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# Macroscopic Stability TSG XP status mid-run 2010


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NSTX Macroscopic Stability Topical Science Group


**NSTX Mid-run Assessment**

August 27th, 2010

Princeton Plasma Physics Laboratory

v1.2

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*Colorado Sch Mines*
*Columbia U*
*Comp-X*
*General Atomics*
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*Hebrew U*
*Ioffe Inst*
*RRC Kurchatov Inst*
*TRINITI*
*KBSI*
*KAIST*
*POSTECH*
*ASIPP*
*ENEA, Frascati*
*CEA, Cadarache*
*IPP, Jülich*
*IPP, Garching*
*ASCR, Czech Rep*
*U Quebec*

# 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 8/27/10

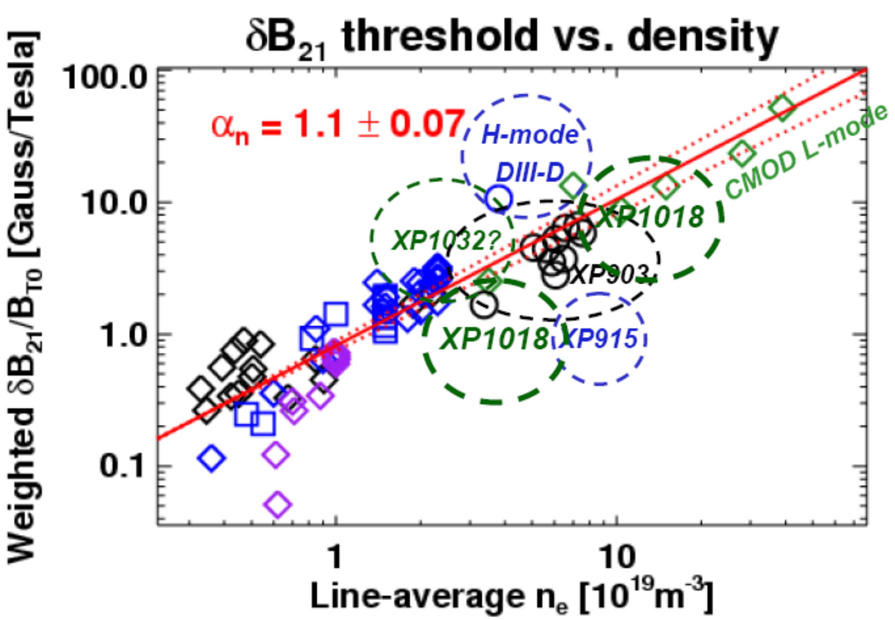
| Author | Proposal Title | NSTX Forum Allocations / Priority | | | XP / Status |
|---|---|---|---|---|---|
| J. Park | Error field threshold study at high-beta - reduced torque | 1.0 | 1 | 0.50 | XP1018 |
| Menard | Effects of non-res. fields on low/moderate beta locking threshold | 1.0 | 1 | 0.50 | |
| 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 aims to 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 (needs 2MW+)

# XP 1032: Error Field Threshold Scaling in H Modes

- **Status: XP drafted awaiting review and experiment time**
- **Goal:**
  - Elucidate toroidal field & density scaling of error field mode thresholds in intermediate $\beta_N$ H modes
    - Basis for extrapolating required correction requirements to future devices
- **Needs:**
  - Run time – up to 17 good shots.
  - N=1 field ramps, 3 beams, range of TF & Ip, $\beta$ feedback if poss.
  - Usual MHD diagnostics – CHERS, MSE,
  - Good machine conditions for shot reproducibility (li for ELMs?)
- **Availability: From Sept 7th onwards**

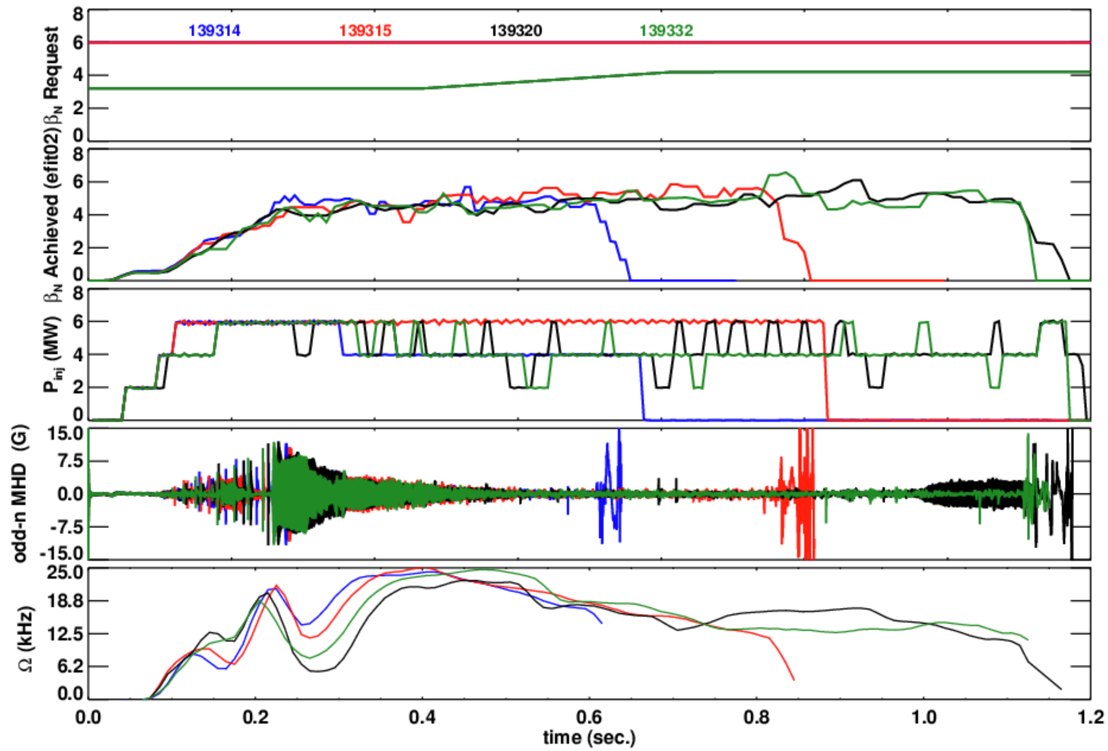
- Presently on run schedule
- Suggest that final arrangements for Richard's visit be made

# XP-1019 Developed $\beta_N$ Control

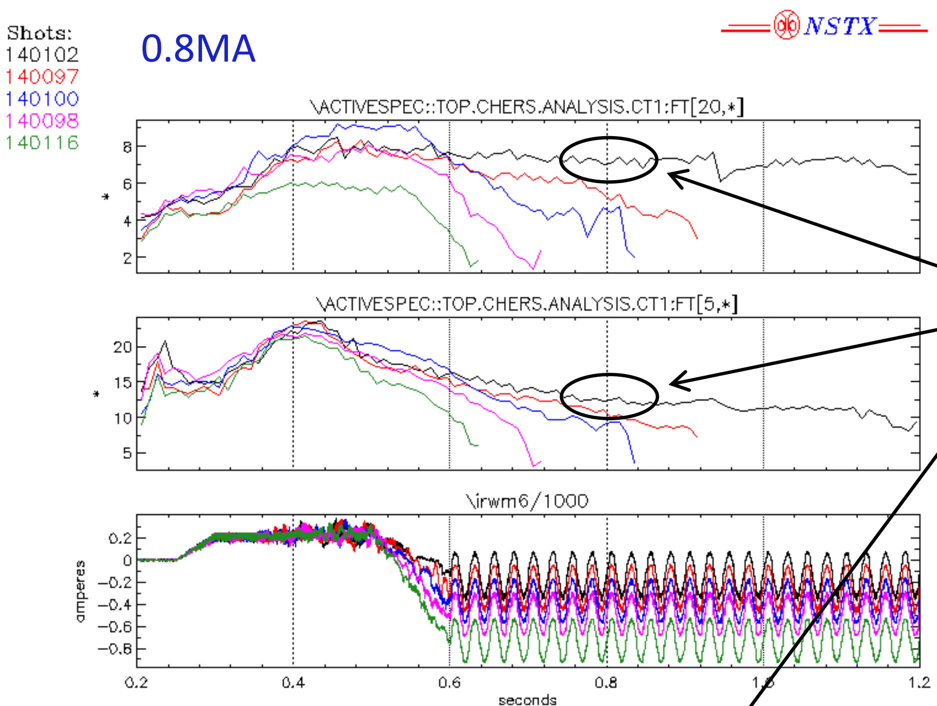
- XMP commissioned the algorithm, including a new PID scheme compared to 2009.
  - Thanks Mike and Egemen for useful suggestions.
- Completed XP over two 1/3 day runs.
- $\beta_N$ control system is ready for use as desired for XPs.
  - Use is encouraged, but you should talk to SPG about setting it up,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

***Example***

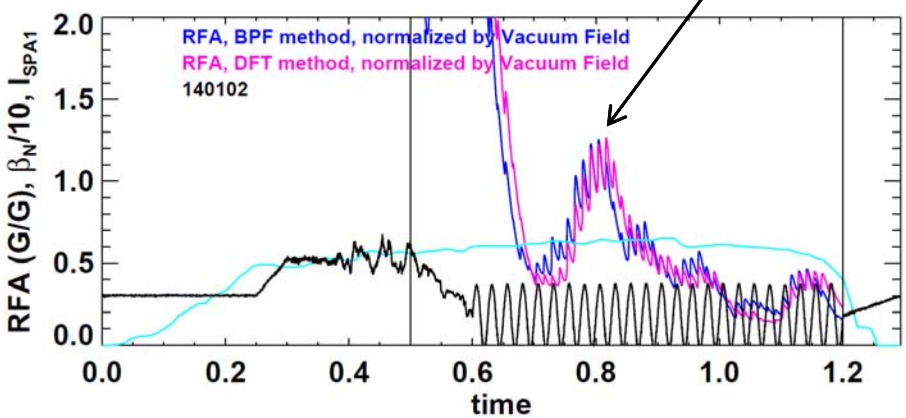
- High-κ discharge appropriate for ASC or MS performance XPs
- Discharges disrupts with high-β MHD at 4 & 6 MW
  - 4 MW case further evidence of the Berkery weak RWM stability rotation state?
- Discharges with $\beta_N$ control last considerably longer.
- Intermediate $\beta_N$ was apparently optimal.

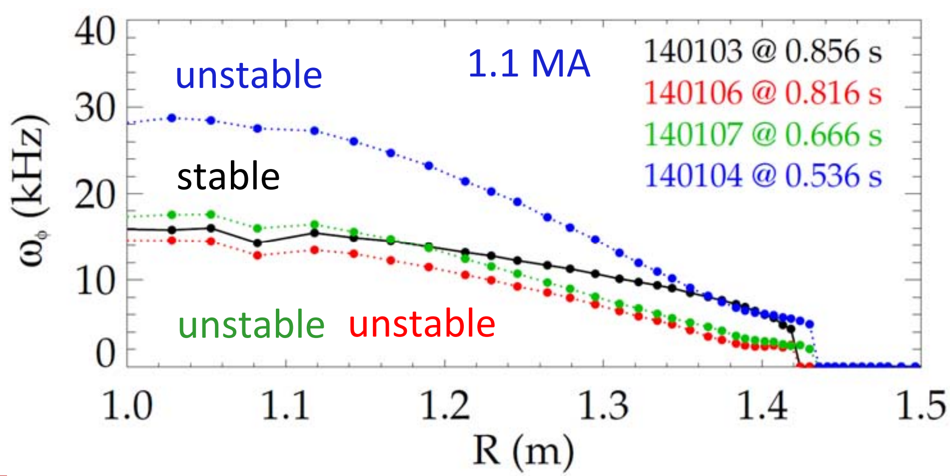


# XP1020 explored RWM stability with $\omega_\phi$ and EP fraction, with RFA measurements, for comparison to kinetic theory




- Two half-days 4/15 and 8/19:
  - Second day successful in low li target.
- $\omega_\varphi$ slowed with n=3 magnetic braking for various EP fractions ($I_p$, $B_t$ scan)
  - Weak stability region at intermediate $\omega_\varphi$ shows in RFA (examine further).
  - 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.

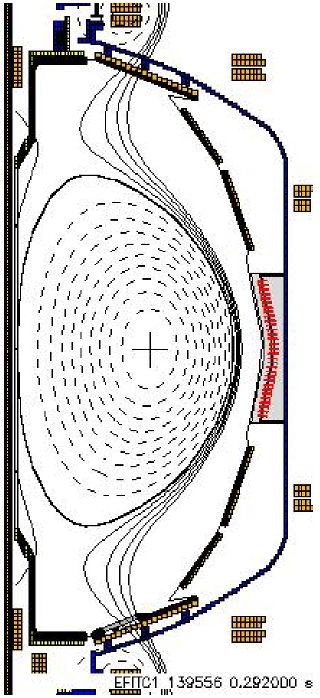


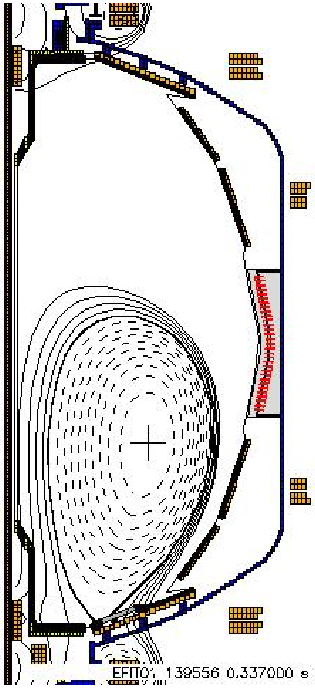
# XP1021 Halo current study with extended diagnostic capability - progress

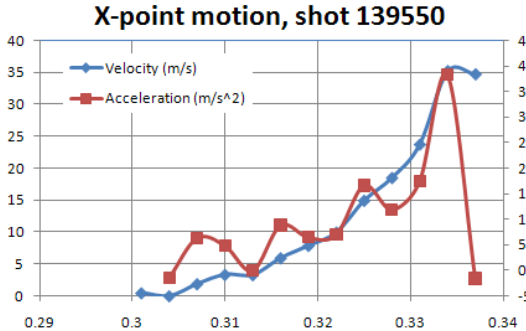
- Excellent afternoon on 8/4/2010, shots 139529-139557
- Developed 2 MW inner-wall limited L-mode shot with reliably triggered VDE using an 80 V downward bias on PF3.
- Performed scans of $600<I_p<800$ kA and $0.35<B_t<0.55$ T ($0.45<I_p^2/B_t<1.83$).
- Found halo current magnitude to be significantly less than found in previous conditions of XP833 (~1/2), possibly due to presence of Li.
- Applied n=1 fields with two different phases. Saw apparent locking of the halo current pattern to the applied field phase.

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



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



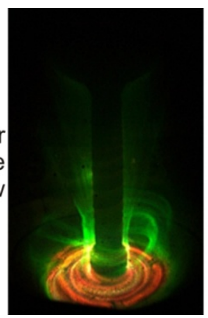


# Results motivate continued run time

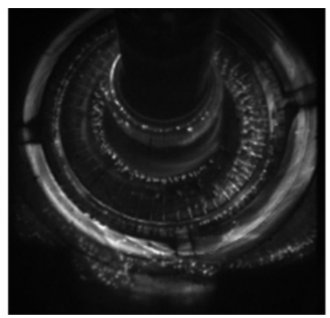
XP Completed 8/27/10

- 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)

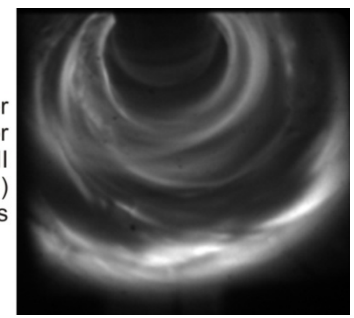
Color Midplane View



Lower divertor Li I (670 nm) 1 μs



Lower divertor Li II (548 nm) 2 μs

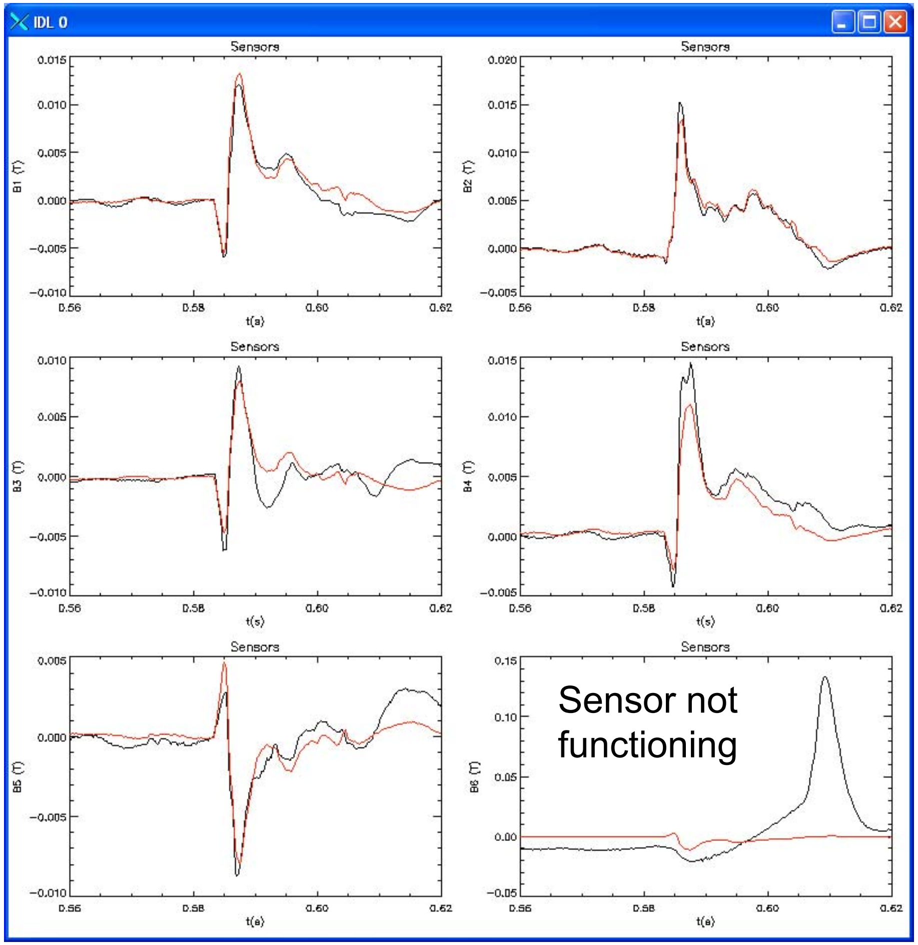


- Continued 1/2 day will allow some worthy follow up:
  - 1: Injected power/stored energy scan.
  - 2: Refine data on halo-current locking to n=1 field -> ITER relevance
  - 3: Repeat cases identical to previous years to test Li effect on halo currents, home in on the cause of the reduced HC compared to 2009

# 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



# XP1023: Optimized RWM feedback control for high $<\beta_N>_{pulse}$ at low collisionality and $l_i$

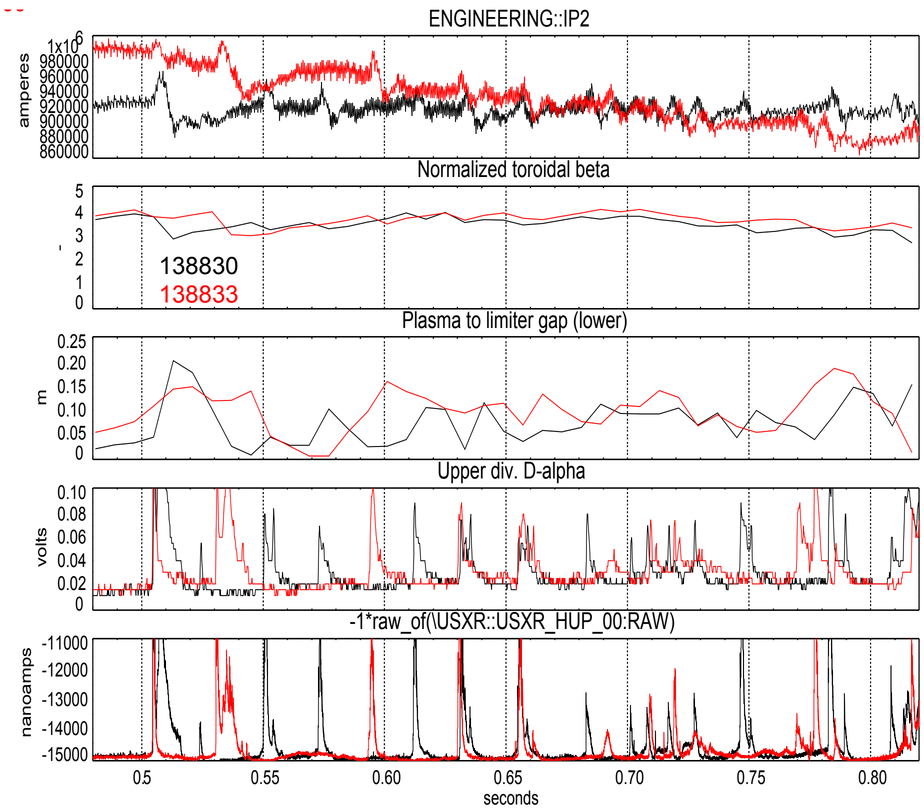
- **Motivation / overall goal**
  - Next-step ST devices (including the planned upgrade of NSTX) aim to operate at plasma collisionality and li below usual NSTX levels
    - Past low $l_i$ operation showed significantly higher RWM activity, lower $\beta_N$ limit, at reduced $l_i$
  - Improve reliability of RWM stabilization at low $l_i$ (and all plasmas)
- **Progress**
  - Generated reduced $l_i$ target plasmas, unstable RWMs without $V_\phi$ 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 $\beta_N$ with very high $\beta_N/l_i$ 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
    - Need to complete XP by completing low plasma rotation scan (0.5 day)

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

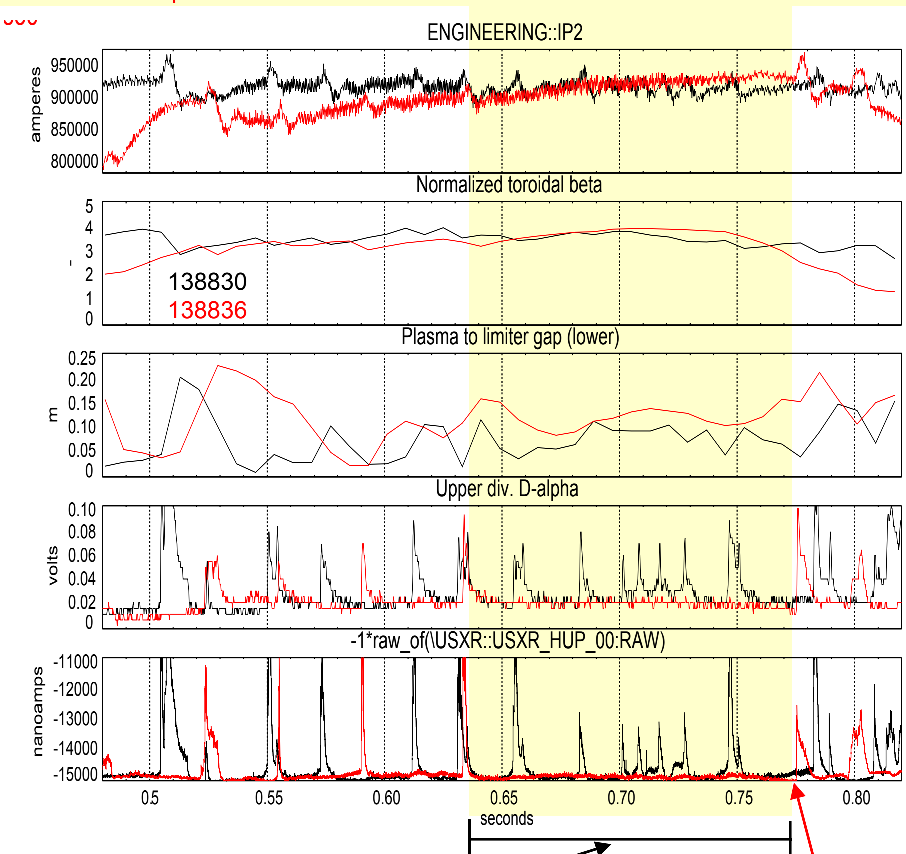
- Goals/Approach
  - Test expectations ELM stability theory considering changes to edge toroidal current density, field-aligned thermoelectric current, and collisionality
    - 1) Generate target
    - 2) Vary TE current connection length at fixed 3D field (Vary x-point height; DRSEP)
    - 3) Vary 3D 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
  - Request (< = 0.5 day)
    - Vary 3D field amplitude, reproduce ELM stabilization with positive $I_p$ ramp, USN

# XP1031: Evidence of ELM stabilization with positive current ramp + 3D field during ELMing phase

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

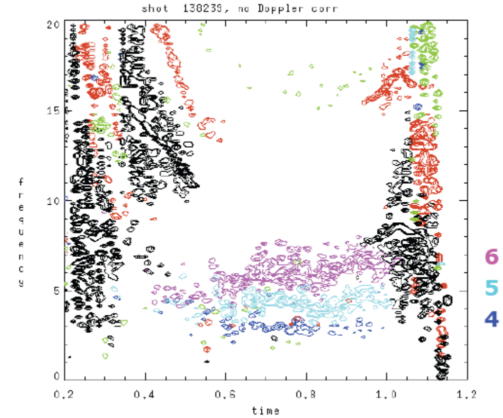
# XP1068 RF Amplification of EHOs in Lithium-pumped ELM-Free Plasmas

## Propose to Modify EHOs Using Modulated HHFW

- Easy to amplitude modulate HHFW
- HHFW couples to the edge plasma in ways we don't completely understand
- Maybe we can use it to drive EHOs and even control impurity influx.
    - Evidence of coupling would motivate theory.
- If RF coupling doesn't work, hook up SPAs to HHFW antenna? Much harder experimentally, easier to understand theoretically. Do modulated RF first.
- C-MOD has a Mini-Proposal to use modulated ICRF to drive their QCMs, at much higher f.
- BOY WOULD THIS BE A GOOD RESULT FOR ITER.

## We See EHOs on Mirnov Coils

- Eric's MODE code
- Tuned for low frequency (long samples)
- Tuned for low amplitude (measures dB/dt)




- Studied current, field and power scans from XP - 1043.
    - ELM-free, lithiated
- Best cases are 4 MW, 800 kA, 4.5T
- Need a time window between n = 1 modes early and late
- Not claiming that EHOs reduce density rise (yet)

- New XP
- requests 1.0 run days (CCE time)
- requires RF

# XP-1060 Would Test For Improvements in RFA Suppression With Improved RWM Sensor Compensations

- *New compensations implemented in the RWM "mode-identification" algorithm*
    - *"AC Compensations" remove pickup from d$I_{RWM}$/dt driven eddy-currents.*
    - *"OH x TF Compensations" removed pickup from tilting TF coil.*
    - *> 600 coefficients required to implement these compensations in real-time.*
    - *When combined, should allow for improved detection of the plasma n=1 field.*
- *XP would test for improved error field control with new compensations*
    - *Goal: Determine optimal feedback gain and phase for dynamic error field correction.*
        - *Then test the "new" optimal gain for fast+slow RWM control.*
    - *Applied n=1 fields to provide RFA "seed" field…algorithm should "correct itself"*
    - *Test optimization against the intrinsic OHxTF error field*
- *How it differs from other XPs*
    - *Study $B_P$ and $B_R$ sensor based RFA suppression independently.*
    - *Use a "fiducial" plasmas for the target.*
        - *Test if new "optimal" $B_P$ feedback phase is result of low-$l_i$ target, or something else.*
- *Minimum useful time is ½ day*

# XP 1061: Tearing Mode Sensitivity to q Profile

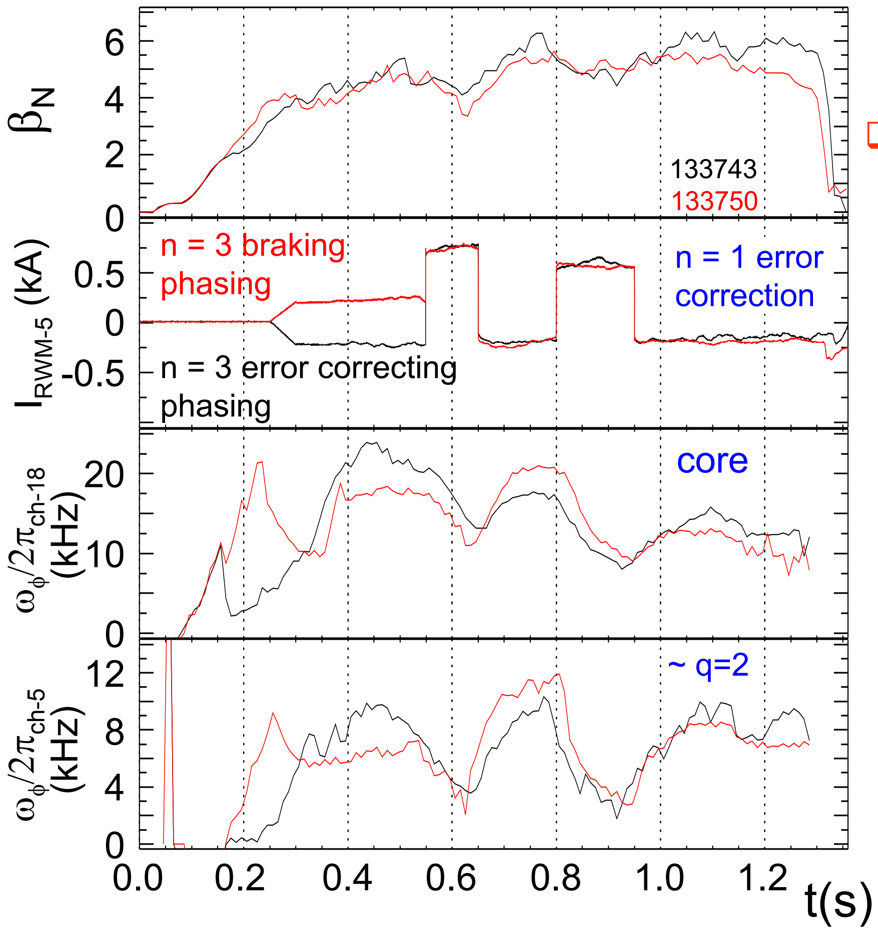
- **Status: XP drafted awaiting review and experiment time**
- **Goals – elucidate how:**
  - 2/1 NTM beta limit changes as q evolves vs time ($q_{min}$ falls: 2→1)
  - Error field sensitivity changes as q evolves vs time
    - Understand q profile optimization and physics of these modes
- **Needs:**
  - Run time – up to 16-24 good shots.
  - 3 beams, n=1 field ramps, $\beta$ feedback if poss.
  - Usual MHD diagnostics – CHERS, MSE,
  - Good machine conditions for shot reproducibility (li for ELMs?)
- **Availability: From Sept 7th onwards**

# XP1062 aims at next-step goals from XP933, allowed by LLD, RF operation

- Goals / Approach
  - Compare magnetic braking with largest variation of $\nu_i^*$ using LLD
    - Target a comparison of two conditions: low vs. high $\nu_i^*$
    - Concentrate on new low $\nu_i^*$ condition
    - Compare to past braking XPs if high $\nu_i^*$ condition is difficult to produce
  - Generate greater variation of key parameter $(\nu_i/\varepsilon)/|nq\omega_E|$
    - Operate some shots with 1 NBI source (higher $\omega_E$)
    - Mostly run 2 - 3 NBI sources generate lowest $\nu_i$, vary $\omega_E$ with braking as before
    - Concentrate on low $\omega_E$ to further examine superbanana plateau regime/theory
    - Additional $nq\omega_E$ variation possible by comparing n = 2 vs. 3 if time allows
  - Determine NTV offset rotation
    - Standard approach: attempt to observe offset by operating at near-zero $\omega_\phi$ (might be easier with LLD)
    - Consider new approach using RF (based on RF XPs from 2009)
      - Generate $\omega_\phi$ 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 $\omega_\phi$ changes
      - Note that if NTV offset is indeed only in counter-$I_p$ direction, the $\omega_\phi$ profile will change (it's presently counter in core, co at the edge
  - Data needed for IAEA waited for verdict on LLD / survey XP
    - Request 0.5 run days to complete scans from XP933 / XP1062

# XP1062: Significant variations to $nq\omega_E(R)$ to examine effect on NTV braking (follows from XP933)

XP933 example: variation of initial $\omega_\phi$




- Earlier work
  - $V_\phi$ damping consistent with "1/ν regime" magnitude & scaling ($T_i^{5/2}$)
- XP933 status
  - NTV braking observed over all $\nu_i/nq\omega_E(R)$ variations made in experiment
    - Strong braking at increased $T_i$ with lithium, even if $(\nu_i/\varepsilon)/nq\omega_E < 1$
    - Want greater $(\nu_i/\varepsilon)/nq\omega_E$ variation; better quasi-steady-state $w_\phi$ condition
  - Apparent braking of resonant surfaces plasmas at low $\omega_\phi$, but without locking (e.g. $\omega_\phi$ goes to ~ zero locally, then increases)
  - Apparent lack of $1/\omega_\phi$ scaling of drag torque on resonant surfaces at low $\omega_\phi$
    - Provocative result – is current layer / island width decreasing at low $\omega_\phi$
    - …or perhaps drag due to "island NTV" ~ $\omega_\phi$ (K.C. Shaing et al., PRL **87** (2001))
    - …or perhaps due to superbanana plateau physics (K.C. Shaing et al., PPFC **51** (2009))

# Needs for remainder of the run – Macrostability TSG XPs

- Run XPs presently on run schedule
  - XP1018 Error field threshold at low torque input (J. Park): REQUIRES RF
  - XP1032 Error field scaling in H-modes (Buttery)
  - XP1021 Halo currents/extended diagnostics (McLean): Aug. 27th (completed)
- XPs needing more time (directly supporting IAEA, APS, ITPA, milestones)
  - XP933/XP1062 NTV high/low n, low $V_\phi$ (Sabbagh) – FOR IAEA (need soon) (+APS) !
    - Expanded range of $(\nu_i/\varepsilon)/nq\omega_E$, complete tests of superbanana plateau regime (0.5 day)
    - RF component in XP1062 to define NTV offset rotation (+0.5 day) REQUIRES RF
  - XP1022 RWM state space control (Y. Park) – for APS/IAEA
    - Clarify physics of state space mode control following initial operation (0.5 day)
  - XP1020/XP1023 RWM stability physics / control (Berkery/Sabbagh) – for APS/IAEA
    - Low plasma rotation scans not completed (0.5 day)
  - XP1060 Comparison of RFA suppression, different sensors (Gerhardt) (0.5 day)
- ITER / CCE XPs
  - XP1031 Global MHD / ELM stability (Sabbagh)
    - Vary 3D field amplitude, reproduce ELM stabilization with positive $I_p$ ramp, USN (<= 0.5 day)
  - XP1068 (new) RF Amplification of EHOs (Goldston) – CCE run time REQUIRES RF
- Estimated run time to complete XPs
  - Active XPs: 3.0 run days (+ new cross-cutting XP1068 (Goldston))
  - Scheduled XPs: 1.5 run days

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| 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 | - | |
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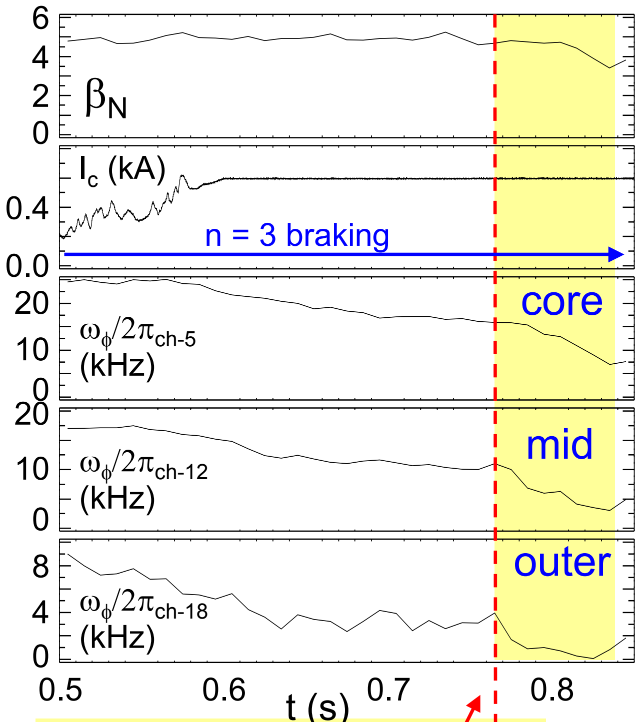
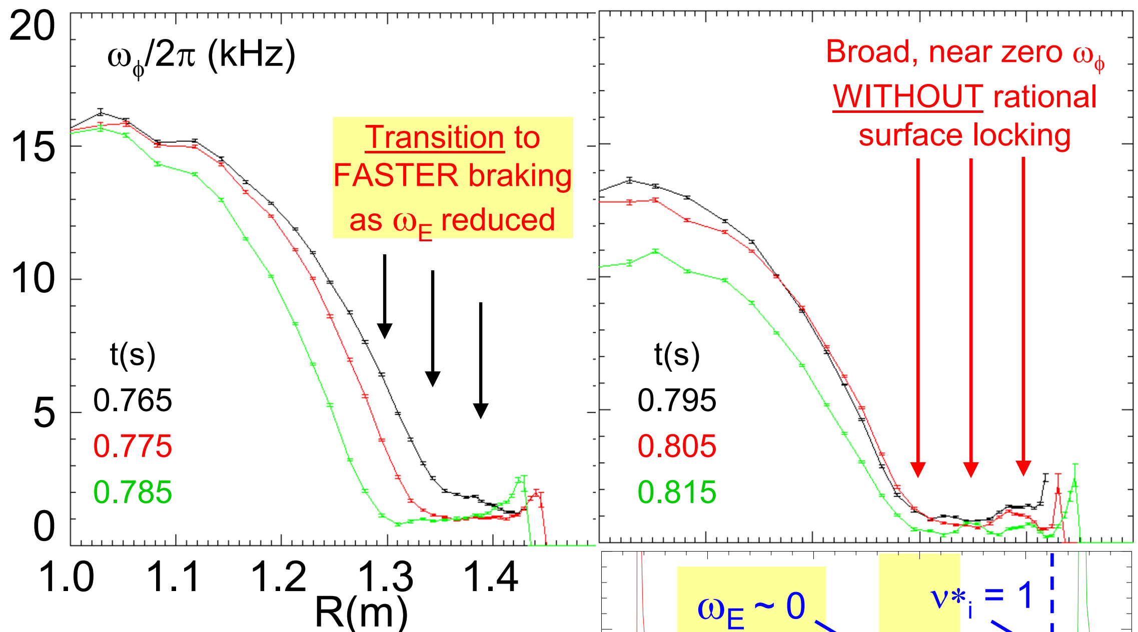
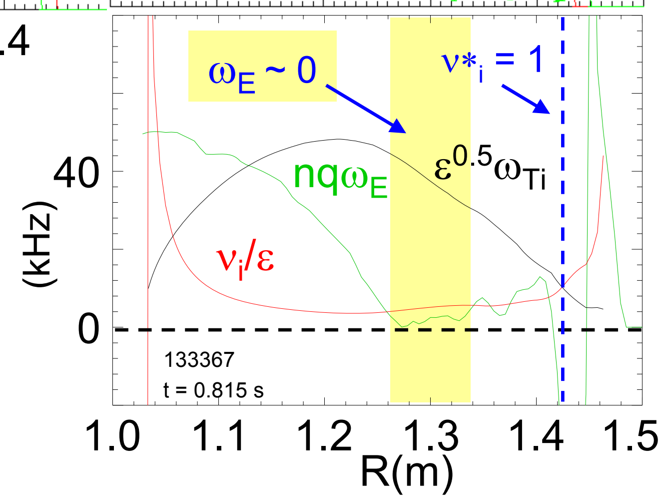
| Sabbagh | Optimized RWM feedback for high <bN>pulse at low n and li | 1.0 | 1 | 1.00 | XP1023 |
| Gerhardt | Comparison of RFA suppression using different sensors | 1.0 | 2 | 1.00 | XP1060 |
| Buttery | 2/1 NTM stability (and EF sensitivity) vs q profile | 1.0 | 2 | 0.50 | XP1061 |
| Sabbagh | NTV 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 |
|---|---|---|---|---|---|

# Stronger braking with constant n = 3 applied field as $\omega_E$ reduced – accessing superbanana plateau NTV regime




- Faster braking with
  - Constant $\beta_N$, applied n = 3 field
  - No rotating mode activity
- Torque not $\propto 1/\omega_\phi$ (non-resonant)
  - NTV in "1/ν regime" ($|nq\omega_E| < \nu_i/\varepsilon$ and $\nu^*_i < 1$)
  - Stronger braking expected when $\omega_E \sim 0$ (superbanana plateau)

K.C. Shaing, et al. (PPCF **51** (2009) 035004; 035009