Princeton Plasma Physics Laboratory
NSTX-U Experimental Proposal

Title: **Characterizing the SOL Losses of HHFW Power in H-Mode Plasmas**

OP-XP-1510	Revision:	Effective Date: *(Approval date unless otherwise stipulated)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Responsible Author:	Date
SG, TSG or TF Leader (assigned by RC):	Date
Run Coordinator (RC):	Date

Responsible Division: Experimental Research Operations

RESTRICTIONS or MINOR MODIFICATIONS
(Approved by Experimental Research Operations)

NSTX-U EXPERIMENTAL PROPOSAL

TITLE: **Characterizing the SOL Losses of HHFW Power in H-Mode Plasmas** No. **OP-XP-1510**
AUTHORS: **Rory Perkins, Joel Hosea, Gary Taylor, Nicola Bertelli, Randy Wilson, Cornwall Lau, John Caughman, David Smith** DATE:

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1. Overview of planned experiment

The main goal of this experiment is to understand the conditions that yield optimal coupling of HHFW power into H-mode plasmas by minimizing the amount of power lost to the SOL. In support of this main goal, diagnostic upgrades will allow the following measurements:

1) the total fraction of HHFW power lost to the RF spirals to the lower divertor,
2) the spiral intensity as a function of length along the spiral,
3) the RF voltage at the most intense portion of the spiral,
4) SOL density profiles in front of the HHFW antenna.

These quantities will be systematically measured under a variety of conditions: magnetic field strength, antenna phasing, RF power level. This will allow a far more quantitative assessment of the assertion that the SOL losses are intimately tied to the position of the righthand cutoff in the SOL and should point to the conditions of optimal coupling for NSTX-U.

This experiment also supports three other goals: measurements of the HHFW wavefields using BES, obtaining SOL density profiles using an upgraded reflectometer for RF-model validation, and investigating the influence/control of impurity transport by means of HHFW heating.

2. Theoretical/ empirical justification

The NSTX research team has expressed a desire to couple more HHFW power into H-mode plasmas, which is known to be a non-trivial challenge [Hosea 08, Taylor09]. Improvements to the HHFW heating efficiency were previously observed with higher antenna phasing, increased magnetic field, and lower SOL density, suggesting that the loss of HHFW power is related to the location of the righthand cutoff in the SOL. While this assertion has found support in numerical simulations [2009 Green PRL, N. Bertelli NF], it has not been demonstrated rigorously in an experiment. If true, effective coupling should be obtained by suitable tailoring of the edge density and should become more accessible at higher fields (such as those that will hopefully be available on NSTX-U).

What will be different this time around?? Upgraded diagnostic coverage will allow some critical questions to be addressed that could previously be treated only superficially.

- **Wide-angle IR camera**: the wide-angle view will capture much of the lower divertor, allowing for thermographic measurements of most of the RF spiral. This will allow us to determine:

  - *the total power deposited to the divertor underneath the lower RF spiral, a quantity that could only be estimated in a rough manner previously [Perkins13 RF Conf],*
  - *whether the losses in the RF spiral account for the majority of the HHFW power not reaching the core, and thus whether other loss mechanism (e.g. PDI) are important,*
  - *the variation of heat flux under the spiral as a function of length along the spiral, which, even with the limited measurements previously available, showed interesting structure [Perkins13 NF].*
- **Radial arrays of RF Langmuir probes**: six-probe arrays on both the upper and lower divertor has been situated at Bay I, close to the most intense portion of the RF spiral. The signal cables are suitable for transmitting RF frequencies, and the electronics will allow for direct measurement of the RF-component of the collected current.
  - *Direct measurement of the RF component will determine definitively whether RF rectification is occurring within the spiral.*
  - *The direct measurement of the RF component and the array location near the spiral maximum will allow us to estimate the peak heat flux in the spiral due to RF rectification [R. J. Perkins, J. C. Hosea, M. A. Jaworski et al., Phys. Plasma]. This will then be directly compared to IR camera measurement from the same location and definitively quantify the role that RF rectification plays in heat flux.*
- **Upgraded SOL Reflectometer:** has been upgraded to be compatible with the higher fields in NSTX-U. While SOL reflectometer data was taken previously, the full capability of this diagnostic was not exploited, as measured SOL density profiles were not used in RF models.
  - *Comparing SOL density profiles to measurements of the RF losses will allow a detailed assessment of the statement that RF losses are enhanced as the region of FW propagation approaches the antenna.*
  - *The SOL density profile obtained will be used in RF models to predict the magnitude of RF losses in the SOL.*

Finally, full-wave simulations HHFW propagation in NSTX using the AORSA code show that the can be a substantial increase in the RF field amplitude in the SOL when the righthand cutoff is moved close to the antenna. Measuring the HHFW wavefield via BES offers the potential to verify this experimentally.

3. Experimental run plan

This experiment was allocated 0.5 days of Priority 1 runtime and 0.25 days of Priority 2 runtime in weeks 5-8, and an equal amount of time over weeks 9-16. Assume 24 shots per day (20 minutes per shot) for 15 “Priority 1” shots and 6 “Priority 2” shots in weeks 5-8. In planning the run, I am assuming a shot efficiency of 50%, meaning that one of every two shots will be no good due to machine conditions or antenna trips. Note that the HHFW power and phase can both be adjusted within a shot, which may allow for a more rapid scan in these parameters. However, the slow IR camera has 30 Hz acquisition rate, and we want to acquire at least three or four frames of data with these parameters fixed, meaning each power/phase setting requires about 120 ms of flat-top time. Thus, the pulse duration at the time of the run will influence the number of shots needed to complete the scans.

We want to run this experiment in two configurations: RF-only H-modes, and NBI + RF H-modes. Developing NBI + RF H-modes is a priority for making the HHFW system a (more) widely available tool for NSTX-U research. However, RF-only H-modes are of interest as they can provide low-torque beam-less targets. Also RF-only shots in helium are particularly suitable to RF experimentation, as the discharge is stable and edge density is lower. RF-only discharges can also be run in deuterium; the higher edge density may be more appropriate for the SOL losses studied here. The decision over which configuration to use in weeks 5-8 will be made after the commissioning (XMP 026). Given that weeks 5-8 will be in boronized (pre-lithium) wall conditions, we may lean towards RF-only helium H-modes for this first experiment.

The following run plan can be applied to either RF-only or RF+NBI H-modes. It consists of three important scans: toroidal field strength, antenna phase, and RF power. After there are several ideas for any remaining shots.

Major scans, in order of importance

Magnetic field scan (4/8): vary the toroidal magnetic field strength and observe diagnostic response and core heating. As the SOL losses are field-aligned, it is very desirable to keep q_{95} fixed so that the spiral is more or less fixed for consistent diagnostic measurements. Apply strong but not maximal HHFW power. Start at $B_T = 0.45$ T and increment B_T in 0.1 T steps up to maximum toroidal field at time of operation. If 0.75 T is not available, perform shots at 0.60 T and 0.65 T to give two data points beyond NSTX. For each shot, vary antenna phase from 180° -> 90° -> 30° for 120 ms each (match HHFW tuning system to 180°). Ideally, this would take 4 shots, which we assume will actually take 8 shots.

Antenna Phase Scan (2/4): Set toroidal field to maximum value. Tune matching system to 30° and use one shot to scan 0° -> 30° -> 60° for 120 ms each. Retune for 150° match and scan 120° -> 150° -> 180°. This would ideally need 2 shots, in practice 4 shots. Time-permitting later in the experiment, change order of phases within scan to check for ‘hysteresis.’

RF Power Scan (3): Select a phase that gives substantial SOL losses and medium toroidal field strength. We will tailor an RF staircase waveform to ramp the power up to the maximum power available. Repeat at two different q_{95} values for a total of 6 shots. Time-permitting, repeat (without q_{95} scan) at two more phases.

Runtime for BES measurements of RF fields

BES Dedicated Shots (6): The experiment for BES measurements of RF fields has been given explicit run time (0.25 days, or 6 shots). This would be a good point to take those shots, as the BES system will have been run in piggyback mode up to this point, so an educated decision can be made on how to optimize the discharges for these measurements.

Ideas for using Priority 2 shots

Gas Puffing (3): Attempt to change local density in front of antenna via gas puffing. Select one or more valves as "diagnostic" values. In middle of HHFW pulse, open diagnostic valves and measure density at antenna [SOL reflectometer] and the change in SOL losses.

Increased lithium evaporation (4): Obviously, this can only be run in weeks 9-16 after the boronization period of the campaign. Lithium surface conditioning reduced recycling and thus lowers the SOL density. We have plans to use the SOL reflectometer to study the change in SOL density profile as lithium is introduced. In this experiment, gradually increase lithium evaporation over the course of four shots and observe change in SOL losses and density profile.

Switch from He -> D (4): If operating RF-only H-modes in helium for a length of time, switching to deuterium will gradually change the recycling and SOL density. We could observe the change in SOL profile using the reflectometer and compare this against any change in antenna loading and SOL losses.

Radiative Divertor (2): the RF spirals are perhaps due to FW propagating to the divertor and setting up RF sheaths, or are due to parasitic absorption of FW power in the SOL which then streams to the divertor along field lines. If a radiative divertor could be established, we can test which process is occurring. Discussions with Vlad will determine if this is feasible to test and will use maybe two shots.

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

- XMP 026 is a pre-requisite for checking out the HHFW system end-to-end under plasma, for conditioning the antenna, and for compatibility of HHFW system with NBI systems.
- To perform RF + NBI H-modes, we need at least one neutral beam with enough power to generate an H-mode (2 MW). We prefer Beam 1 Source A for diagnostic purposes.

5. Planned analysis

- EFIT and/or LRDFIT for equilibrium reconstruction; followed by SOL field-line mapping (SPIRAL).
- IR thermographic analysis to determine heat flux.
- AORSA and perhaps TORIC for wave propagation and absorption calculations. AORSA will probably use density profiles obtained from processing SOL reflectometer data.
- TRANSP to analyze HHFW heating of core
- Available impurity transport models to assess impact of HHFW

6. Planned publication of results

We want to generate a number of 2016 IAEA presentations: roughly, one focusing on the RF-spiral heat-flux properties, one on modeling based these results, one on SOL density measurements. Those that are accepted will also publish papers in Nuclear Fusion. Those that are not will still be submitted to peer-review journals.

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:________ Estimated Total Neutron Production:________________

PHYSICS OPERATIONS REQUEST

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

Previous shot(s) which can be repeated: TBD from XMP 026

Previous shot(s) which can be modified: TBD from XMP 026

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

B_T Range (T): **0.45-0.75 T** Flattop Duration (s): **> 0.6**

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

Configuration: **DN or LSN**

Equilibrium Control: **Outer gap**

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

Elongation: **TBD** Triangularity (U/L): **TBD** OSP radius (m): **TBD**

Gas Species: **D / He** Injector(s):

NBI Species: **D** Heating Duration (s): **0.5 s**

Voltage (kV) 50 cm (1C): 60 cm (1B): 70 cm (1A): 2 MW

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

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

CHI: **Off** Bank capacitance (mF):

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

EFC coils: Off/On

DIAGNOSTIC CHECKLIST [1]

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Note special diagnostic requirements in Sec. 4

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

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
MAPP		
Mirnov coils – high f.		
Mirnov coils – toroidal array		
MSE-CIF		
MSE-LIF		
Neutron detectors [2]		X
Plasma TV	X	
Reflectometer – 65GHz		
Reflectometer – correlation		
Reflectometer – FM/CW		
Reflectometer – fixed f		
Reflectometer – SOL	X	
SSNPA [2]		X
RF edge probes		X
Spectrometer – divertor		X
Spectrometer – MonaLisa		
Spectrometer – VIPS		
Spectrometer – LOWEUS		X
Spectrometer – XEUS		X
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]:

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:

Change only the blue cells					
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]
$0<I_p\le400$	200	0	0	0.00E+00	0.00E+00
$400<I_p\le600$	500	0	0	1.00E+14	0.00E+00
$600<I_p\le800$	700	0	0	2.00E+14	0.00E+00
$800<I_p\le1000$	900	1	1.5	3.00E+14	4.50E+14
$1000<I_p\le1200$	1100	10	1	4.00E+14	4.00E+15
$1200<I_p\le1400$	1300	0	0	5.00E+14	0.00E+00
$1400<I_p\le1600$	1500	15	4	8.00E+14	4.80E+16
$1600<I_p\le1800$	1700	1	1	1.30E+15	1.30E+15
$1800<I_p\le2000$	1900	0	0	2.00E+15	0.00E+00
Total # of Discharges		27	Total Fluence		5.38E+16

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

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