium-pumped ELM-Free Plasmas		CCE	1.00	XP1068

Group review	Team review	XP signoff	Started	Near Complete	Completed

XP1018 (only Tier 1 XP without run time) - extend locked mode error field threshold study to moderate / high beta, low input torque RF plasmas

- The best parametric scaling with total resonant field:

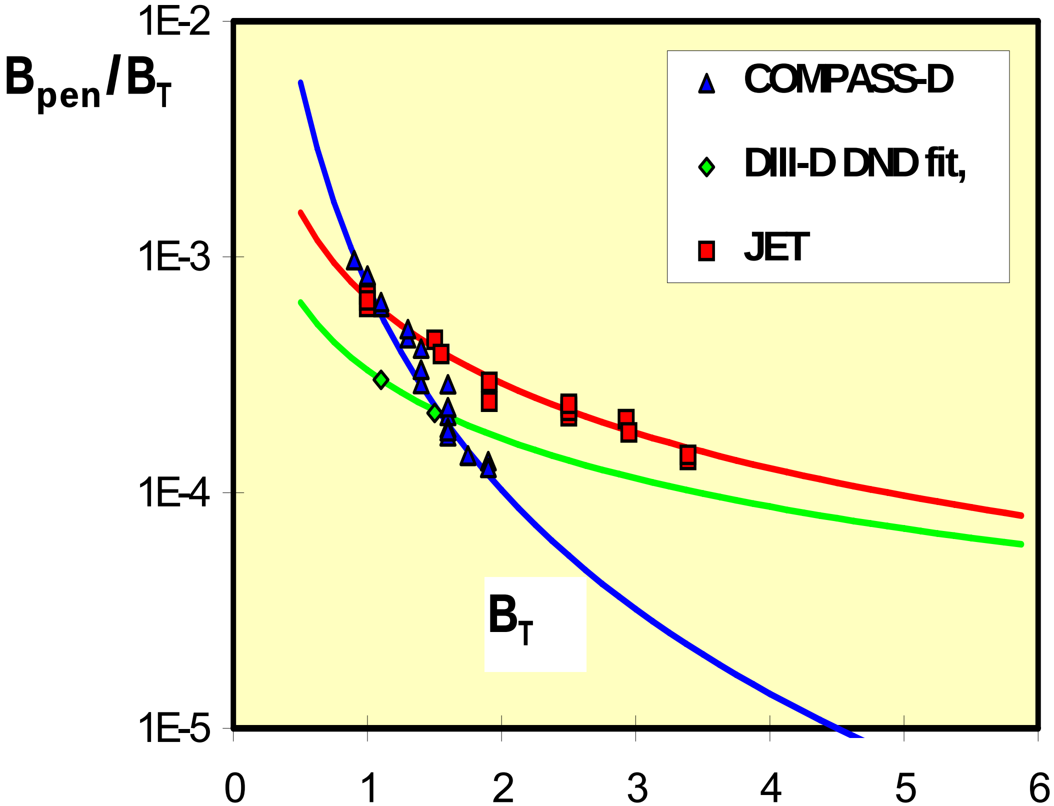
$$\frac{\delta B_{21}}{B_{T0}} \leq 0.9\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.1}\left(B_{T0}[T]\right)^{-1.4}\left(R_0[m]\right)^{0.61}$$



- Reliable error field threshold scaling needed for ITER
- Past XPs (903, 915) investigated error field threshold
- Complimentary to XP1032 Error field threshold scaling in H-modes (Buttery)
- Presently on the run schedule if RF can support (2MW+), OR run ohmic if RF can't support

XP 1032 Goal: Obtain Scaling of Error Field Threshold in H-modes to Predict Future Devices

- **Error field threshold dictated by a torque balance**
  - When electromagnetic torque overcomes inertia & viscosity
  - Shielding response bifurcates to resonant widespread tearing



- Scalings obtained for Ohmic regimes, but H mode may differ:
  - Proximity to NTM: weak Δ' stability?
  - Underlying rotation may scale differently from Ohmic

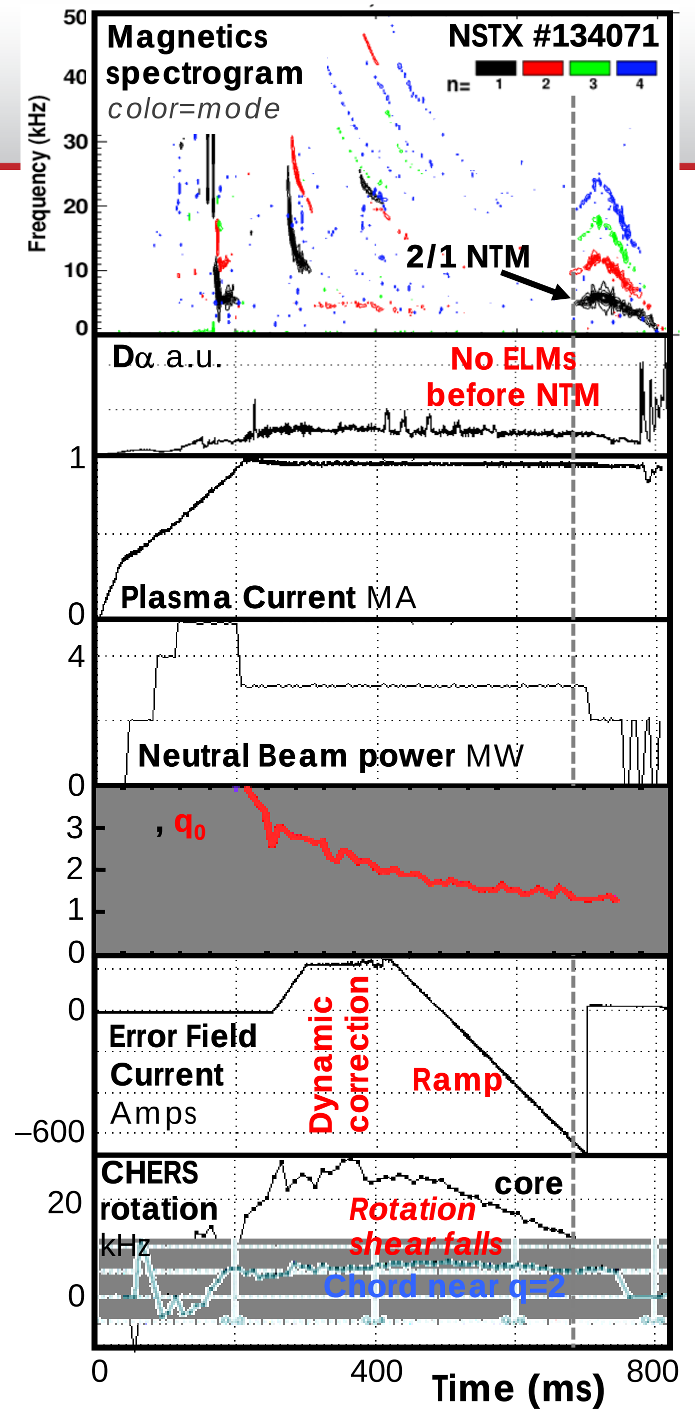
➔ Experiments to measure principal scalings with B_T and density

  - Infer machine size scaling from dimensional invariance:

$$B_{pen}/B_T \propto n^{\alpha_n} R^{\alpha_R} B^{\alpha_B} q^{\alpha_q}$$

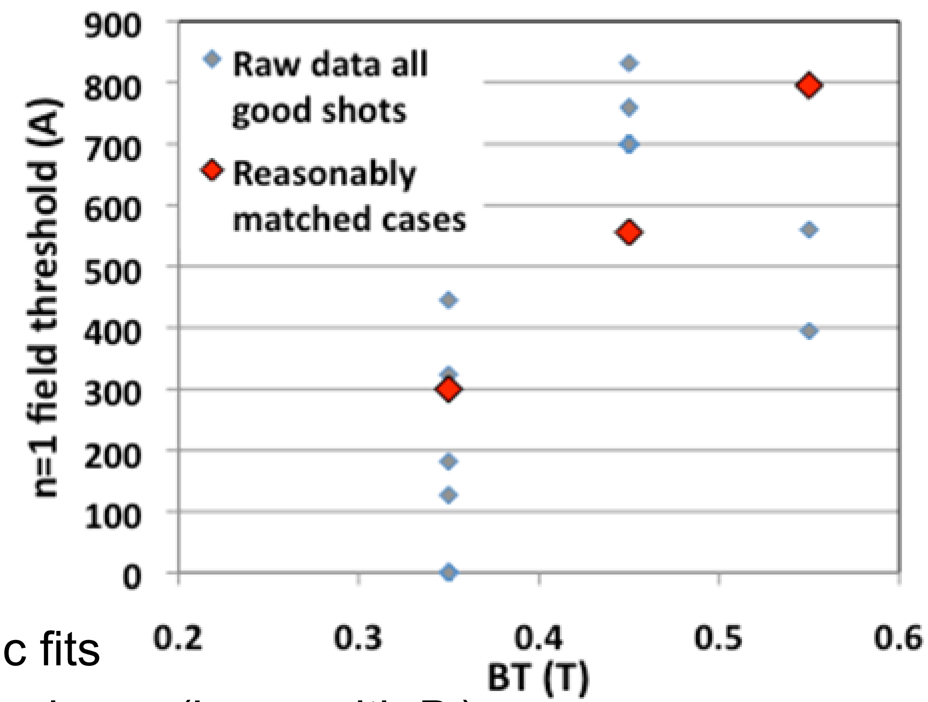
XP1032 Experiment Summary

- Built on 2009 shot (shown)
  - β_N feedback added to give constant β_N with time
    - Worked well at 3 different B_t values
    - Avoided need to repeated retuning of discharges to reach target
  - Lithium to control ELMs & conditions
    - Avoid as tearing trigger
    - Required more this year: 150mg/shot
- n=1 field ramps to trigger mode
  - ✓ Scan 3 B_T at constant q_{95}
  - ✓ Adjustments to field ramp and gas to compensate for density & q_0 variation



XP1032 First results: A significant dependence with B_t, possibly partly explained by density variation

- Full B_T range explored – lowest, highest & middle
  - 0.35T/0.7MA to 0.55T/1.1MA
- Wide variation in thresholds
  - β_N, density, q profile play a role in changing threshold & varied somewhat across points taken
  - Requires careful analysis to strip out – ***data taken to enable this***
- Some reasonably matched points show preliminary trend
  - Well fitted by offset linear or quadratic fits
  - But possible underlying density dependence (lower with B_t)
- Good scan obtained to pull out principal scalings, analysis underway and should be able to pull out main trends

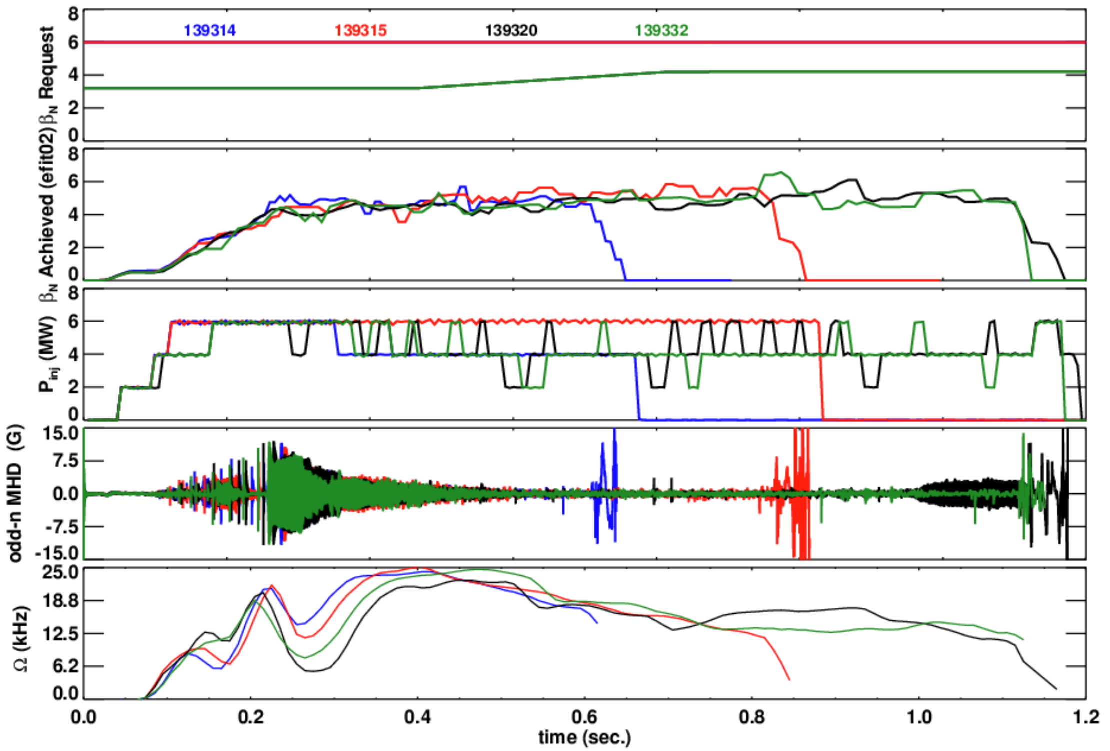


XP-1019 Developed β_N Control

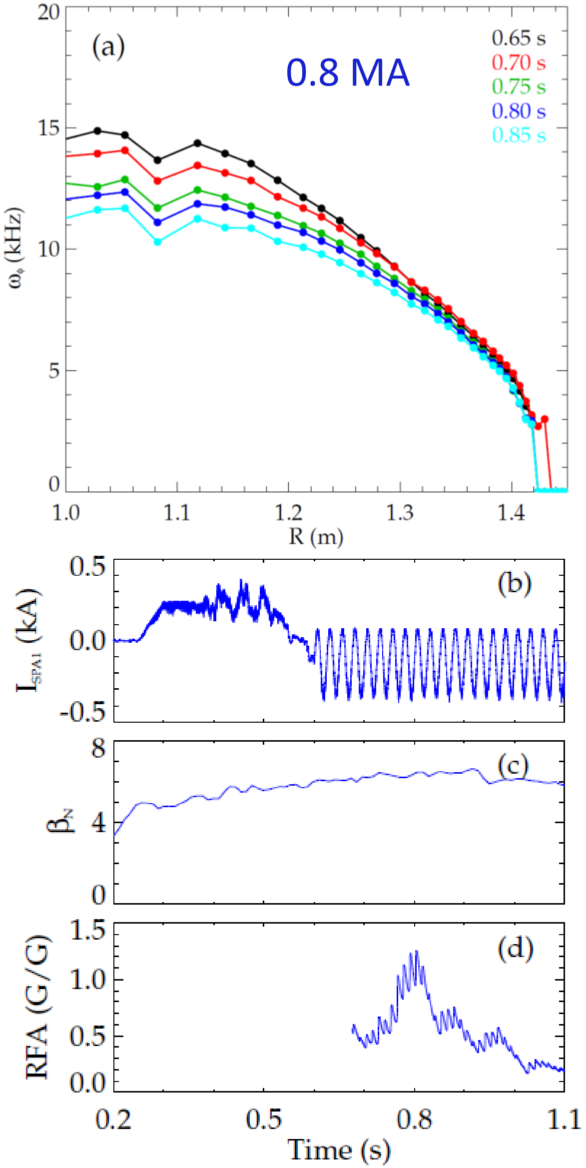
- XMP commissioned the algorithm, including a new PID scheme compared to 2009.
  - Thanks Mike and Egemen for useful suggestions.
- Completed XP over two 1/3 day runs.
- β_N control system is ready for use as desired for XPs.
  - Use is encouraged, but you should talk to SPG about setting it up, and whether extra complication would really be worth it for your XP.

Example

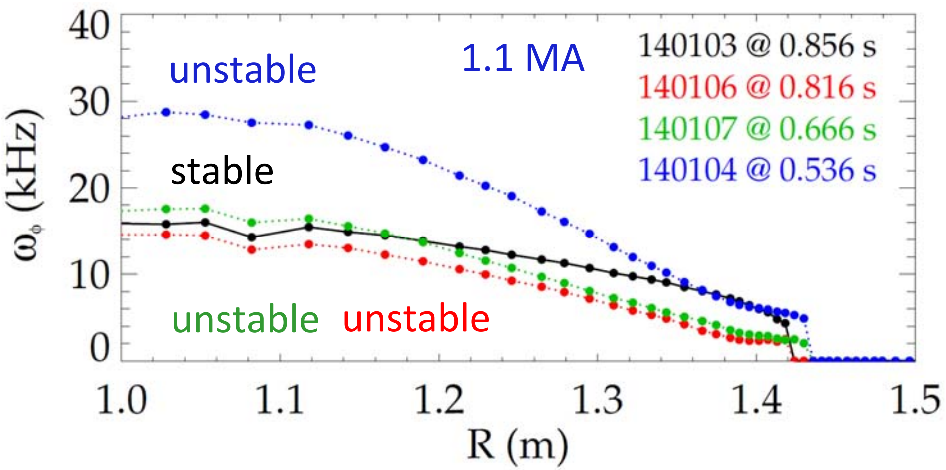
- High-κ discharge appropriate for ASC or MS performance XPs
- Discharges disrupts with high-β MHD at 4 & 6 MW
  - 4 MW case further evidence of the Berkery weak RWM stability rotation state?
- Discharges with β_N control last considerably longer.
- Intermediate β_N was apparently optimal.



XP1020 explored RWM stability with ω_ϕ and EP fraction, with RFA measurements, for comparison to kinetic theory



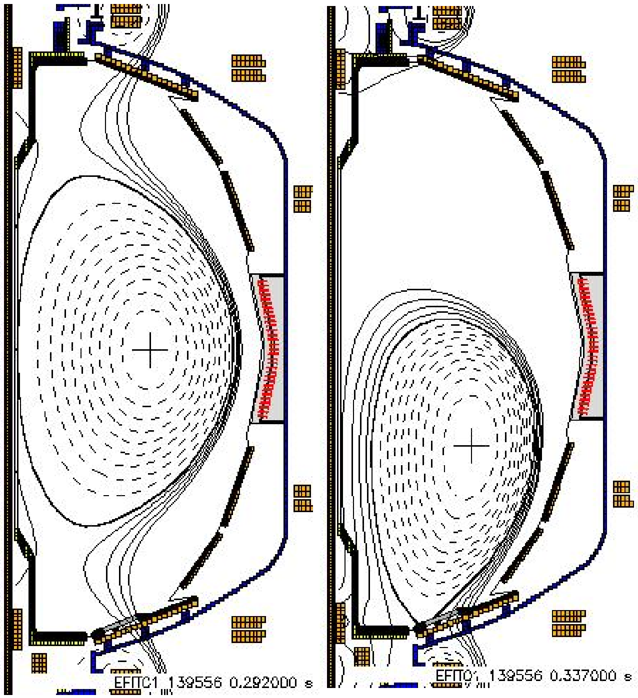
- Two half-days 4/15 and 8/19:
  - Second day successful in low li target.
- ω_φ slowed with n=3 magnetic braking for various EP fractions (I_p, B_t scan)
  - Weak stability region at intermediate ω_φ shows in RFA?
  - Plasma can survive it (left), or not (below).
  - Further analysis with MISK must be performed.
  - Many shots with long, slow, rotation decreases and many RFA periods were obtained.

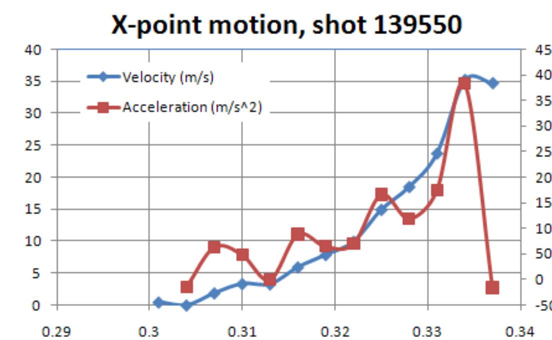


XP1021 Halo curent study - accomplishments in 2010

- Excellent afternoon on 8/4/2010, shots 139529-139557, and morning of 8/27/2010, shots 140438-140461
- Developed 2 MW inner-wall limited L-mode shot with reliably triggered VDE using an 80 V downward bias on PF3.
- Performed scans of $600<I_p<800$ kA and $0.35<B_t<0.55$ T ($0.45<I_p^2/B_t<1.83$).
- Injected power/stored energy scan: P_{NBI} at 0.0, 0.3, 1.0, 2.0, 3.0, and 4.0 MW.
- Repeat cases identical to previous years to test Li effect on halo currents, home in on the cause of the reduced HC compared to 2009

139556, t=0.292 sec. *139556, t=0.337 sec.*

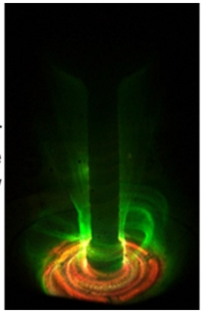




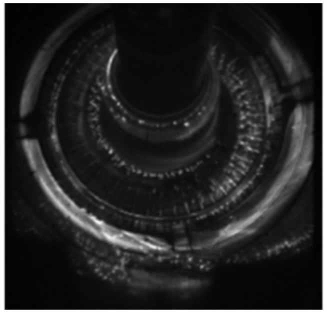
XP1021: Halo current/disruption study results to date suggests significant role of lithium

- Found halo current magnitude to be significantly less than found in previous conditions of XP833 (~1/2), possibly due to presence of Li.
- Linear trend in HC magnitude vs. B_t/I_p^2 but offset from 2009
- Extremely high surface heat fluxes through disruption with dual-band fast IR camera (1.6 KHz, 10 us integration time); estimated at >100 MW/m^2 (Ahn/McLean)
- Structure observed in I_{sat} of high density Langmuir probe array during disruptions, ripe for T_e measurements (Jaworski)
- Full fast camera view of lower divertor will allow estimation of Li and C fluxes from the floor through disruption (Scotti/Roquemore)

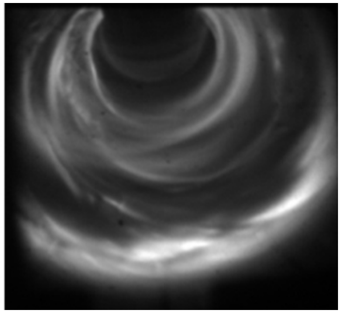
Color Midplane View



Lower divertor Li I (670 nm) 1 μs



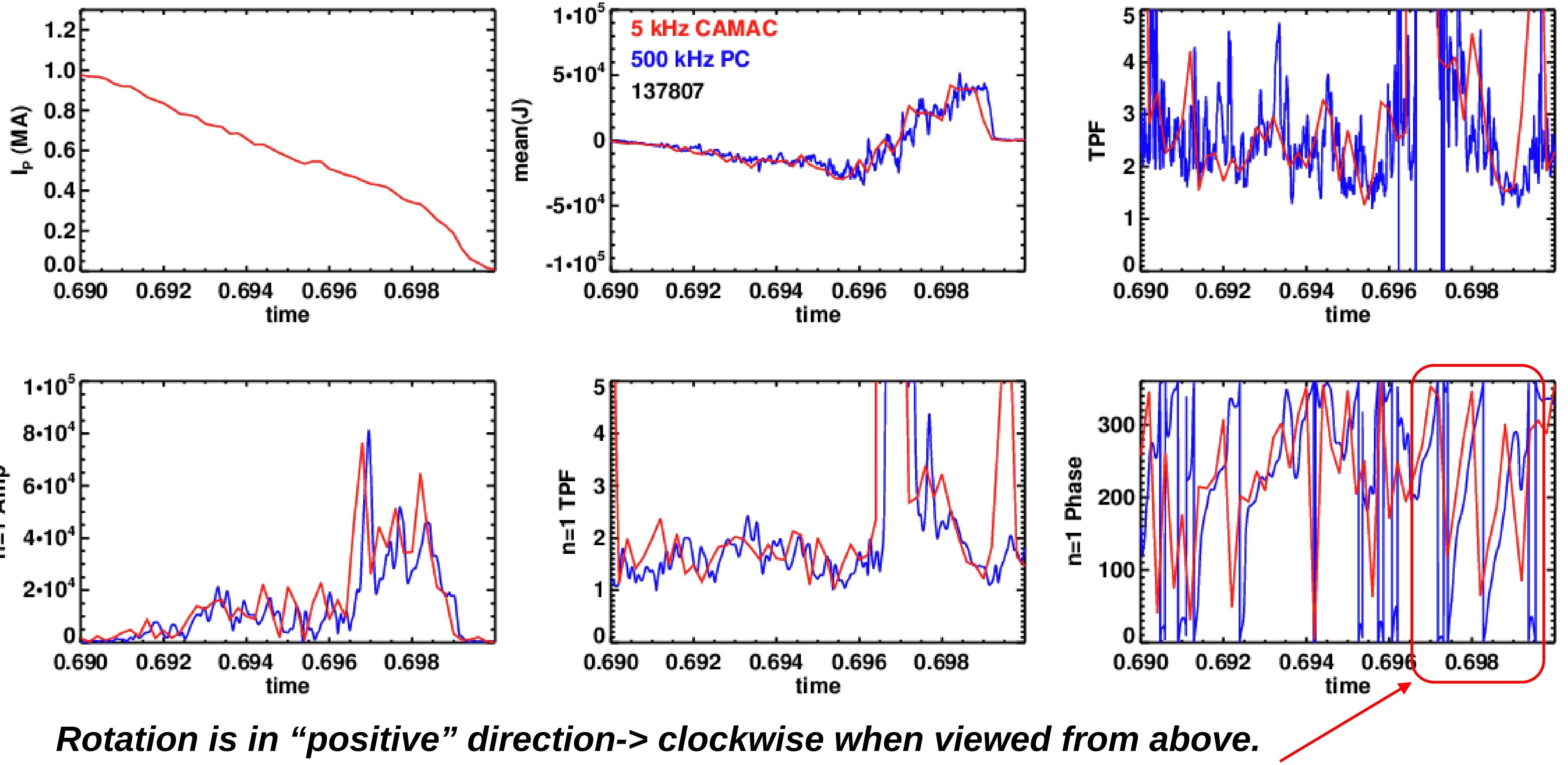
Lower divertor Li II (548 nm) 2 μs



- Applied n=1 fields with two different phases.
  - Unable to prevent halo current pattern from rotating with n=1 fields
  - Not explored further in 2010; further study may lead to recommendations for 2011

Fourier Analysis Confirms That the Halo Current Pattern Is Indeed Rotating

$$I\left(I_0(t), I_1(t), \phi_1(t)\right) = I_0(t) + I_1(t)\cos\left(\theta - \phi_1(t)\right)$$



Rotation is in “positive” direction-> clockwise when viewed from above.

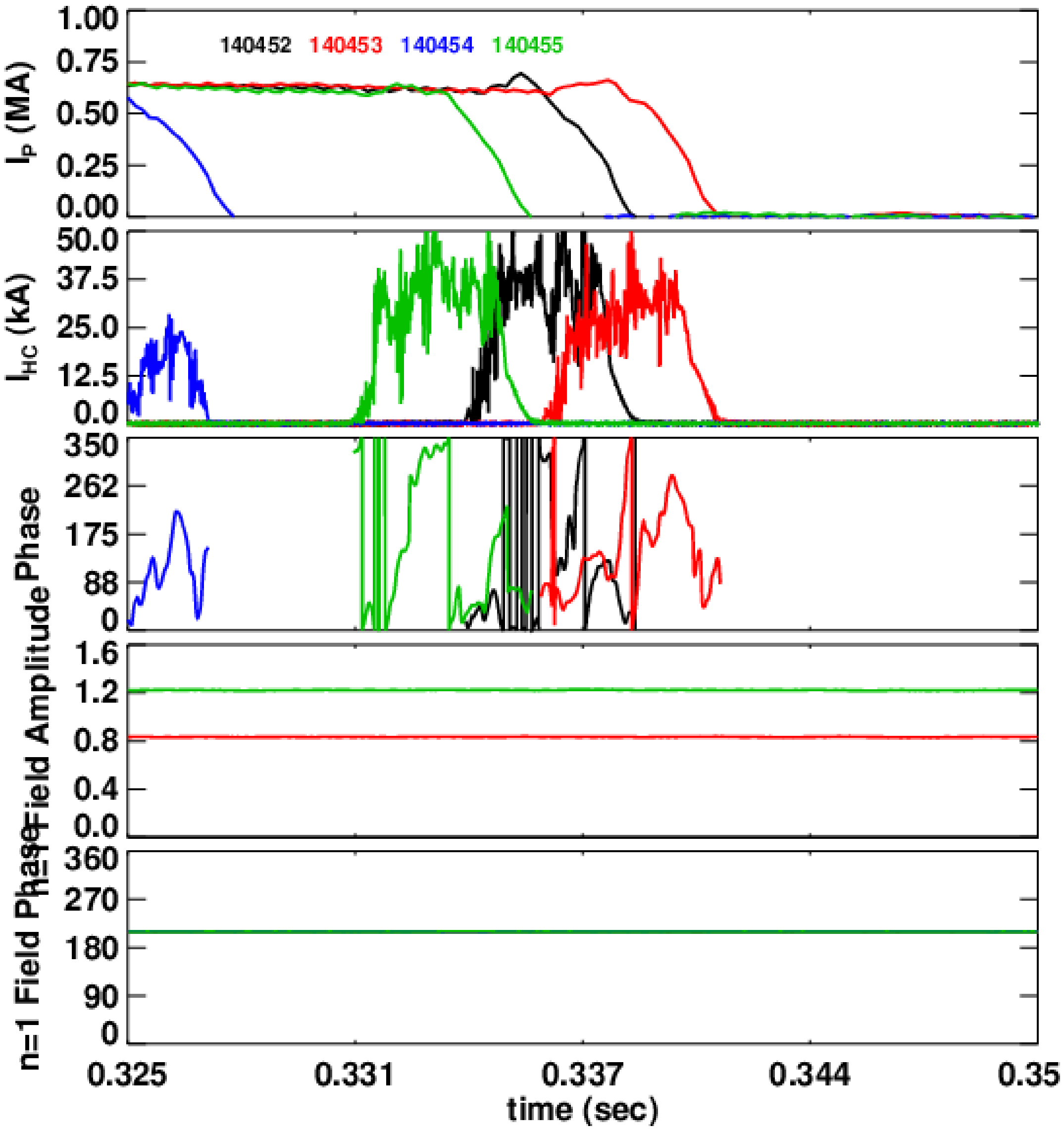
Opposite to both the plasma current and flat-top rotation direction.

Rotation frequency is ~1 kHz

S. Gerhardt

XP1021: Unable To Prevent Halo Current Pattern From Rotating With n=1 Fields

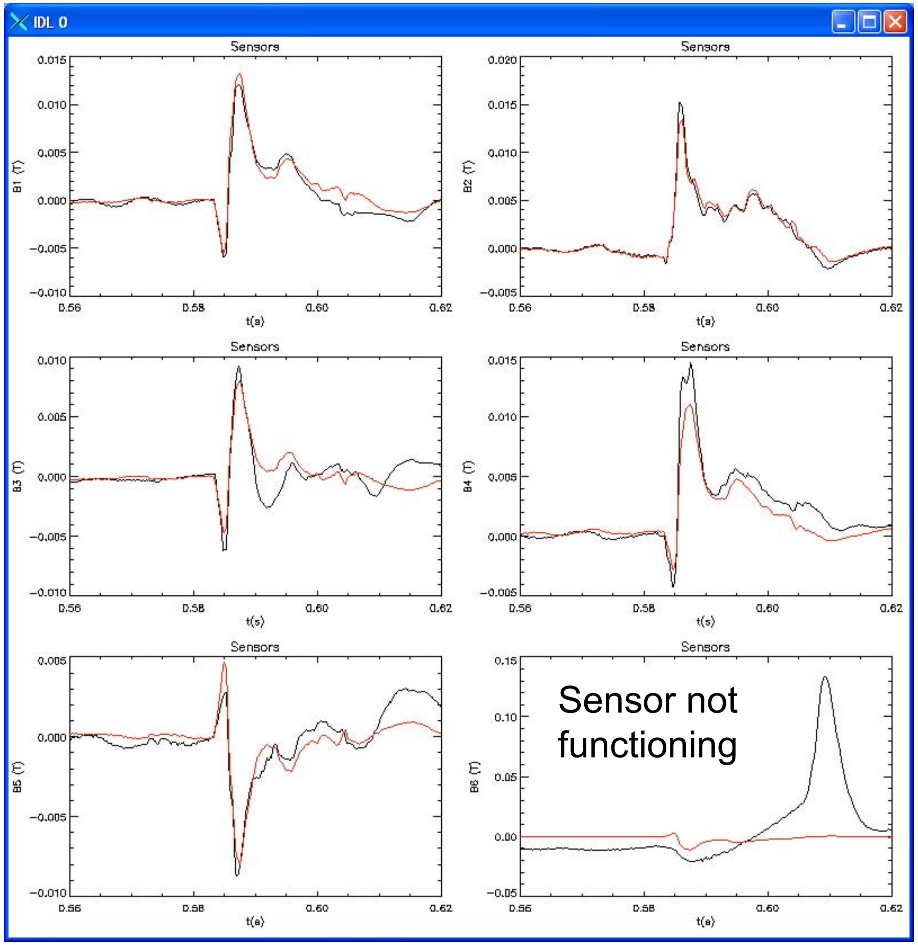
- Deliberate VDEs in L-mode 1 source shots
- Large halo current pulse proceeding and during disruption.
- Phase continues to rotate…
- …despite >1 kA of n=1 RWM coil current.
- ITER would like to control HC rotation to avoid mechanical resonances…not an encouraging result.



XP1022 RWM State Space Control in NSTX – maiden voyage of new, versatile controller

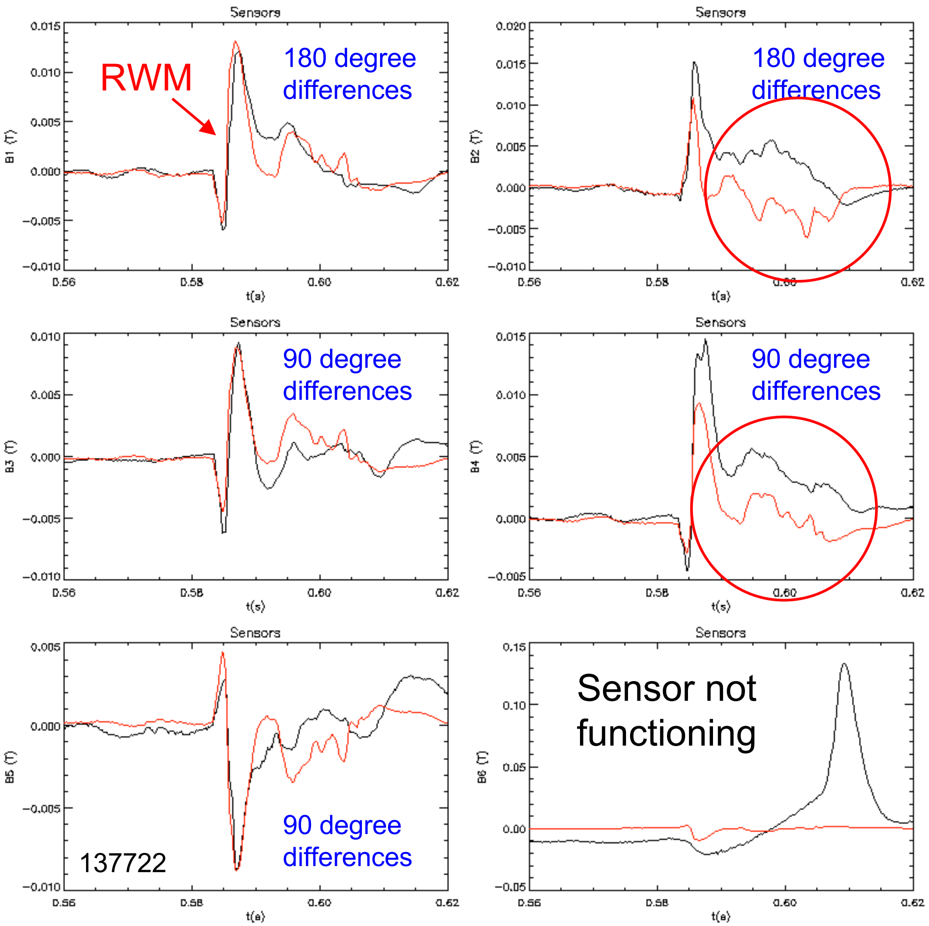
- New NSTX RWM state-space controller, implemented by Columbia U. and PPPL
  - Expandable to accommodate new SPA unit, independent RWM coil control, n > 1
- First run
  - Control of resonant field amplification of both DC and AC applied n = 1 fields examined
  - primary controller parameters were varied
  - Variations in mode control were observed as feedback phase was varied
  - Long pulse I_p = 1MA target plasmas at low l_i and high normalized beta were produced
    - "record values" achieved at I_p = 1MA – analysis ongoing
- First application of such a controller in low collisionality, high beta plasmas
  - Additional run time needed to fully establish mode control physics (0.5 day)

RWM B_p UPPER Sensor differences

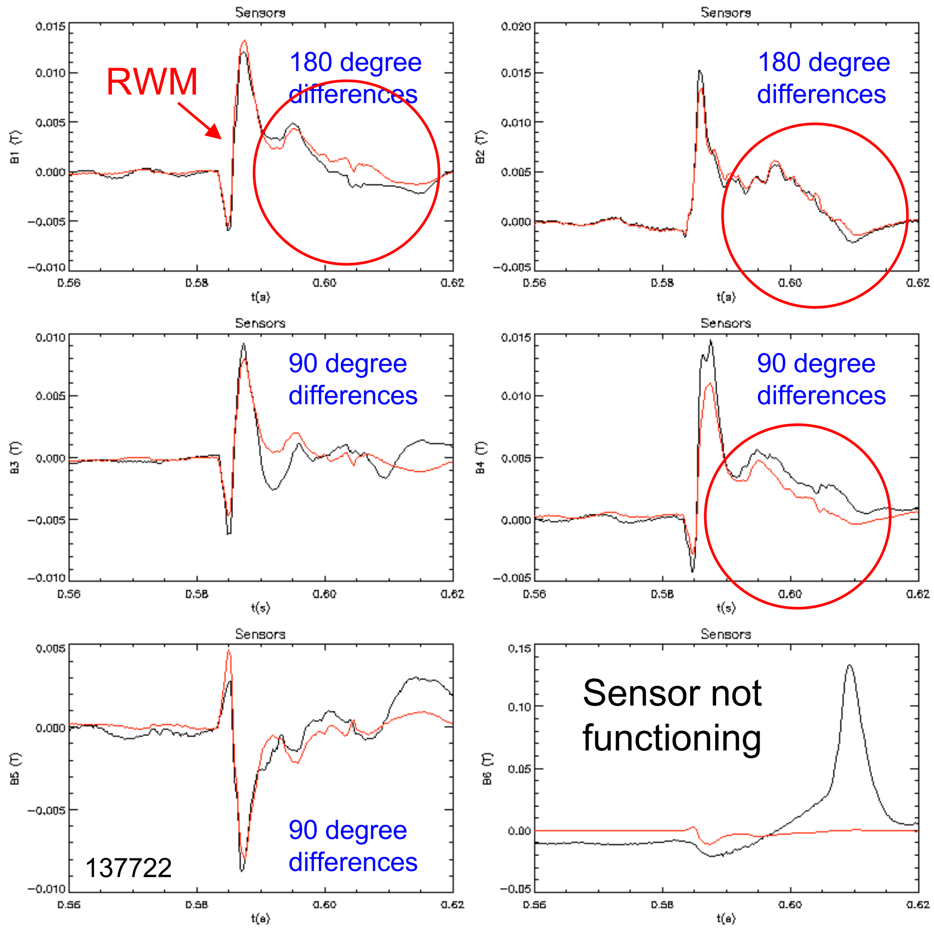


Offline testing: RWMSC observer with 2 states reproduces initial sensor response to mode, 7 states improves match overall

B_p UPPER Sensor differences – 2 states



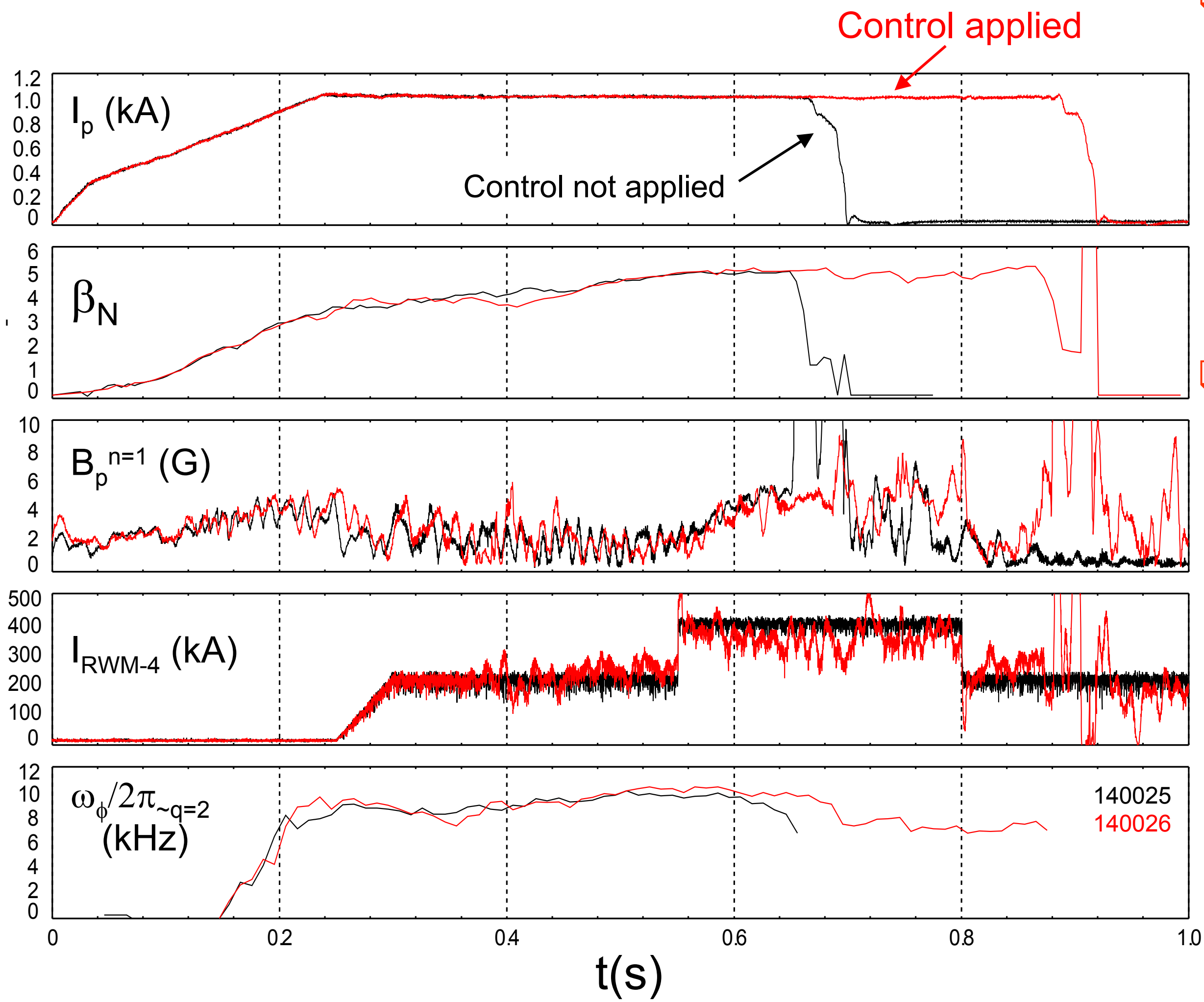
B_p UPPER Sensor differences – 7 states



- Reasonable match to all sensors during RWM onset, large differences late in time
- Better match to sensors late in time, some mismatch to 90 degree sensors (n = 2?)

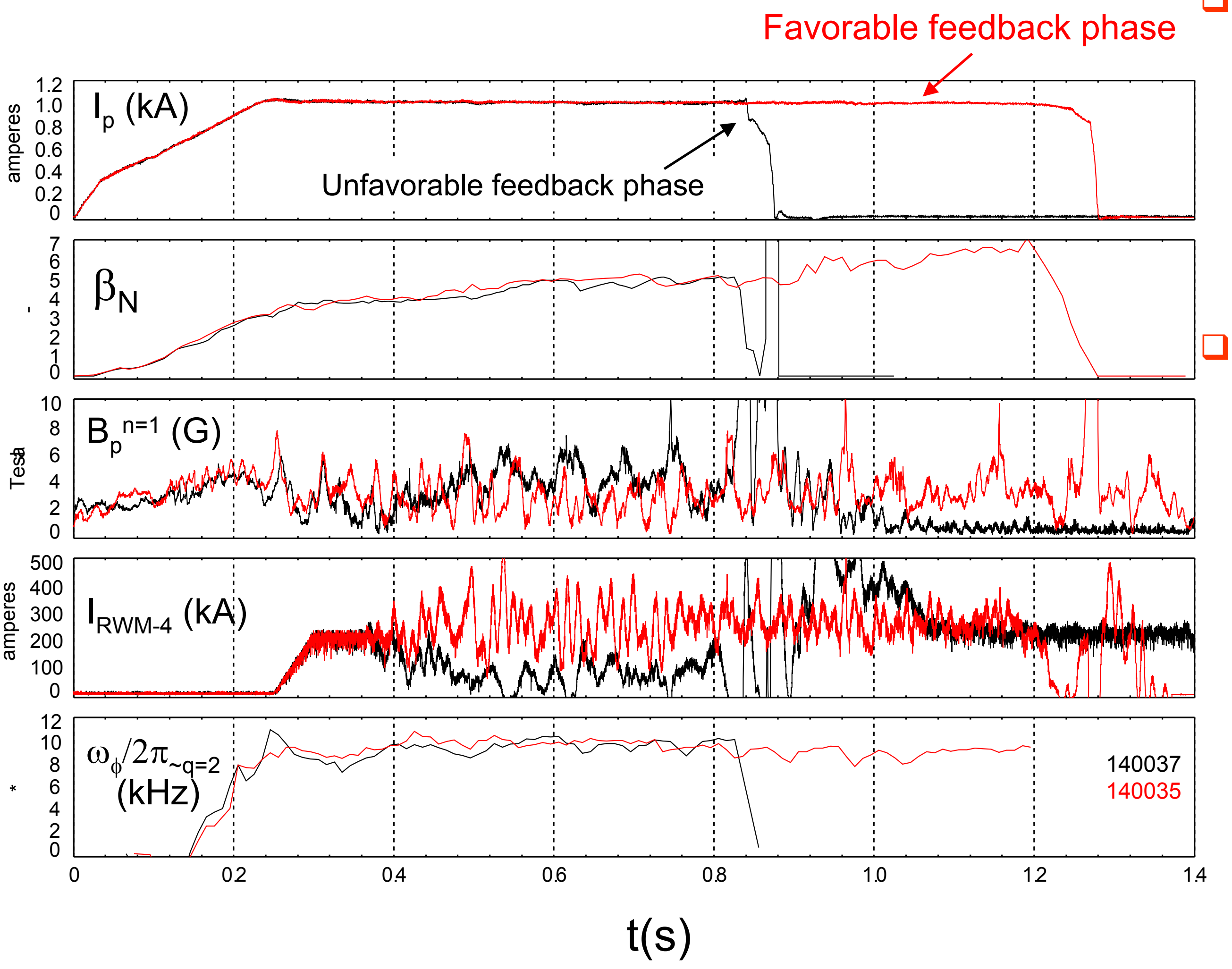
Black: PID
Red: offline RWMSC

XP1022 RWM state space controller sustains an otherwise disrupted plasma caused by DC n = 1 applied field



- n = 1 DC applied field
  - Simple method to generate resonant field amplication
  - Can lead to mode onset, disruption
- RWM state space controller sustains discharge
  - With control, plasma survives n = 1 pulse
  - n = 1 DC field reduced
  - Transients controlled and do not lead to disruption
  - NOTE: initial run – gains NOT optimized

XP1022 Feedback phase scan for RWM state space controller shows favorable/unfavorable settings

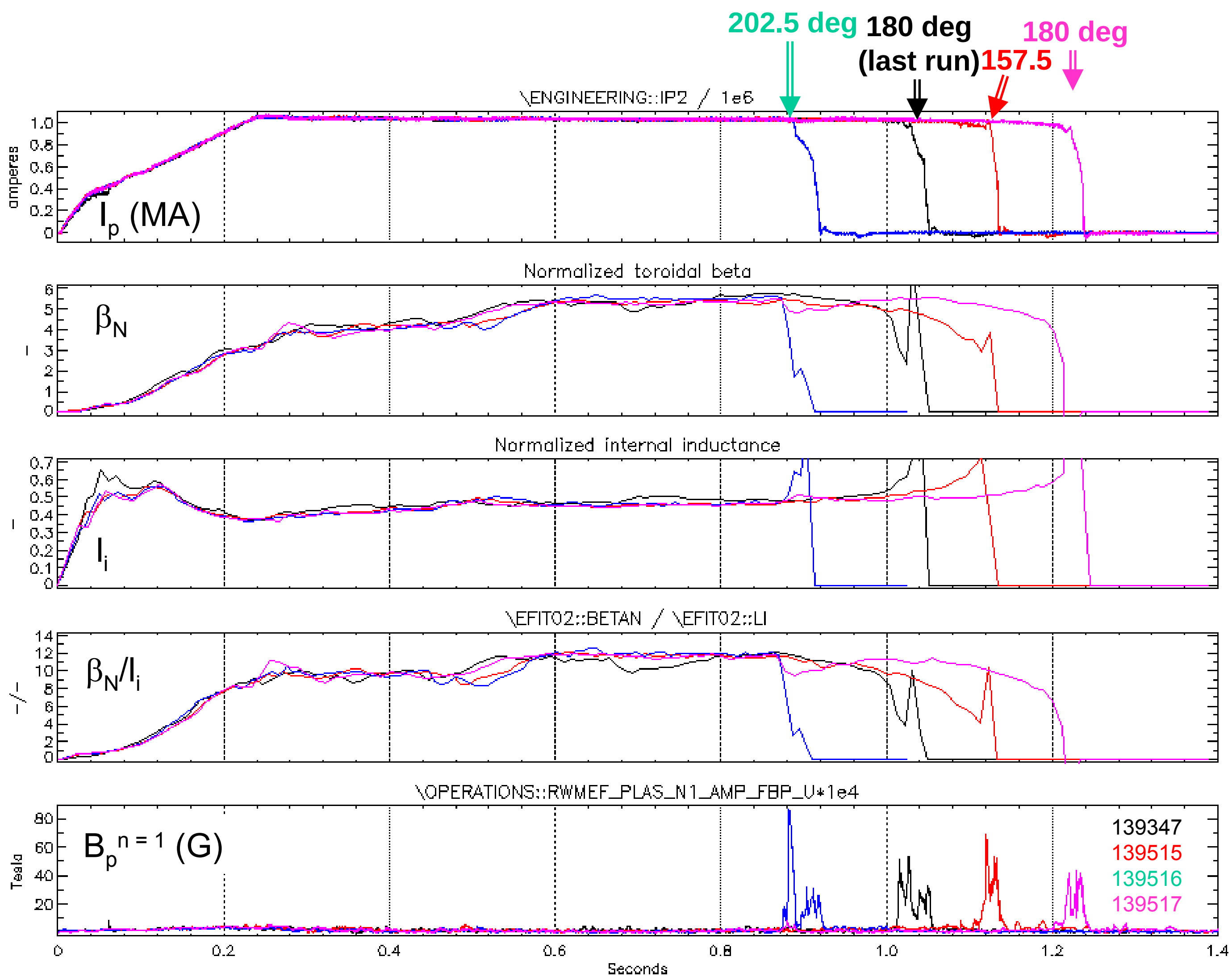


- Feedback phase scan
  - 8 settings taken, two examples shown
  - Favorable settings found
    - long pulse, high β_N
    - sustained rotation
- Significant stability performance reached with RWMSC on
  - Highest pulse length for I_p = 1 MA plasma
  - High β_N exceeding 6.4 at I_p = 1 MA
    - Record β_N/l_i exceeding 13
  - NOTE: initial run – gains NOT optimized
    - gains should be increased, based on comparison to PID controller results

XP1023: Optimized RWM feedback control for high $\langle\beta_N\rangle_{pulse}$ at low collisionality and l_i

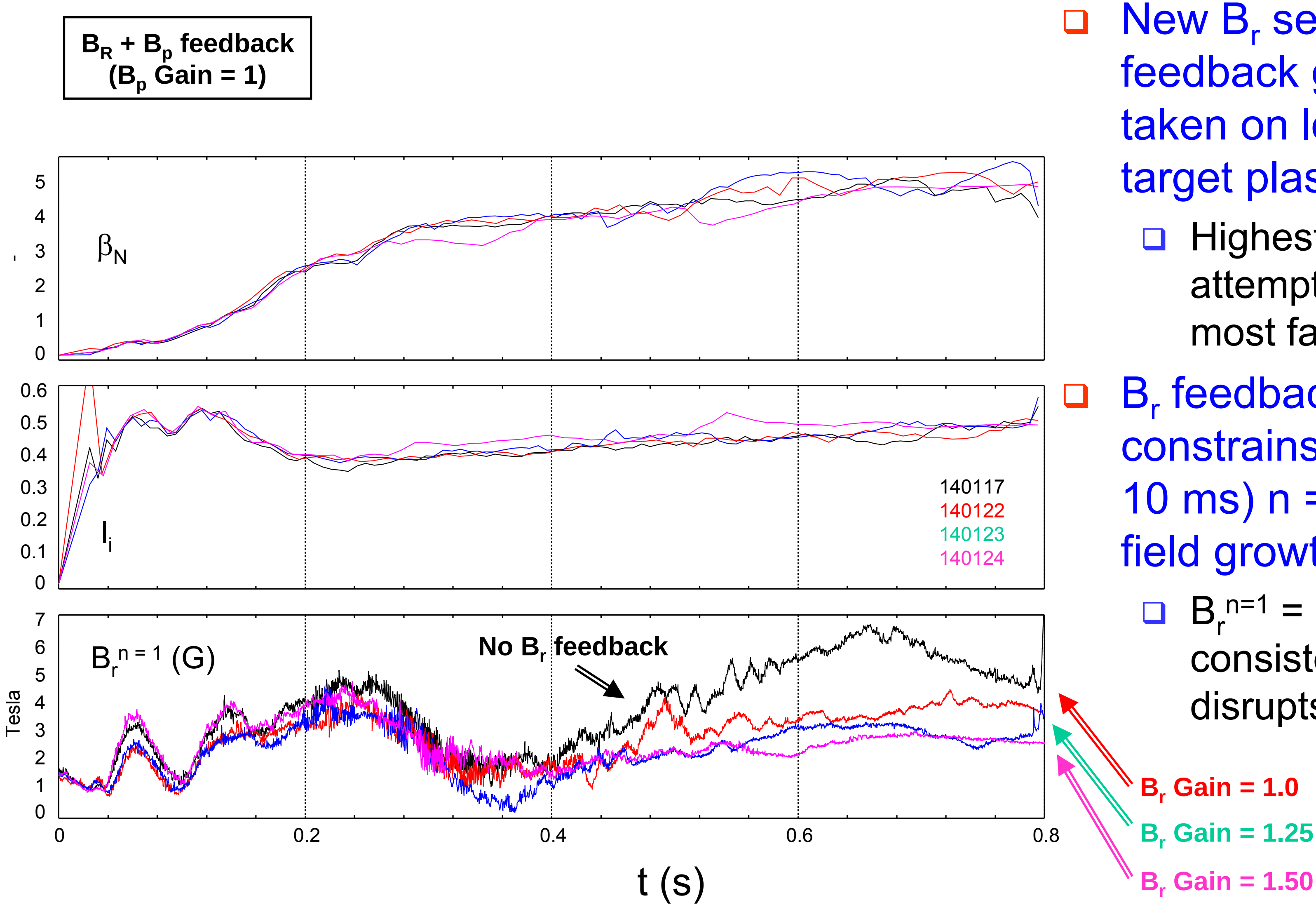
- Motivation / overall goal
  - Next-step ST devices (including the planned upgrade of NSTX) aim to operate at plasma collisionality and li below usual NSTX levels
  - Improve reliability of RWM stabilization at low l_i (and all plasmas)
    - Past low l_i operation showed significantly higher RWM activity, lower β_N limit, at reduced l_i
- Progress
  - Generated reduced l_i target plasmas, unstable RWMs without V_ϕ reduction
  - New optimal settings for n = 1 RWM control have changed significantly
    - Due to new, improved "miu" mode ID algorithm, the low l_i plasma, B_r spatial phasing (or all)
  - Feedback on B_r sensors works (and works well); feedback phase setting very different than found in XP802, etc.
    - most likely due to the OHxTF compensation of B_r in the miu algorithm
  - Generated many good shots: low l_i (~ 0.45) at high β_N with very high β_N/l_i of 12 – 13+
    - Both B_p and B_R sensors now used in feedback
    - Gain and feedback phase scans made for both B_p and B_R sensors
    - "Optimal" settings found (now running in fiducial / similar high delta shots very well)
    - FAR GREATER control than for past shots (I_p = 0.8 and 1.0 MA plasmas, shots repeated)
    - I_p = 1.1 MA targets have not generated such high performance (yet), did generate RWMs
  - Shots presently limited by loss of low l_i state, rather than RWM instability
    - Great deal of physics here – edge cooling e.g. due to low frequency (~ 200 Hz) edge activity
    - Completed XP by completing low plasma rotation scan – low plasma rotation accessed (9/24/10)

XP1023: Changing B_p sensor feedback phase around 180 degrees led to long-pulse, low l_i, high β_N/l_i



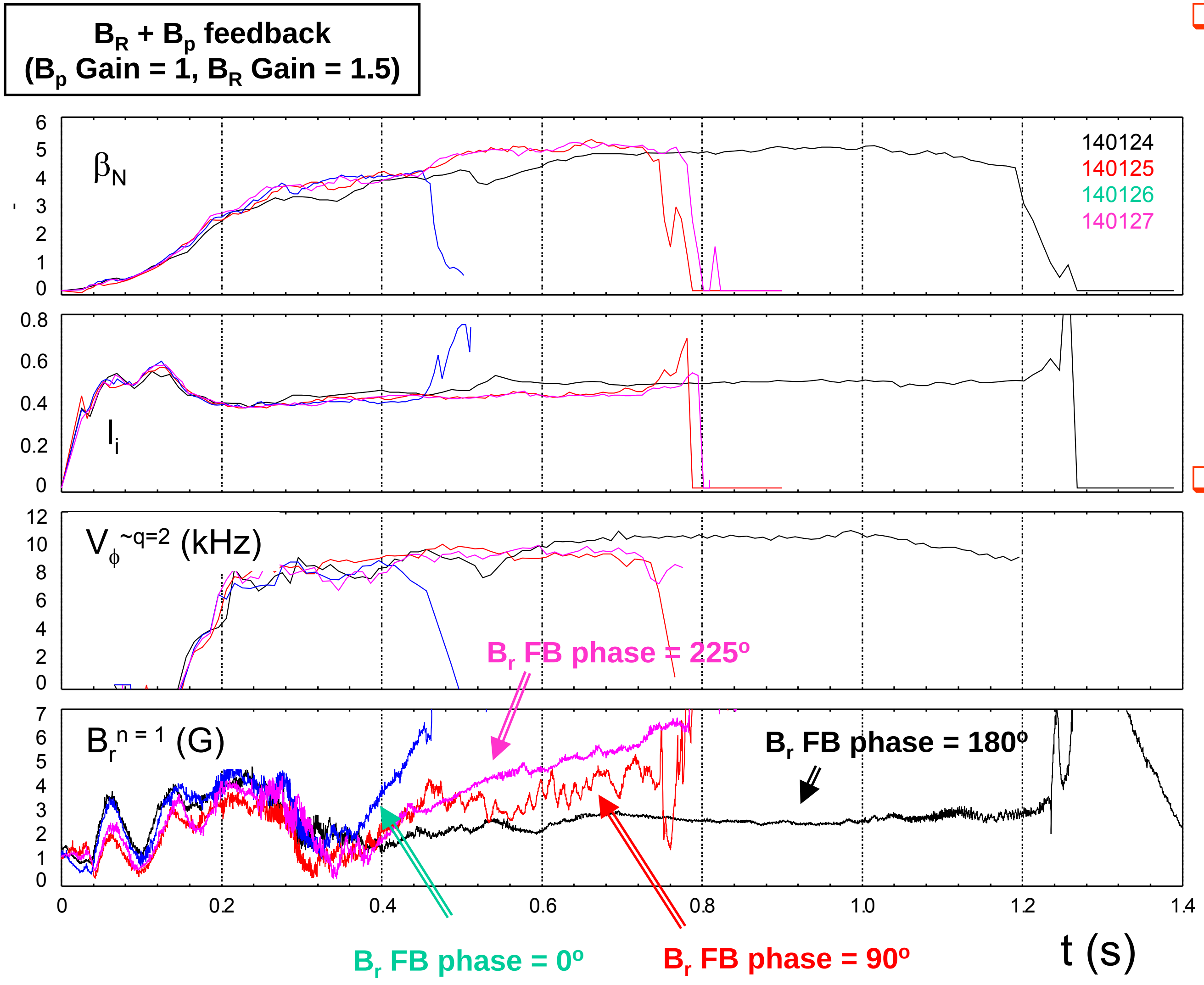
- Steady, high β_N/l_i
  - Between 12 – 13
- Low l_i state retained

XP1023: RWM B_R sensor feedback reduces n= 1 radial error field significantly



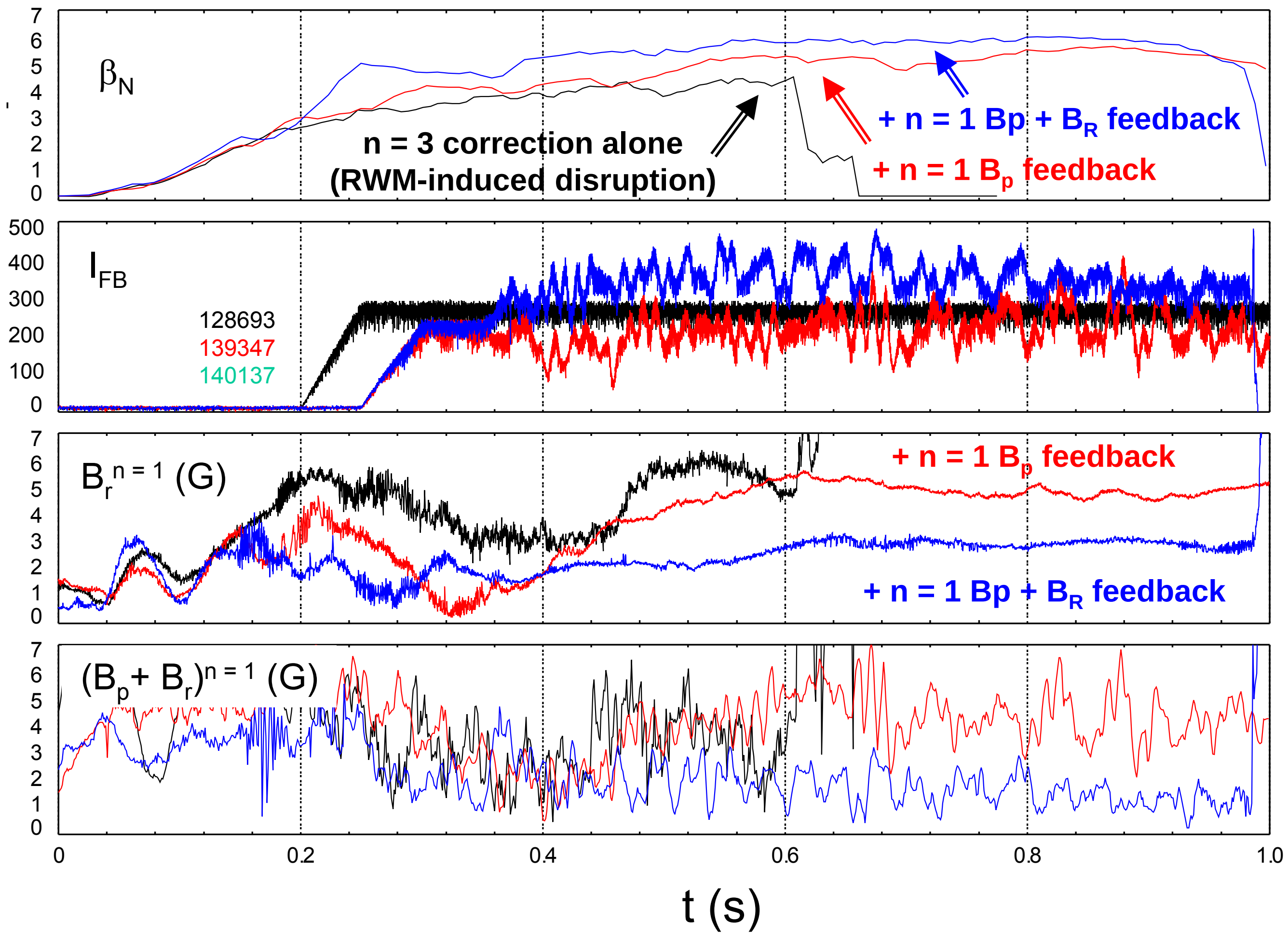
- New B_r sensor feedback gain scan taken on low l_i target plasmas
  - Highest gain attempted (1.5) most favorable
- B_r feedback constrains slow (~ 10 ms) n = 1 radial field growth
  - $B_r^{n=1}$ = 9G consistently disrupts plasma

XP1023: RWM B_R sensor n= 1 feedback phase variation shows clear settings for positive/negative feedback



- B_r sensor feedback phase scan shows superior settings
  - Result clarified significantly by new MIU algorithm OHxTF compensation
- Positive/negative feedback produced at expected phase values
  - 180° negative FB
  - 0° positive FB
  - n=1 growth/decay of other settings bracketed by 0°, 180° settings

XP1023: Use of combined RWM sensor n= 1 feedback yields best reduction of n = 1 fields / improved stability



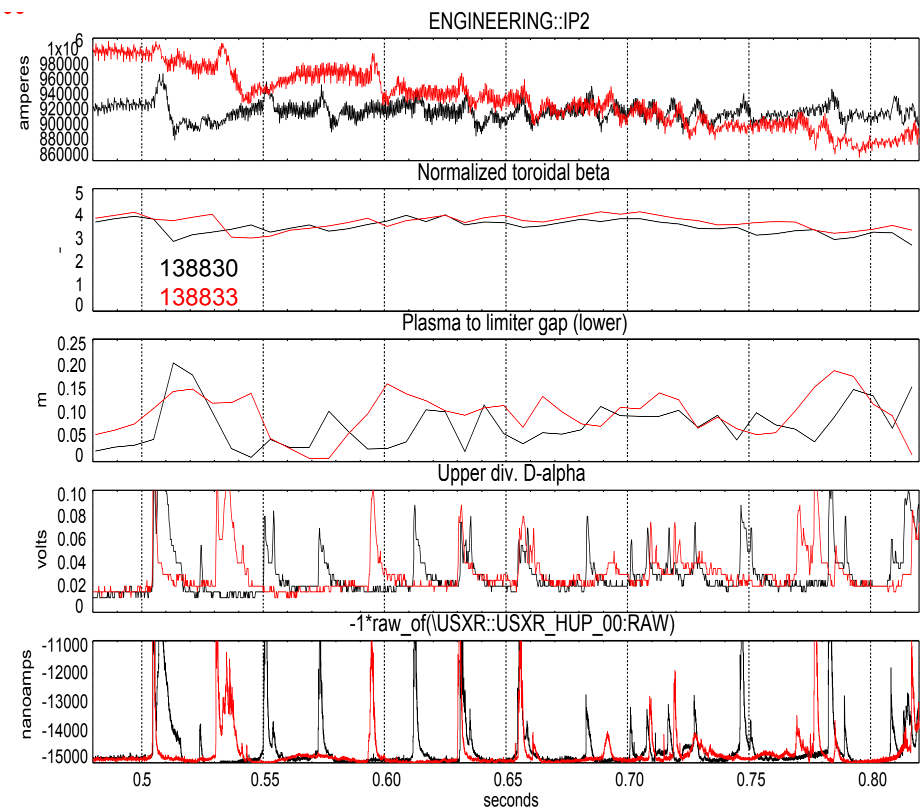
- Varied levels of n > 1 field correction
  - n = 3 DC error field correction alone more subject to RWM instability
  - n = 1 B_p sensor fast feedback sustains plasma
  - Addition of n = 1 B_R sensor FB prevents disruptions when amplitude reaches ~ 9G, better sustains rotation

XP1031 MHD/ELM stability dependence on thermoelectric current, edge J, ν

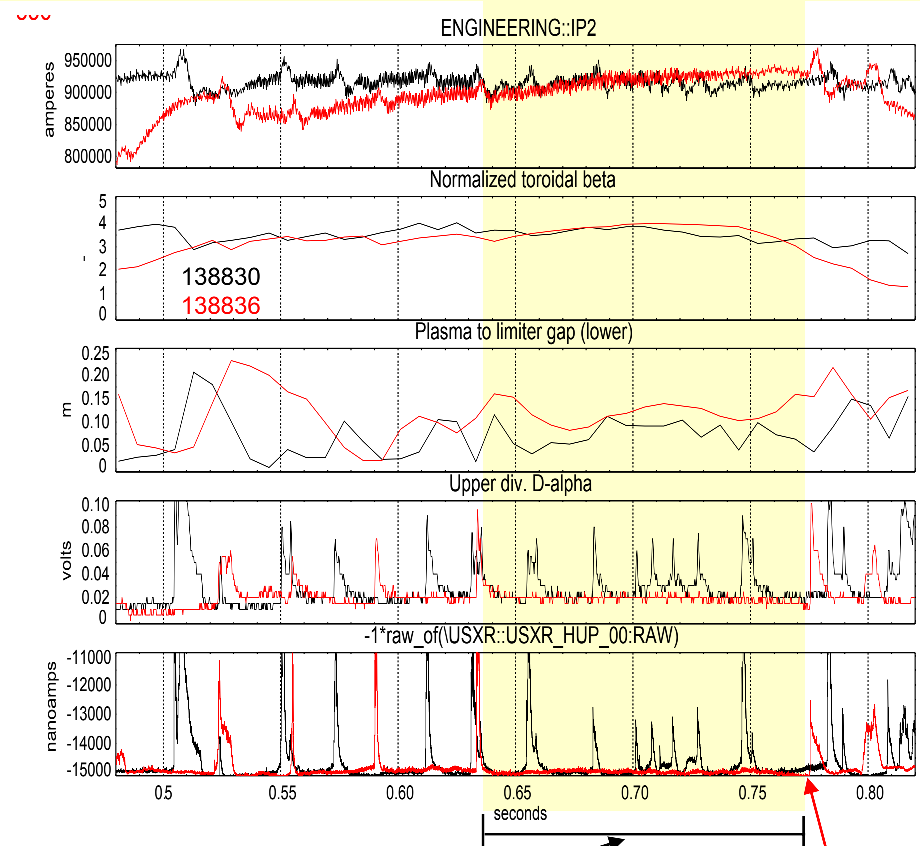
- Goals/Approach
  - Test expectations ELM stability theory considering changes to edge toroidal current density, field-aligned thermoelectric current, and collisionality
    - 1) Generate target
    - 2) Vary TE current connection length at fixed 3D field (Vary x-point height; DRSEP)
    - 3) Vary 3D field amplitude
    - 4) Vary toroidal current density near the edge
    - 5) Vary collisionality with LLD
- Present data
  - Ran many shots on list (except reduced ν); need to examine data in detail
    - X-point height and DRSEP varied separately (tricky for operators early on)
      - ELMs change with variation – much detail to sort out here
    - Target reproduced with ELMs induced by 3D field
    - 50 Hz n = 3 field primarily used, DC field tried but led to rotation issues
    - Scrape-off layer currents detail measured by LLD shunt tiles / Langmuir probe arrays
      - e.g. n = 1 clearly seen during initial part of ELM, changing to n = even
    - Evidence of ELM stabilization when positive edge current applied (constant B_t)
- XP nearly completed
  - 2 hours requested to complete I_p ramp scan with 3D fields

XP1031: Evidence of ELM stabilization with positive current ramp + 3D field during ELMing phase in medium triangularity plasma

Constant I_p and decrease edge J: similar ELMing



Constant I_p and increase edge J: ELM-free period found



ELM-free period (plasma in H-mode)

H-L back-transition

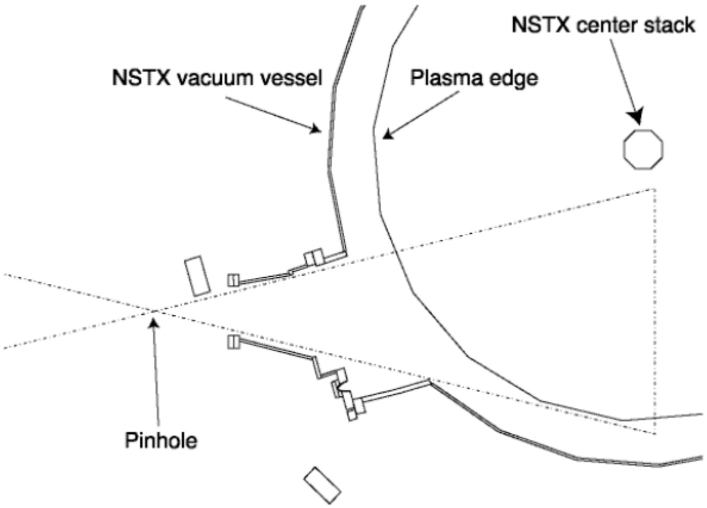
- Recent run with fiducial target did not stabilize ELMs with positive current ramp
  - Due to higher triangularity target, different q profile (possible resonance effect)?
  - Due to stronger n=3 field in more recent shot?

XP1062 started: Verify NTV physics for next-step devices (NSTX-U to ST-CT / ITER), and support NSTX rotation control system design

- **Motivation**
  - Verify neoclassical toroidal viscosity physics for next-step devices (NSTX-U to ST-CT / ITER), and to support design of NSTX rotation control system
- **Goals / Approach**
  - Compare magnetic braking with largest variation of ν_i* using LLD
    - Target a comparison of two conditions: low vs. high ν_i* , favor low ν_i* condition
    - Compare to past braking XPs if high ν_i* condition is difficult to produce
    - RESULT: NTV braking detail measured at lower ν_i* by at least a factor of 2, due to lack of prefill gas in 3 braking shots
  - Generate greater variation of key parameter $(\nu_i/\varepsilon)/|nq\omega_E|$
    - Concentrate on low ω_E to further examine superbanana plateau regime/theory
    - RESULT: NTV braking brought plasma to low rotation (< 7kHz core, < 2kHz ~ q=2) – increase in braking torque observed at low ω_E, analysis continues
  - Determine NTV offset rotation
    - Standard approach: attempt to observe offset by operating at near-zero ω_ϕ (might be easier with LLD)
    - RESULT: Further data taken – no indication of a large NTV offset rotation (< 1kHz)
    - Consider new approach using RF (based on RF XPs from 2009) – not yet run!
      - Generate ω_ϕ with RF at highest T_i, W_{tot} possible, diagnose similar to Hosea/Podesta 2009
      - Repeat for different *initial* values of n = 3 braking field, determine of initial ω_ϕ changes

SXR camera system on NSTX upgraded to capture full-shot data at speeds up to 125 kHz (analysis shown in movie)

- Fast tangential SXR camera
  - Midplane, full-radius imaging
  - Remotely selectable pinholes (2 – 8 cm spatial resolution) & filters



- PSI5 CCD replaced with Phantom CMOS

	PSI5 (CCD)	Phantom 4 (CMOS)	Phantom 7 (CMOS)
Max Frame Rate	500 kHz (64 x 64)	58 kHz (64 x 64)	121 kHz (64 x 64)
Exposure	Fixed by fps	Selectable	Selectable
Max frames	300	65k	200k
Readout noise	20e RMS	Probably larger	Probably larger
Quan Eff (540 nm)	50%	22%	35%

D. Battaglia