Princeton Plasma Physics Laboratory
NSTX-U Experimental Proposal

Title: **Multi-machine studies of the L-H power threshold dependence on aspect ratio**		
OP-XP-1511	Revision: **1.1**	Effective Date: *(Approval date unless otherwise stipulated)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Responsible Author: M. Bongard, D. Smith, M. Churchill, A. Loarte	Date
SG, TSG or TF Leader (assigned by RC): R. Maingi	Date
Run Coordinator (RC): J. Menard	Date

Responsible Division: Experimental Research Operations

RESTRICTIONS or MINOR MODIFICATIONS
(Approved by Experimental Research Operations)

NSTX-U EXPERIMENTAL PROPOSAL

TITLE: **Multi-machine studies of the L-H power threshold dependence on aspect ratio** No. **OP-XP-1511**

AUTHORS: **M.W. Bongard, R.J. Fonck, G.R. McKee, J.A. Reusch, D.R. Smith, K.E. Thome, R.M. Churchill, A. Loarte** DATE: **6/26/15**

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1. Overview of planned experiment

The goal of this experiment is to document the L-H power threshold P_{LH} in NSTX-U at low aspect ratio as part of a broader multi-machine study to investigate P_{LH}'s dependence on *A*. The multi-machine study is comprised of experiments conducted on Pegasus (*A* ~ 1.2), NSTX-U (*A* ~ 1.6), and are proposed for DIII-D (*A* ~ 2.5). Measurements of P_{LH} and edge turbulence will be obtained in plasmas with varied magnetic topology, edge safety factor, and collisionality, guided by a recent L-H transition model (denoted FM^3) by Fundamenski *et al*. that makes testable predictions of P_{LH} in relation to these quantities.[1] Boronized wall conditioning is acceptable for this experiment. To facilitate comparisons to DIII-D and Pegasus, we will target configurations that closely match dimensionless parameters such as q and β_N. 2D BES measurements will observe edge turbulence dynamics across the L-H transition.

Characterizing the H-mode power threshold and edge turbulence properties of low-*A* NSTX-U plasmas provides information in support of the R15-1 and R15-3 milestones.

2. Theoretical/ empirical justification

A predictive, experimentally validated, physics-based model of P_{LH} does not exist, despite considerable effort since the discovery of the H-mode. In its absence, empirical scalings have been developed to serve as a basis for extrapolation (with considerable uncertainty) of P_{LH} to next-step devices such as ITER; obtaining a physics understanding of the L-H transition is a high-priority ITER research task.[2]

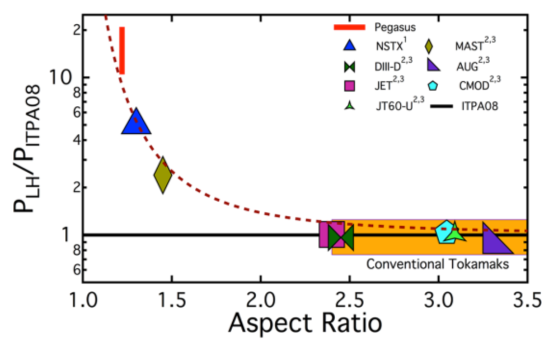

Fig. 1: P_{LH}(A) normalized to ITPA08 scaling.

Observations show that aspect ratio plays a role in L-H transition physics, but multi-machine empirical scalings developed on conventional aspect ratio tokamaks fail to capture the *A* dependence (among other "hidden variables"). Experimental P_{LH} values at low-*A* exceed that given by the latest-available ITPA08 scaling[3] (Fig. 1), with new observations from Pegasus highlighting an increasing deviation as $A \rightarrow 1$. At conventional *A*, diverted configurations yield the lowest P_{LH} values. In contrast, diverted and limited P_{LH} values are

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[1] W. Fundamenski *et al.*, Nucl. Fusion **52**, 062003 (2012)
[2] S.M. Kaye *et al.*, Nucl. Fusion **51**, 113019 (2011)
[3] Y.R. Martin *et al.*, J. Phys.: Conf. Ser. **123**, 012033 (2008)

similar in Pegasus at near-unity *A*. An additional experimental discrepancy with respect to P_{LH} scalings is a non-monotonic dependence on density, with increasing P_{LH} at low density observed on high-*A* devices[3] and MAST.[4]

The recent FM[3] model proposes the L-H transition occurs when the parallel Alfvénic time in the edge becomes comparable to the perpendicular transport time (the "Wagner number" $Wa \sim 1$). This condition allows nonlinear electromagnetic drift-wave instabilities to occur, providing a free energy source, and provides a mechanism for zonal flow formation through drift-Alfvén wave coupling. This criterion is related to local edge and scrape-off layer parameters, providing expressions for P_{LH} in terms of them for relation to empirical scalings. The model also accounts for some "hidden" variables and predicts the existence and scalings of a non-monotonic P_{LH} as a function of density. Of most relevance here is a prediction of the "penalty" in P_{LH} incurred by operating in limited versus favorable single-null and/or double-null magnetic topology, which is posited to scale with the edge safety factor as $q^{-7/9}$. Portions of the model have had favorable comparison with experiment on Alcator C-Mod[5] ($P_{LH}(n_e)$ / $n_{LH,min}$, SOL connection length $L_{||}$ [Fig. 2]), TCV[6] (X-point height), and Pegasus[7] (limiter/divertor penalty). NSTX-U edge turbulence and Thomson scattering data from this experiment represent a means to measure the Wagner number directly (independent of model free parameter assumptions).

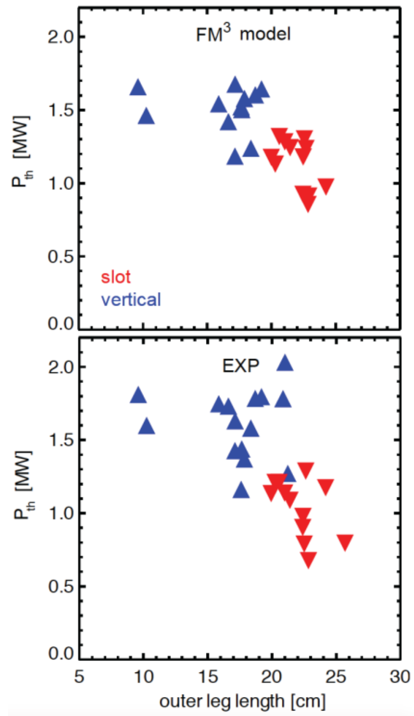

Fig. 2: C-Mod $P_{LH}(L_{||})$ compared to FM[3] scaling.[5]

3. Experimental run plan

Objectives

The primary focus of this experiment is to measure P_{LH} in several magnetic topologies with fixed B_T = 0.65 T at two I_p levels using stepped NBI power input. Edge turbulence and profile evolution will be documented through the L→H transition, providing measurements relevant to testing L-H transition models. H→L back-transitions will be attempted and similarly documented by reducing P_{NBI} in a stepwise fashion after a reasonable H-mode duration in these discharges. The role of NBI beam mix (dominant core vs. high tangency radius source) on P_{LH} will be explored at two I_p levels in favorable single null magnetic topology after P_{LH} has been reliably determined using conventional on-axis NBI.

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[4] H. Meyer *et al.*, Nucl. Fusion **53** 104008 (2013)
[5] Y. Ma *et al.,* 24th IAEA FEC, San Diego, No. EX/P2-04 (2012)
[6] Y. Martin *et al.*, Nucl. Fusion **54**, 114006 (2014)
[7] K.E. Thome *et al.*, TTF 2015

Methodology

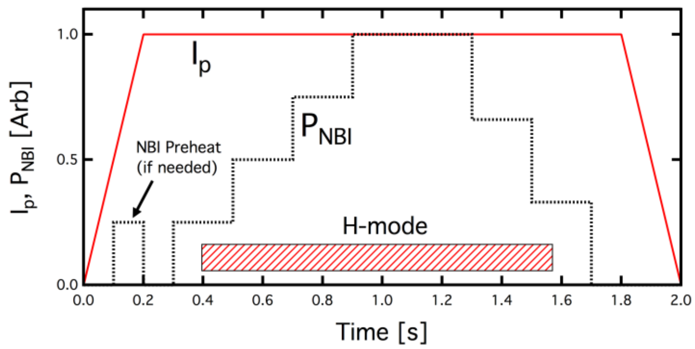

Fig. 3: Nominal shot evolution. NBI power steps of variable beam mix induce L-H-L transitions. Phase 1 increases P_{NBI}; for L-H; Phase 2 decreases P_{NBI} for H-L.

Figure 3 shows the nominal discharge evolution for shots in this experiment. For a given I_p, B_T, and magnetic topology, the discharge is established over ~0.2 s while remaining in L-mode.[8] A ~100 ms quiescent L-mode phase will be taken following the latter of attaining I_p flattop or termination of NBI preheat to allow dW/dt terms in P_{LH} determination to stabilize. Two subsequent logical discharge phases corresponding to NBI power application follow, as detailed below. The first phase utilizes increasing P_{NBI} to induce an L-H transition over four 200 ms steps; the second utilizes stepwise P_{NBI} reduction to attempt H-L back-transitions, with an optional short 200 ms pulse at the beginning of the phase to induce a brief H-mode scenario if it had not been achieved in phase 1.

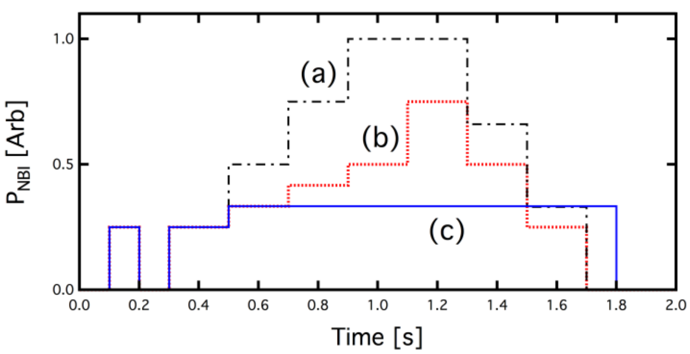

Fig. 4: NBI power waveforms in coarse (a), fine (b), and confirmation (c) shots used to determine P_{LH}. Waveforms (b)-(c) assume the L-H transition occurs near 0.5 s in (a).

P_{LH} will be determined by a series of shots in a particular plasma configuration. Four equally-spaced NBI power levels (Fig. 4) will be used in the L-H inducing waveform; two power levels in the H-L back-end, each with 200 ms duration. The first shot will utilize a 'coarse' P_{NBI} step size $\Delta P_{coarse} = P_{max}/4$ [Fig. 3(a)]. The second shot will utilize a finer-scale NBI waveform, with the initial NBI power level set to that below the observed L-H transition in the 'coarse' shot and ΔP_{NBI} step size reduced by a factor of 3 to better bracket the NBI power level that induces the L-H transition [Fig. 3(b)]. As a contingency, if an L-H transition is not achieved during the Phase 1 power ramp (for instance, due to increasing $n_e(t)$ during the fine-scale ramp), an additional shot with step size increased to $\Delta P_{coarse}/2$ will be taken. Finally, a "confirmation shot" will be taken, halting the P_{NBI} waveform at a level slightly below the determined threshold power level. This discharge is anticipated to remain in L-mode in its entirety.

The NBI beam mix in these scenarios will predominantly use beam line 1, providing core heating deposition. It will be varied in two scenarios as outlined below after a 'confirmation' shot has been performed, thereby providing a reasonable knowledge of P_{NBI} needed to achieve an L-H transition with core heating. The beam mix will then be altered to provide the maximum amount of source 2A (highest R_{tan}) in a fashion that matches the 'fine' scenario's total NBI power ramp input.

[8] A lower dI_p/dt and/or brief NBI preheat may be needed to conserve V-s and/or slow q_0 evolution for MHD stability optimization; this will be determined in requested prerequisite XP 1522.

Several plasma scenarios will be investigated using the above P_{LH} measurement procedure. All primary targets are deuterium plasmas with $B_T = 0.65$ T and either "high" $I_p = 1.2$ MA or "low" $I_p = 0.6$ MA and varied magnetic topology. In diverted topologies, the X-point radius and height should be matched to the extent possible in order to avoid its (empirically known) influence on P_{LH} in this study. In priority order, these are: (1) high I_p with favorable LSN magnetic topology, including a beam R_{tan} mix scan; (2) low I_p, LSN, including a beam R_{tan} mix scan; (3) high I_p, inner wall limited; and (4) high I_p, DN. These operating points are chosen in order to document P_{LH} in NSTX-U baseline scenarios ($q_{95} \sim 10$) and to facilitate comparison of NSTX-U results with those obtained in the high $q_{95} > 15$, $A \sim 1.2$ Pegasus ST.

Time/success permitting, two additional scenarios will be pursued. The fifth scenario is comprised of low I_p and DN magnetic topology. The sixth scenario will attempt P_{LH} measurements in a DIII-D-like lower q_{95} space, with $I_p = 1.4$ MA, LSN magnetic topology, and reduced $B_T = 0.4$ T. A lower dI_p/dt during the I_p ramp phase is anticipated in order to maintain early MHD quiescence in this more challenging operational scenario. These scenarios are summarized and prioritized in Table 1.

I_p [MA] / B_T [T]	**0.6**	**1.2**	**1.4**
0.4			*DIII-D-like low q_{95}* LSN [6]
0.65	*Pegasus-like, high q_{95}* LSN [2] DN [5]	*NSTX-U nominal q_{95}* LSN [1] LIM [3] DN [4]	

Table 1: Operating scenarios for P_{LH} evaluation. Scenarios are numbered by their prioritization.

Shot budget

- Main Plan
  - Scenario 1: 6 shots
    - P_{LH} in high I_p scenario, LSN [3 shots; course, fine, confirm; 1 contingency]
    - Beam mix [1 shot, 1 contingency]
  - Scenario 2: 6 shots
    - P_{LH} in low I_p scenario, LSN [3 shots; course, fine, confirm; 1 contingency]
    - Beam mix [1 shot, 1 contingency]
  - Scenario 3: 5 shots
    - P_{LH} in high I_p scenario, inner-wall limited [4 shots; extra course, course, fine, confirm; 1 contingency]
  - Scenario 4: 4 shots
    - P_{LH} in High I_p scenario, DN [3 shots; course, fine, confirm; 1 contingency]
  - 21 TOTAL [using all 6 contingency shots]

- Secondary Goals [Time/Success Permitting]
  - Scenario 5: 4 shots
    - P_{LH} in low I_p scenario, DN [3 shots; course, fine, confirm; 1 development/contingency]
  - Scenario 6: 4 shots
    - P_{LH} in I_p = 1.4 MA, B_T = 0.4 T, LSN [3 shots; course, fine, confirm; 1 development/contingency]

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

This XP should be run after XP 1522, which intends to develop ~ 0.8 s stable L-mode discharges at I_p = 1 MA, B_T = 0.65 T, $n_e \sim 3\text{-}4 \times 10^{19}$ m^{-3} in order to minimize scenario development efforts. This condition is needed here only for ~ 100 ms after I_p flattop prior to application of NBI to measure P_{LH}.

MPTS, CHERS, and MSE profile diagnostics are required. Edge turbulence diagnostics (2D BES, GPI, reflectometry) are strongly preferred. Neither RF nor CHI is required. Availability of NBI source 2A (130 cm) is required for the beam tangency radius mix scan.

Therefore, supporting diagnostic XMPs for MPTS outer gap alignment (Diallo) and CHERS compatibility with 2nd NBI line should additionally precede this XP.

5. Planned analysis

EFIT/LRDFIT equilibrium reconstruction + TRANSP for power balance analysis. 2D BES correlation and other turbulence analysis. Interpretive XGC1 simulations.

6. Planned publication of results

Presentations at APS-DPP if schedule permits. Data will contribute to an IAEA / Nuclear Fusion paper when entire multi-machine data set is collected and analyzed. Other presentations and publications may also arise (*e.g.* H-mode workshop/Nuclear Fusion) from the data set.

7. Estimated Neutron Production

of Shots used in Estimate:___23_____ Estimated Total Neutron Production:______2e16_______

(Assumes no contingency in main run plan and realization of all secondary goals.)

PHYSICS OPERATIONS REQUEST

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Brief description of the most important operational plasma conditions required and any special hardware requirement:

Quiescent L-mode phase for ~ 100 ms following latter of I_p flattop or NBI preheat in I_p ramp

Previous shot(s) which can be repeated:

Previous shot(s) which can be modified: Anticipated to leverage XP 1522 startup

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

B_T Range (T): **0.4 – 0.65** Flattop Duration (s): **> 1.2**

I_P Range (MA): **0.6 – 1.4** Flattop Duration (s): **> 0.8**

Configuration: **Limiter / DN / LSN /** ~~USN~~

Equilibrium Control: ~~Outer gap~~ / **Isoflux** (rtEFIT) / ~~Strike-point control (rtEFIT)~~

Outer gap (m): **0.1-0.12 [TBD via MPTS XMP]**

Inner gap (m): **0-*TBD*** Z position (m): **0**

Elongation: **~2.3** Triangularity (U/L): **~0.6-0.7** OSP radius (m):

Gas Species: **D** Injector(s): **TBD**

NBI Species: **D** Heating Duration (s): **< 1**

Voltage (kV) 50 cm (1C): *TBD* 60 cm (1B): *TBD* 70 cm (1A): *TBD*

Voltage (kV) 110 cm (2C): *TBD* 120 cm (2B): *TBD* 130 cm (2A): *TBD*

ICRF Power (MW): **N/A** Phase between straps (°): **N/A** Duration (s): **N/A**

CHI: **Off** / ~~On~~ Bank capacitance (mF): **N/A**

LITERs: Off / ~~On~~ Total deposition rate (mg/min) or dose per discharge (mg): **N/A**

EFC coils: ~~Off~~ / **On for error field correction**

DIAGNOSTIC CHECKLIST [1]

TITLE: **Multi-machine studies of the L-H power threshold dependence on aspect ratio** No. **OP-XP-1511**

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Note special diagnostic requirements in Sec. 4

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

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
MAPP		
Mirnov coils – high f.		
Mirnov coils – toroidal array		
MSE-CIF	X	
MSE-LIF	X	
Neutron detectors [2]		
Plasma TV		X
Reflectometer – 65GHz		X
Reflectometer – correlation		X
Reflectometer – FM/CW		X
Reflectometer – fixed f		X
Reflectometer – SOL		X
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[9]:

Acceleration Voltage [kV]	MW per Source	MW per Beamline	Pulse Length [s]
65	1.1	3.2	8
70	1.3	3.8	7
75	1.5	4.5	6
80	1.7	5.1	5
85	1.9	5.8	4
90	2.1	6.4	3
95	2.4	7.1	2
100	2.6	7.7	1.5
105	2.8	8.4	1.25
110	3.0	9.0	1

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

Appendix #2: Table for neutron rate estimations:

I_p Range [kA]	Center of I_p Range [kA]	Number of Discharges	Typical Discharge Time [s]	Assumed Neutron Rate [N/s]	Fluence at this I_p [N]
$0<I_p\leq400$	200	0	0	0.00E+00	0.00E+00
$400<I_p\leq600$	500	0	0	1.00E+14	0.00E+00
$600<I_p\leq800$	700	4	2	2.00E+14	1.60E+15
$800<I_p\leq1000$	900	0	0	3.00E+14	0.00E+00
$1000<I_p\leq1200$	1100	15	2	4.00E+14	1.20E+16
$1200<I_p\leq1400$	1300	0	0	5.00E+14	0.00E+00
$1400<I_p\leq1600$	1500	4	2	8.00E+14	6.40E+15
$1600<I_p\leq1800$	1700	0	0	1.30E+15	0.00E+00
$1800<I_p\leq2000$	1900	0	0	2.00E+15	0.00E+00
Total # of Discharges		23		Total Fluence	2.00E+16

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

[9] J.E. Menard, et al., Nuclear Fusion **52**, 2012 (83015)