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| **Princeton Plasma Physics Laboratory**  **NSTX-U Experimental Proposal** | | | |
| Title: **Resonant Error Field Threshold with Non-resonant Braking** | | | |
| **OP-XP-1543** | Revision: **0** | Effective Date:  *(Approval date unless otherwise stipulated)*  Expiration Date:  *(2 yrs. unless otherwise stipulated)* | |
| **PROPOSAL APPROVALS** | | | |
| **Responsible Author: Jong-Kyu Park** | | | Date:  **April 28, 2016** |
| **SG, TSG or TF Leader (assigned by RC): Stanley M. Kaye, John W. Berkery** | | | Date:  **April 28, 2016** |
| **Run Coordinator (RC): Jonathan E. Menard** | | | Date:  **April 28 2016** |
| **Responsible Division: Experimental Research Operations** | | | |
| **RESTRICTIONS or MINOR MODIFICATIONS**  (Approved by Experimental Research Operations) | | | |
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NSTX-U EXPERIMENTAL PROPOSAL

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| TITLE: **Resonant Error Field Threshold with Non-resonant Braking** | No. **OP-XP-1543** |
| AUTHORS: **J.-K. Park, J. E. Menard, C. E. Mayer, M. Lanctot, R. J. La Haye, Z. R. Wang et al.** | DATE: **April 28, 2016** |

# 1. Overview of planned experiment

This experiment is to study n=1 locking threshold in the presence of non-resonant rotation braking, utilizing the new 6-independent control capability. Two main goals of this experiment are:

1. To quantify the variation of n=1 error field threshold depending on rotation by non-resonant braking, and also when the spectrum of non-resonant field is varied from n=2, n=3 and to n=2+3. The latter part is important to verify if rotation is the only channel that non-resonant field can take effects in resonant locking. In practice, the data will be highly useful to develop error field threshold scaling and correction for ITER, particularly in low torque.
2. To investigate n=2 or n=3 field effects on disruption driven by n=1 locked islands. This is motivated by KSTAR observations, and can be important not only for non-linear physics of islands, but also for disruption mitigation in practice.

(A) has the focus at the onset of locking, and (B) has one at the final crash stage of locking. Data for both can be obtained in each discharge if n=1 field is strong enough to open islands and induce a disruption.

The experimental approach is to ramp n=1 from the baseline error field correction until locking, in two significantly different levels of rotation by each n=2, n=3 and n=2+3. In summary,

(1) Target: L-mode with NBI for rotation measurement.

(2) Resonant field: n=1 ramp-up from PF5-proportional EFC until locking.

(3) Non-resonant field: n=2 pulse to reduce rotation down to 1/3 and 2/3 level of reference, and repeat this with n=3, and n=2+3.

# 2. Theoretical/ empirical justification

The n=1 error field can drive magnetic islands and lead to a disruption in tokamaks, and thus should be compensated to the level below a threshold. The critical field component to drive locking is typically the resonant field at the q=2 surface, i.e., dB21 field driving magnetic islands. If this quantity is estimated correctly by including perturbed plasma currents, empirical scaling for locking dynamics becomes reliable across devices and coils. For example, the error field threshold scaling has been developed for Ohmic plasmas using IPEC field and is given by , based on NSTX, DIII-D, CMOD, JET, and KSTAR experiments [1].

The above scaling for density and toroidal magnetic field is highly robust as found in a number of different Ohmic experiments, but theory of locking physics implies that such scaling may critically fail if a significant torque is introduced and thereby rotation is established differently from natural rotation. The previous NSTX high-beta n=1 experiment using n=3 braking clearly showed this trend with rotation scaling  [2] and also DIII-D studied and showed the significant change in the threshold by non-resonant field [3] and torque [4]. The modified rotation will change cross-field viscosity, and thereby the balance between viscous force and electromagnetic force that is critical at the onset of locked modes.

Non-resonant magnetic braking is one of the best tools to modify rotation by neoclassical toroidal viscosity (NTV), without affecting other kinetic parameters such as density, as proposed in this experiment. RTV measurements for XP1506 already showed that 1-2kA n=2 field can reduce rotation significantly, without variation in density and temperature evolution.

On the other hand, the balance between viscous force and electromagnetic force can be directly affected by non-resonant field, since the total viscous force can be changed by NTV [5] itself and the electromagnetic force can also be changed by mode coupling between resonant and non-resonant field. Therefore, it is also important to check if the error field threshold can be changed in the same level of rotation when the rotation is produced by different non-resonant fields. This experiment will attempt to produce two significantly different level of rotation from natural level by each n=2, n=3 and n=2+3, and thus can test this hypothesis.

Another interesting observation for n=1 locked modes in the presence of non-resonant field was obtained in KSTAR. It was shown that the n=2 field can reduce the n=1 error field threshold at the onset as expected, but surprisingly the disruption driven by locking was delayed and mitigated when n=2 field is increased. A theory by Aydemir suggests that the n=1 island in non-linear phase can be shrink geometrically by flux surface wobbling caused by non-resonant field, possibly explaining the mitigation of disruption as well as the n=1 signal reduction in the non-linear phase [4]. This experiment will continue the n=1 ramp-up until disruptive events in the presence of n=2 or n=3, and thus can test the theory and compare the results with KSTAR.

[1] J.-K. Park et al., IAEA FEC (2012)

[2] J.-K. Park, J. E. Menard et al., Nucl. Fusion **52** (2012) 023004

[3] R. J. La Haye et al., APS (2012)

[4] R. J. Buttery et al., ITPA MHD (2012)

[5] A. Cole et al., Phys. Rev. Lett. **99** (2007) 065001

[6] J. Kim, Y. In, A. Aydemir, J.-K. Park, submitted to Nature communication (2015)

# 3. Experimental run plan

The reference target will be a stable 700kA L-mode discharge with 1.1MW NBI (source 1B 65kV), in which will enable the fast rotation measurement. Then the various combinations of n=1+2+3 will be applied to test n=1 error field threshold with non-resonant braking. The required amplitudes of n=2 or 3 may be high up to 1-2kA to change rotation, and thus the distribution of the currents when different n’s are combined becomes important to produce them under the SPA limitation, 3.3kA.

The suggested waveform, on the top of PF5-proportional EFC is:

IRWM=(0.088IPF5 - In=1)cos(φ-15) + In=2cos(2φ-75) + In=3cos(2φ-180),

where φ=0,60,120,180,240,270 for RWM1,..,6 respectively. This distribution is expected to afford In=2~3kA, In=3~2kA, In=2~1.5kA+In=3~1.8kA, on the top of In=1~1.2kA which is about 1.5 times larger than what is expected for locking In=1,lock, based on XP1506.

The detailed shot plans are below (10 shots):

1. (L-mode ref. #204146 or Ohmic) reference target + PF5-proprotional EFC (0.088A/A, φn=1=15)
2. EFC + n=1 locking (0.7s-1.2s, 2.4kA/s ramp-up, φn=1=195)
3. EFC + n=2 pulses (1kA 0.5s-0.8s, 2kA 1.1s-1.4s, φn=2=90)
4. EFC + In=2 long pulse + In=1 ramp-up (and steady after In=1=1.2kA)
5. EFC + 2In=2 long pulse + In=1 ramp-up
6. EFC + n=3 ramp up to check In=3 level to match rotation by In=2 and 2In=2
7. EFC + n=3 pulses for double check (In=3,1 0.5s-0.8s, In=3,2 1.1s-1.4s)
8. EFC + In=3,1 long pulse + In=1 ramp-up
9. EFC + In=3,2 long pulse + In=1 ramp-up
10. EFC + In=2 + In=3,1 long pulse + In=1 ramp-up (Assume linearity for rotation change)

This requires 10 shots without failure, but doable for 0.5 day. If time permitting, it is interesting to try the step 2,4,5 step for Ohmic target, to directly compare the results with KSTAR.

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

Machine:

RWM coils and SPA power supplies for best EFC.

Require NBI B source, 65kV as used for the reference.

Diagnostics:

RTV is the one critical measurement. 1kHz sampling rate may be adjusted to 100Hz for better S/N.

Require all magnetic diagnostics, including RWM/EF sensors.

Require EFIT.

Require Thomson scattering.

Desire toroidal CHERS, MSE, ERD, etc.

Prerequisite XPs:

XP-1506: Low-β, low-density locked mode studies

Desirable XPs:

XP-1515: High-beta locked mode studies

XP-1512: Perturbative momentum analysis

# 5. Planned analysis

EFIT, IPEC for 3D perturbed equilibrium, locked mode scaling, PENTRC for NTV analysis. The scaling will be compared with 2012 R. La Haye’s model, 2012 R. Fitzpatrick’s with polarization effects, and 2007 A. Cole’s with NTV.

# 6. Planned publication of results

Error field threshold dependency on non-resonant field spectrum vs. rotation is new and will be reportable to plasma physic journal if successful.

# 7. Estimated Neutron Production

Based on the number of shots, plasma current levels, and expected durations, estimate the maximum neutron production of this experiment. See calculator in Appendix #2 for this calculation.

# of Shots used in Estimate: 13 Estimated Total Neutron Production: 3.9e+15

PHYSICS OPERATIONS REQUEST

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| AUTHORS: **J.-K. Park, J. E. Menard, C. E. Mayer, M. Lanctot, Z. R. Wang, R. J. La Haye et al.** | DATE: **April 28, 2016** |

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| **Brief description of the most important operational plasma conditions required and any special hardware requirement:**  L-mode reference with NB1B  RTV measurements  RWM sensors, coils, and full SPAs |
| **Previous shot(s) which can be repeated: None**  **Previous shot(s) which can be modified: 240146** |
| **Machine conditions** *(specify* ***ranges*** *as appropriate, strike out inapplicable cases)*  BT Range (T): **0.65T** Flattop Duration (s): **1-1.5s**  IP Range (MA): **700kA** Flattop Duration (s): **1-1.5s**  Configuration: **slightly LSN**  Equilibrium Control: **Outer gap / Isoflux** (rtEFIT)  Outer gap (m): **~0.05m** Inner gap (m): **~0.05m** Z position (m):  **-0.01m**  Elongation: **1.6~1.7** Triangularity (U/L): **0.3~0.4** OSP radius (m): **N/A**  Gas Species: **D2** Injector(s): **As appropriate**  **NBI** Species: **D2** Heating Duration (s): **1.5-2s**  Voltage (kV) 50 cm (1C): 60 cm (1B): 65kV 70 cm (1A):  Voltage (kV) 110 cm (2C): 120 cm (2B): 130 cm (2A):  **ICRF** Power (MW): **OFF** Phase between straps (°): Duration (s):  **CHI**: **Off** Bank capacitance (mF):  **LITERs: Off** Total deposition rate (mg/min) or dose per discharge (mg):  **EFC coils: On** |

DIAGNOSTIC CHECKLIST [1]

|  |  |
| --- | --- |
| TITLE: | No. **OP-XP-** |
| AUTHORS: | DATE: |

*Note special diagnostic requirements in Sec. 4*

| **Diagnostic** | **Need** | **Want** |
| --- | --- | --- |
| Beam Emission Spectroscopy |  |  |
| Bolometer – midplane array |  |  |
| CHERS – poloidal |  |  |
| CHERS – toroidal |  | **X** |
| Divertor Bolometer (LADA) | **X** |  |
| Divertor visible cameras |  |  |
| Dust detector |  |  |
| Edge deposition monitors [2] |  |  |
| Edge neutral density diag. |  |  |
| Edge MIGs [2] |  |  |
| Penning Gauges [2] |  |  |
| Edge rotation diagnostic |  | **X** |
| Fast cameras – divertor [2] |  |  |
| Fast ion D\_alpha - poloidal |  |  |
| Fast ion D\_alpha - toroidal |  |  |
| Fast lost ion probes - IFLIP |  |  |
| Fast lost ion probes - SFLIP |  |  |
| Filterscopes [2] |  |  |
| FIReTIP |  |  |
| Gas puff imaging – divertor |  |  |
| Gas puff imaging – midplane |  |  |
| H cameras - 1D [2] |  |  |
| Infrared cameras [2] |  |  |
| Langmuir probes – divertor |  |  |
| Langmuir probes – RF |  |  |
| Langmuir probes – RF ant. |  |  |
| Magnetics – Diamagnetism | **X** |  |
| Magnetics – Halo currents |  |  |
| Magnetics – RWM sensors | **X** |  |

*Note special diagnostic requirements in Sec. 4*

|  |  |  |
| --- | --- | --- |
| **Diagnostic** | **Need** | **Want** |
| MAPP |  |  |
| Mirnov coils – high f. |  | **X** |
| Mirnov coils – toroidal array | **X** |  |
| MSE-CIF |  | **X** |
| MSE-LIF |  |  |
| Neutron detectors [2] | **X** |  |
| Plasma TV |  | **X** |
| Reflectometer – 65GHz |  |  |
| Reflectometer – correlation |  |  |
| Reflectometer – FM/CW |  |  |
| Reflectometer – fixed f |  |  |
| Reflectometer – SOL |  |  |
| SSNPA [2] |  |  |
| RF edge probes |  |  |
| Spectrometer – divertor |  |  |
| Spectrometer – MonaLisa |  |  |
| Spectrometer – VIPS |  |  |
| Spectrometer – LOWEUS |  |  |
| Spectrometer – XEUS |  |  |
| TAE Antenna |  |  |
| Thomson scattering | **X** |  |
| USXR – pol. Arrays |  |  |
| USXR – multi-energy |  |  |
| USXR – TG spectr. |  |  |
| Visible Brems. det. [2] |  |  |

Notes:

[1] Check marks in this table do not guarantee diagnostic availability. Check with diagnostic physicists or research operations management to ensure diagnostic coverage.

[2] In some cases, a given line represents multiple diagnostics. For instance, there are multiple SSNPAs, multiple IR cameras, multiple neutron detectors, and multiple Langmuir probe arrays.

**Appendix #1: Allowed Neutral Beam Power vs. Pulse Duration**

Heating of the primary energy ion dump limits the beam duration to that given in the following table[[1]](#footnote-1):

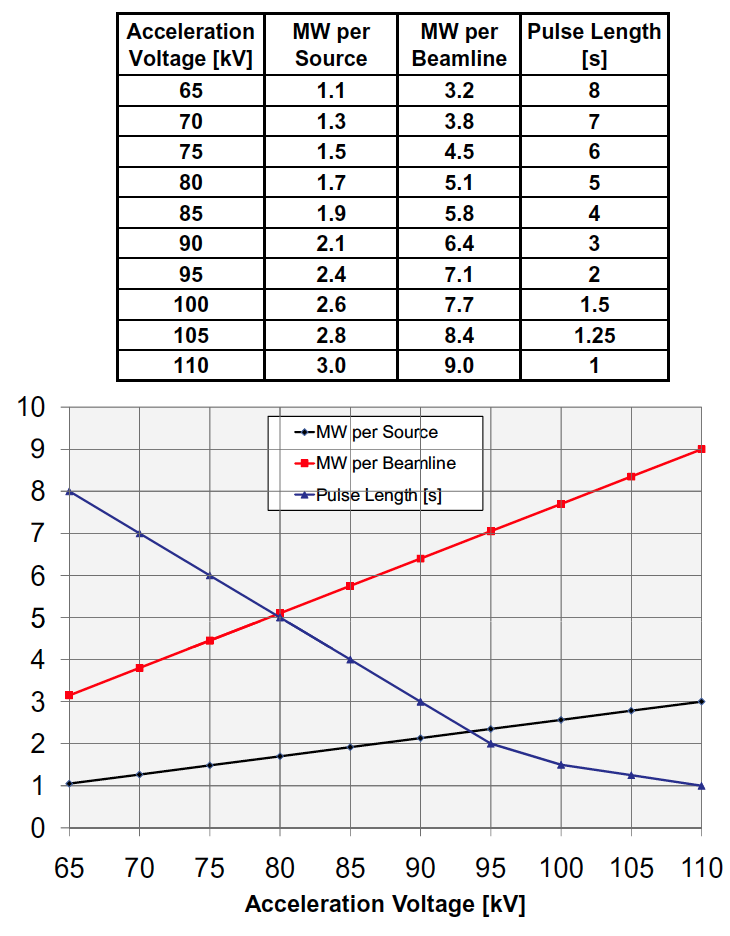


Table A1: Beam power and pulse length as a function of acceleration voltage

**Appendix #2: Table for neutron rate estimations:**



Table A2: Neutron Emission Rate Calculator. Double click to open in excel for automatic calculation. Change only the blue cells.

1. J.E. Menard, et al., Nuclear Fusion **52**, 2012 (83015) [↑](#footnote-ref-1)