Princeton Plasma Physics Laboratory

NSTX Experimental Proposal

Title: **Influence of rotation and error fields on tearing mode beta limits**		
OP-XP- 915	Revision:	Effective Date: **6/109** *(Approval date unless otherwise stipulated)* Expiration Date: **6/1/11** *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS	
Responsible Author: R.J. Buttery	Date 6/1/09
ATI – ET Group Leader: S.A. Sabbagh	Date 6/1/09
RLM - Run Coordinator: : R. Raman	Date 6/1/09
Responsible Division: Experimental Research Operations	

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

NSTX EXPERIMENTAL PROPOSAL

TITLE: **Influence of rotation and error fields on tearing mode beta limits** No. **OP-XP- 915**

AUTHORS: **R. J. Buttery, S. Gerhardt, R. J. La Haye** DATE: **05/05/09**

1. Overview of planned experiment

This proposal explores rotation and error field effects on NTM β_N thresholds, by making use of key capabilities on NSTX to apply n=3 and n=1 fields independently to brake and interact with the plasma. Key elements we wish to study are:

- How the n=1 error field sensitivity of the plasma changes with rotation, at β_N values in proximity to the 2/1 NTM β limit.
- How this interaction is manifest – as a direct error field 'penetration' to locked mode, or through modification to the intrinsic tearing stability

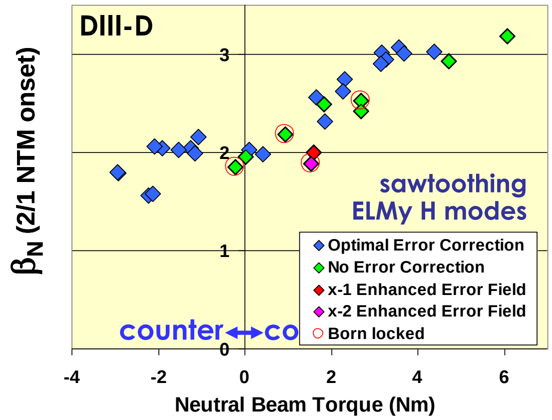
By deploying n=1 and n=3 fields on NSTX, it is anticipated that resonant and indirect (through rotation profile) parts of the interaction can be discriminated. This may further allow a clearer discrimination of rotation from rotation shear effects. Finally, it is important to look for any 'resonances' in the limit behaviour – such as arise in error field sensitivity to induce tearing modes as the NTM beta limit is approached, or in identifying how rapidly thresholds change with rotation as zero is approached (a linear effect?) – in order to understand how close to the 'limits' tokamaks can sail and what the requirements are to avoid the mode in terms of rotation and β_N.

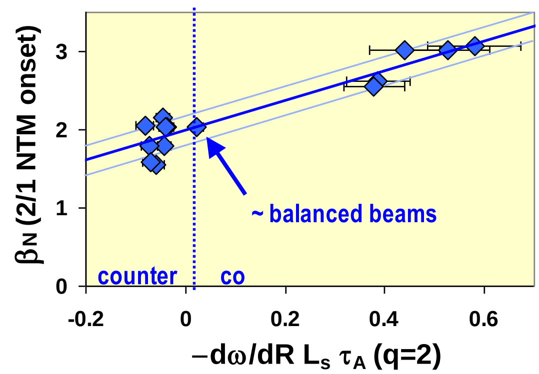
The planned experiments will therefore explore n=1 error field ramps at various fixed values of n=3 field and heating power to achieve a scan in rotation and β_N. They will be combined with other NTM studies (notably XP 914) with shared shot scenario development and possible alternating sequencing of discharges.

A key point to emphasize is that this XP gets at both the neoclassical tearing mode and error field physics. These aspects appear strongly linked at intermediate β_N values, although understanding of the interactions can be somewhat decoupled by exploring discharge phenomenology – eg the resonant braking and possible locked modes arising from direct error field interaction, and the modifications to intrinsic tearing stability through rotation changes. This XP will deal with these issues head on and help separate out our understanding of which modes happen where and how to avoid them.

A second, independent study (set aside for another XP) may follow to build on this study, by exploring beta limits and error field sensitivity in counter Ip discharges, to test whether there are asymmetries in the rotation dependence and help understand further the nature of the physics of this rotation interaction. This element is not further discussed here.

2. Theoretical/ empirical justification





Theoretically NTM thresholds might be expected to depend on rotation for a number of reasons. Decreased rotation might be associated with decreased shielding of various triggering instabilities. Rotation also enters into much of the underlying physics governing mode stability, such ion polarisation currents, delta prime, and wall stabilisation effects. As most present devices and NTM data are based on high rotation co-injected plasmas, for future low rotation burning devices, it becomes important to understand the trends in the rotation parameter. Such studies also help provide crucial insights into the triggering and threshold physics (exploring processes and which parameters govern trends), which are if anything even more important in having confidence to extrapolate to future devices.

Not least, recent observations from DIII-D have confirmed these concerns (*upper figure right*) but also raised some interesting puzzles in this regard, showing an asymmetry in threshold behaviour between net co and counter rotation, although so far being unclear on whether counter rotation points confirm the downward trend or level off. The basic trend of a lowering of thresholds with co-rotation was also observed on NSTX in 2007. Further analysis of DIII-D data suggested possible mechansims related rotation shear changing delta prime may be most consistent with the trends observed (*lower figure*) although DIII-D lacks capability to deconvolve rotation from rotation shear effects (as recently achieved on NSTX – see Gerhardt et al, just accepted by NF).

In addition to this, error field sensitivity is generally expected to increase at low rotation [eg Fitzpatrick papers], and so error fields might be expected to play a role in triggering modes in low rotation devices that they do not in present strongly co-injected devices (where co- rotation virtually eliminates error field effects below the no wall beta limit). Error fields have also been observed to combine with NTM drives [Buttery, EPS 2005], effectively lowering the 2/1 NTM β limit. The combination of these two observations raises the prospect for a considerably enhanced drive for tearing mode onset in a low rotation device. Thus experiments probing this point are important – to determine whether standard intermediate β_N scenarios are more prone to error fields triggering tearing at low rotation than at high rotation. Again the use of error fields, and observation of processes and trends provides good potential for further physics understanding of the NTM onset process, and so implications for future devices. In particular n=1 fields might brake the plasma more locally via a resonant interaction at q=2, and/or lead to partial tearing of the plasma to trigger NTM onset, while n=3 fields can brake the plasma more uniformly and without a 2/1 resonant interaction at q=2.

3. Experimental run plan

This proposal is for a 0.75 day experiment to address this interaction of error field, rotation and β with regard to 2/1 mode onset. The experiment is closely related to XP914, which measures rotation dependencies in the decay of 2/1 mode to assess the underlying marginal beta physics. Both experiments will be based on the same reference discharges and are somewhat complimentary (XP915 studying mode onset, XP914 studying mode decay and stabilisation requirements), and will share plasma scenario development. However, in XP915 there is a substantial risk that mode onsets with n=1 fields applied may generate locked modes and prevent progress to the decay phase. Thus the experiments have been decoupled, although some mutual benefit is expected, with opportunities to gain test data for XP915 in XP914 (which be the starting experiment) and take any key missing points from XP914 in XP915 (if locked mode problems can be ironed out).

The experiment configuration is based on a 2008 experiment (XP801, XP810). However, problem arose in these previous studies with respect to achieving reliable machine conditions, sustained good H modes (including in the ramp-down phase), the influence of lithium, and obtaining reliable mode onsets and plasma profiles. A number of changes have therefore been developed to address these issues:

- Operation in a well conditioned machine, but away from significant lithium injection phases.
- Adjustment of plasma shape to minimum possible elongation, low triangularity and low X point height – to lower L-H threshold and improve H mode performance.
- Ensuring all profile data obtained on all experiment days.
- For this XP, changing the method of striking the mode from beta ramp (at fixed n=1 field) to n=1 field ramp (at fixed heating power). This has also led to, and allowed a different emphasis in terms of experiment goals and scans possible (see XP 810 overview for a brief resume).

For XP915, we would start from the optimal configuration (including shot redevelopment) obtained in XP914.

Shot design notes:

The principal here is that we consider the n=3 field to apply generalised braking, and therefore a tool to control the plasma rotation, while the n=1 more directly perturbs the 2/1 tearing stability via direct interaction with the q=2 surface – so we use n=1 field ramps to measure the field threshold required to destabilise the modes, and scan this vs rotation (n=3 field) and β_N (power).

- o Default optimal error correction will be deployed throughout, with <u>additional</u> fields as set out in the below plan. n=1 error correction will be by use of the feedback system (with suitable modifications when extra n=1 field is desired – ***n=1 feedback to be gated out during this period***). n=3 correction is determined empirically and will be programmed by the team.

- o All shot waveforms are desired to have a reproducible and fixed 'front end', to establish an ELMy H mode at prescribed power level. Power will then be fixed for the main experiment, with a ramp-down programmed at the end. During this main experiment different preprogrammed levels of n=3 field will be applied to brake the plasma, often deploying a ramp-up of n=3 field to some maximum level, in order to achieve good rotation control.

- A shot to shot scan would be made in level of n=3 field waveforms and heating power. n=3 fields are generally ramped in parallel with n=1 fields, so that we get good data (an n=1 mode onset threshold) every shot (avoid n=3 driving an early mode or some other event before significant n=1 applied).

- A 3rd beam (C) will be operated at lower voltage to achieve a half beam power as needed for scans.

- After mode onset we aim to avoid mode locking or cause mode unlocking by (at some preprogrammed time): (i) applying step down in power; (ii) switching back to optimal error correction (iii) switching off n=3 field, at least for a short interval. In this way it is hoped that a second phase with additional data from a relatively benign rotating 2/1 mode can be obtained for further data for XP914.

Additional notes from XP review – getting a reliable reproducible mode strike:

- **Reliable ELM conditions** are important, aim to achieve ~40 per shot (not ~4 or type III). This would be achieved by adjusting recycling conditions, shape, and other aspects discussed below. Achieving **reliable H mode timing is also important** in shot reproducibility (early mode history) is also important using below control levers.

  - Divertor recycling should be monitored, with adjustments to gas puff (eg HFS) as needed during the day.

  - For reliable instability avoid too early H mode, too high power, or too much lithium → 3MW is base operating point (higher values will be scanned to).

  - To avoid too early H mode, elongation can be increased. Near DN operation can impact threshold.

  - Higher triangularity may be developed to assist XP 914 (see shot development point below). This would be a departure from fiducial shot – not this is not needed for this XP, but if developed for XP 914 would be adopted by this XP if reliable NTMs are being accessed

  - 5MW power blip can provide trigger point for H mode access.

- **Shot development time**, would be worthwhile, together with further assessment of past shot history to understand issue of shot evolution and reliable mode access. Li is not planned for these discharges, but remains an option if the shot development mentioned suggests need for it.

Run plan: (*shot estimate include reasonable allocations for tuning discharges and recovering errors*)

1. **Reference shot:** Start with 3MW constant beam power (1.5 beams) (but early 5MW blip for H mode access) to establish discharge evolution (especially beta) and mode activity. Adjust power as needed (including use of power ramps to 6MW) to be sub-critical to mode and also establish 2/1 tearing mode beta limit with optimal correction. *This provides a reference and time windows for below.* (4 shots).

2. **Pure n=1 threshold:** Repeat at <u>constant power</u> level (anticipated at ~3MW level, but chosen from item 1) with n=1 ramp to 2kA at t=0.35s (time to be adjusted in light of XP 914 experience) to establish threshold for onset of rotating n=1 mode or error field penetration mode (2 shots).

3. **First n=3 influence on n=1 threshold:** Repeat (2) with ramp to 600A of n=3 braking (in parallel with n=1 field ramp) during the high beta phase to measure n=1 threshold with reduced rotation (2 shots).

4. **Scanning n=3 influence on n=1 threshold:** Repeat (3) varying level and rate of n=3 ramp (ramping more quickly to higher value or slowly to lower value) to scan rotation at time of n=1 onset, all at fixed power in high beta phase: go to maximum n=3 field that leads to mode with little n=1 field; scan down intermediate and lower points (4-6 shots).

5. **Test beta effect on n=1 threshold:** Repeat no n=3 (item 2) and high n=3 (from item 3 or 4) points at higher beam levels – eg 4MW, 5MW to achieve scan of n=1 field required vs β_N , and how this changes with rotation (8 shots).

6. **Test for linear/non-linear scaling:** Take intermediate points at higher beam levels of point (5) with intermediate n=3 fields to test whether scaling of n=1 thresholds is linear in β_N and rotation (4 shots).

7. **Fill ins if needed:** (Possible repeats where gaps/trends identified at fixed power and n=3) (0-4 shots).

8. **Alternate recipe to get at key points:** (Further repeats possible with fixed n=1 and beta ramp, if needed to fill gap, or observe more clearly rotating mode effects at low n=1 field levels) (0-4 shots).

Total 24-34 shots for full scan, although some time may be saved on item 1 from XP914.

Note also that this is scheduled to provide most useful new data in earliest stages – so we get most important principals tested at extremes, first:

- by item (3) we compare low and high rotation n=1 thresholds
- item (4) looks for non-linearity in and extension of rotation effect
- item (5) prioritizes the corners in looking for a beta resonance,
- item (6) looks for non linearities in the beta effect vs rotation

- item (7) consolidates database to provide a robust picture.

4. Required machine, NBI, RF, CHI and diagnostic capabilities

Toroidal Field: BT=-4.4 kG

Plasma Current: within range 0.7 - 1.1MA, dependent on XP914 scan (present planned value is 1.0 MA).

Shape: NSTX 130221 with variation (as XP914)

Beams: 3 beams. 1 down-rated to half power with volts or modulation (and option to restore full power if possible).

Essential Diagnostics: Magnetics (fast and slow), RWM detectors,

MSE

CHERS for core Ti and rotation

Thomson

SXR for island width (USXR operators present please)

5. Planned analysis

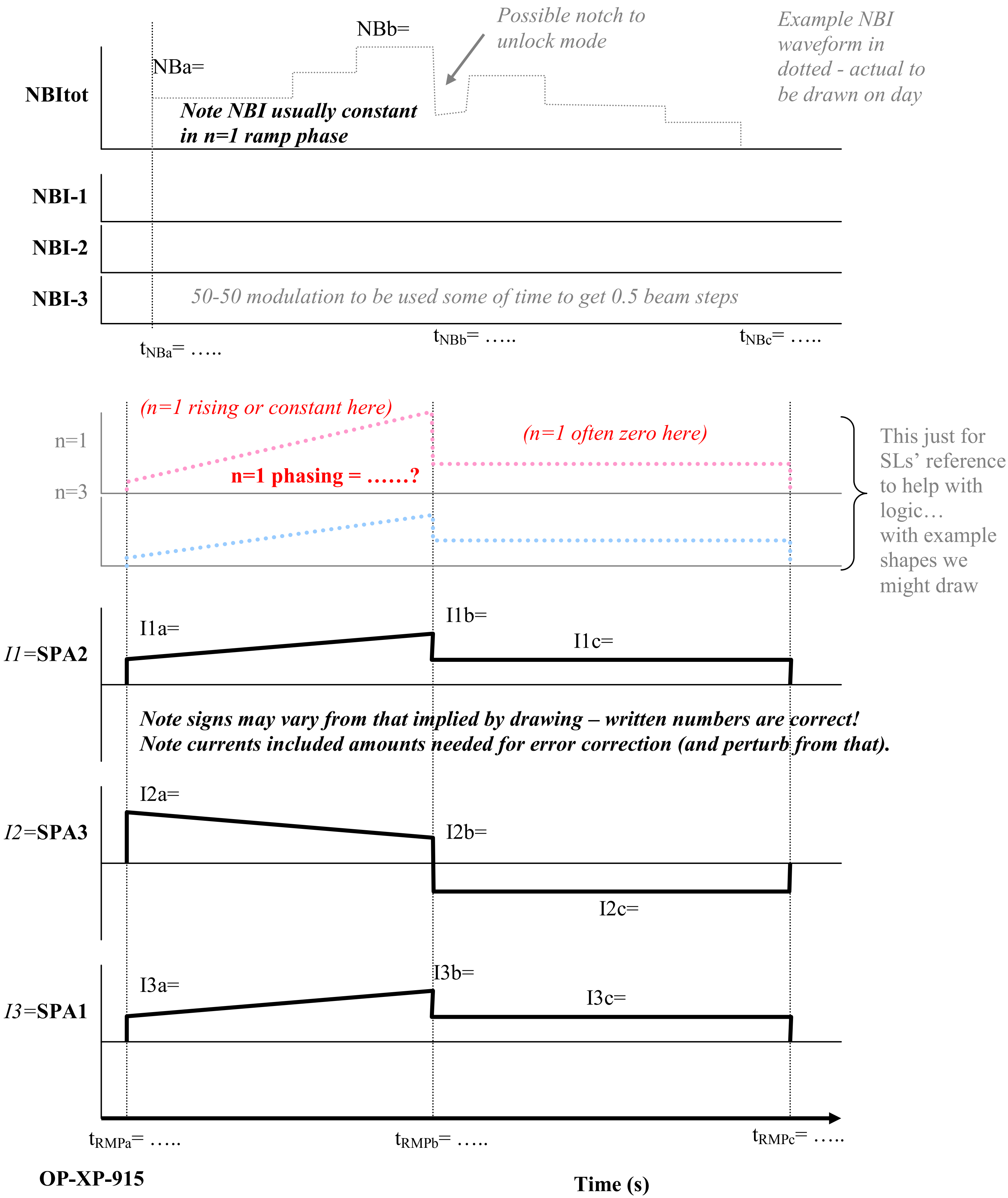
Compiling main tables of results in basic measured parameters. Analysis in terms of local q=2 parameters. Exploring dependencies against measures of rotation and rotation shear. If possible, ascertaining trend in terms of rotation relative to Eperp=0 frame of reference (to test ion polarisation current model). Analysis of mode onset triggers from spectrograms, correlation with ELMS and sawteeth, checks for appearance of locked modes

6. Planned publication of results

Publish as a short letter or journal paper. Report at ITPA under MDC 14 and MDC 4. Conference presentations.

Appendix: Shot waveforms vs time – *to be filled out for each RMP change*

(using ready reckoner and/or table overleaf to fill in values)



RMP coil current calculation table

These tables show typical currents to request in RMP coils for various configurations. More options will be worked as shot waveforms further iterated in preparation/execution of experiment (spreadsheet set up for this; further changes anticipated according to integration with XP 914 and run experience). These to be handwritten on generic plot during the experiment.

Note stage 'c' is set by ramp-down experiment requirements – we assume here a modest level of n=3 is applied only. The level might be expected to vary shot-shot, and might also include some n=1 field in some cases.

Shot ref	t_{RMPa}	t_{RMPb}	t_{RMPc}	I1a	I2a	I3a	I1b	I2b	I3b	I1c	I2c	I3c	Comment for onset experiment
	.3	.6	.8	0	0	0	0	0	0	+0.75	-0.75	+0.75	No n=1; no n=3; ref point
	.3	.6	.8	0	0	0	+0.5	+1.0	+0.5	+0.75	-0.75	+0.75	n=1 ramp 1kA; no n=3
	.3	.6	.8	0	0	0	-0.87	0	+0.87	+0.75	-0.75	+0.75	Adjusted n=1 phase
	.3	.6	.8	+0.4	+0.8	+0.4	+0.4	+0.8	+0.4	+0.75	-0.75	+0.75	Const n=1; no n=3
	.3	.6	.8	-0.69	0	+0.69	-0.69	0	+0.69	+0.75	-0.75	+0.75	…or diff phase n=1
	.3	.6	.8	+0.2	+0.4	+0.2	+0.2	+0.4	+0.2	+0.75	-0.75	+0.75	e.g. lower n=1
	.3	.6	.8	-0.34	0	+0.34	-0.34	0	+0.34	+0.75	-0.75	+0.75	e.g. lower n=1 diff phase
	.3	.6	.8	+0.75	-0.75	+0.75	+0.75	-0.75	+0.75	+0.75	-0.75	+0.75	No n=1; 750A n=3
	.3	.6	.8	+0.75	-0.75	+0.75	+1.15	+0.05	+1.15	+0.75	-0.75	+0.75	n=1 ramp 800, with n=3
	.3	.6	.8	+1.15	+0.05	+1.15	+1.15	+0.05	+1.15	+0.75	-0.75	+0.75	n=1 800, n=3 750
	.3	.6	.8	+0.95	-0.35	+0.95	+0.95	-0.35	+0.95	+0.75	-0.75	+0.75	n=1 400, n=3 750
	.3	.6	.8	+0.75	-0.75	+0.75	+0.06	-0.75	+1.44	+0.75	-0.75	+0.75	As 5a but 90 degrees
	.3	.6	.8	+0.06	-0.75	+1.44	+0.06	-0.75	+1.44	+0.75	-0.75	+0.75	As 5b but 90 degrees
	.3	.6	.8	+0.40	-0.75	+1.10	+0.40	-0.75	+1.10	+0.75	-0.75	+0.75	As 5c but 90 degrees

On the fly formulae: 'a' kA of n=1 at zero degrees to 'b' kA of n=3 → IRMP = (a/2+b , a-b , a/2+b)

'a' kA of n=1 at 90 degrees to 'b' kA of n=3 → IRMP = (b-√3/2a , -b , b+√3/2a) where √3/2 = 0.87

…a spread sheet has been set up to calculate more values on the fly as needed…

Second table of RMP parameters for shots: ***for modified phasing of n=1 field***

This version for estimated optimum phasing from error correction reference #123898 with –ve OH of 13kA at t=0.6s

Shot ref	t_{RMPa}	t_{RMPb}	t_{RMPc}	I1a	I2a	I3a	I1b	I2b	I3b	I1c	I2c	I3c	Comment for onset experiment
	.3	.6	.8	0	0	0	0	0	0	+0.75	-0.75	+0.75	No n=1; no n=3; ref point
	.3	.6	.8	0	0	0	0	0	0	+0.98	-0.98	+0.28	as 1 with n=1 corn if OH=-13
	.3	.6	.8	0	0	0	0	0	0	+0.23	-0.23	-0.46	Pure n-=1 corn; no n=3
	.3	.6	.8	0	0	0	-0.5	+0.5	+1.0	+0.75	-0.75	+0.75	n=1 ramp 1kA; no n=3
	.3	.6	.8	0	0	0	+0.5	-0.5	-1.0	+0.75	-0.75	+0.75	Reversed n=1 phase cf 2a
	.3	.6	.8	-0.4	+0.4	+0.8	-0.4	+0.4	+0.8	+0.75	-0.75	+0.75	Const n=1; no n=3
	.3	.6	.8	-0.2	+0.2	+0.4	-0.2	+0.2	+0.4	+0.75	-0.75	+0.75	e.g. lower n=1 amp
	.3	.6	.8	+0.75	-0.75	+0.75	+0.75	-0.75	+0.75	+0.75	-0.75	+0.75	No n=1; 750A n=3
	.3	.6	.8	+0.75	-0.75	+0.75	+0.35	-0.35	+1.55	+0.75	-0.75	+0.75	n=1 ramp 800, with n=3
	.3	.6	.8	+0.35	-0.35	+1.55	+0.35	-0.35	+1.55	+0.75	-0.75	+0.75	n=1 800, n=3 750
	.3	.6	.8	+0.55	-0.55	+1.15	+0.55	-0.55	+1.15	+0.75	-0.75	+0.75	n=1 400, n=3 750

On the fly formulae: ‘a’ kA of n=1 at 60 degrees to ‘b’ kA of n=3 → IRMP = (-a/2+b , a/2-b , a+b) with a positive for EF enhancement

…a spread sheet has been set up to calculate more values on the fly as needed…

PHYSICS OPERATIONS REQUEST

TITLE: **Influence of rotation and error fields on tearing mode beta limits** No. **OP-XP- 915**

AUTHORS: **R. J. Buttery, S. Gerhardt, R. J. La Haye** DATE: **05/05/09**

(use additional sheets and attach waveform diagrams if necessary)

Describe briefly the most important plasma conditions required for the experiment:

No lithium, well conditioned machine.

Reasonable estimate for n=1 and n=3 error field (or dynamic correction applied).

Previous shot(s) which can be repeated: 130210

Previous shot(s) which can be modified: 130221 ←main reference to use

Machine conditions *(specify ranges as appropriate, strike out inapplicable cases)*

I_{TF} (kA): -4.4 kG field Flattop start/stop (s):

I_P (MA): 1.0 Flattop start/stop (s):

Configuration: **DN**

Equilibrium Control: **Outer gap / Isoflux** (rtEFIT)

Outer gap (m): Inner gap (m): Z position (m):

Elongation κ: Upper/lower triangularity δ:

Gas Species: Injector(s):

NBI Species: **D** Voltage (kV) **A: 90** **B: 90** **C:** 90 Duration (s):

ICRF Power (MW): 0 Phase between straps (°): Duration (s):

CHI: **Off** Bank capacitance (mF): **n/a**

LITERs: Off Total deposition rate (mg/min): **n/a**

EFC coils: On Configuration: **Odd**

See reference shot 130221 for settings and shape.

DIAGNOSTIC CHECKLIST

TITLE: **Influence of rotation and error fields on tearing mode beta limits** No. **OP-XP-915**

AUTHORS: **R. J. Buttery, S. Gerhardt, R. J. La Haye** DATE: **05/05/09**

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
Bolometer – tangential array		X
Bolometer – divertor		X
CHERS – toroidal	X	
CHERS – poloidal		X
Divertor fast camera		X
Dust detector		X
EBW radiometers		X
Edge deposition monitors		X
Edge neutral density diag.		X
Edge pressure gauges		X
Edge rotation diagnostic		X
Fast ion D_alpha - FIDA		X
Fast lost ion probes - IFLIP		X
Fast lost ion probes - SFLIP		X
Filterscopes	X	
FIReTIP		X
Gas puff imaging		X
Hα camera - 1D		X
High-k scattering		X
Infrared cameras		X
Interferometer - 1 mm		X
Langmuir probes – divertor		X
Langmuir probes – BEaP		X
Langmuir probes – RF ant.		X
Magnetics – Diamagnetism	X	
Magnetics – Flux loops	√	
Magnetics – Locked modes	X	
Magnetics – Pickup coils	√	
Magnetics – Rogowski coils	√	
Magnetics – Halo currents	X	
Magnetics – RWM sensors	X	
Mirnov coils – high f.	X	
Mirnov coils – poloidal array	X	
Mirnov coils – toroidal array	X	
Mirnov coils – 3-axis proto.		X

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
MSE	X	
NPA – E||B scanning		X
NPA – solid state		X
Neutron measurements		X
Plasma TV		X
Reciprocating probe		X
Reflectometer – 65GHz		X
Reflectometer – correlation		X
Reflectometer – FM/CW		X
Reflectometer – fixed f		X
Reflectometer – SOL		X
RF edge probes		X
Spectrometer – SPRED		X
Spectrometer – VIPS		X
SWIFT – 2D flow		X
Thomson scattering	X	
Ultrasoft X-ray arrays	X	
Ultrasoft X-rays – bicolor		X
Ultrasoft X-rays – TG spectr.		X
Visible bremsstrahlung det.		X
X-ray crystal spectrom. - H		X
X-ray crystal spectrom. - V		X
X-ray fast pinhole camera		X
X-ray spectrometer - XEUS		X