

**Princeton Plasma Physics Laboratory  
NSTX Experimental Proposal**

**Title: Experiment to Optimize the Conversion of EBWs to X-Mode on NSTX**

**OP-XP- 308**

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*(2 yrs. unless otherwise stipulated)*

**PROPOSAL APPROVALS**

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Date

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Date

**RLM - Run Coordinator: S. Kaye**

Date

**Responsible Division: Experimental Research Operations**

**Chit Review Board** (*designated by Run Coordinator*)

**MINOR MODIFICATIONS** (*Approved by Experimental Research Operations*)

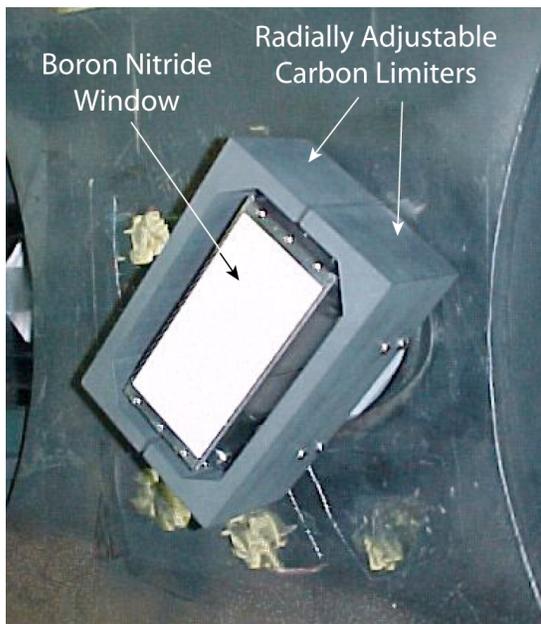
# NSTX EXPERIMENTAL PROPOSAL

**Title: Experiment to Optimize the Conversion of EBWs to X-Mode on NSTX**

**No.: 308**

## 1. Overview of planned experiment

The goals of this experiment are twofold. First, to demonstrate the measurement of the electron temperature on NSTX using mode-converted EBW's in support of an ongoing DoE plasma diagnostic initiative to develop an EBW electron temperature profile diagnostic for overdense ( $\omega_{pe} > \omega_{ce}$ ) plasmas. Second, to demonstrate a B-X conversion efficiency  $\geq 80\%$  on NSTX as a prerequisite for installing an EBW heating and current drive system. A new EBW antenna with two radially adjustable carbon limiters (Fig. 1) has been installed on NSTX to measure extraordinary electromagnetic mode emission converted from electron Bernstein waves (EBWs) (B-X emission) and to optimize the B-X conversion efficiency with a local limiter. The new EBW antenna has two quad-ridge horns that will be used for both EBW radiometry and O-mode reflectometry. The electron density scale length ( $L_n$ ) at the B-X mode conversion layer is an important parameter in determining the B-X conversion efficiency. The O-mode reflectometer will measure  $L_n$  at the B-X mode conversion layer in front of the EBW antenna.



*Figure 1* Photograph showing the new EBW antenna with radially adjustable carbon limiters. The antenna has a white Boron nitride window covering two quad-ridged horns. The antenna is rotated to orient the ridges to be parallel and normal to the edge magnetic field. In addition to EBW radiometry the horns will be used by an O-mode reflectometer to measure  $L_n$  at the B-X conversion layer. There are two carbon limiters that can be moved independently over a major radial of about 3 cm. The antenna includes a port for a gas injection valve.

## 2. Theoretical/ empirical justification

Fundamental EBWs convert and tunnel to the fast X-mode at the upper hybrid resonance (UHR) that usually surrounds the NSTX plasma just outside the last closed flux surface [1-3]. EBWs first convert to the slow X-mode at the UHR. A cutoff-resonance-cutoff triplet formed by the left hand cutoff of the slow X-mode, the UHR, and the right hand cutoff of the

fast X-mode allows the slow X-mode to tunnel through the UHR to the fast X-mode. The mode conversion efficiency ( $C$ ) for  $k_{\parallel} = 0$  is given by [3]:

$$C = 4e^{-\pi\eta} \left(1 - e^{-\pi\eta}\right) \cos^2(\phi/2 + \theta) \quad (1)$$

where  $\cos^2(\phi/2 + \theta)$  is a phase factor relating to the phasing of the waves in the mode conversion region and the term preceding this is the maximum mode conversion efficiency. Here  $\eta$  is a tunneling parameter, which for magnetic scale lengths much greater than the density scale length at the UHR [3], is given by:

$$\eta \approx \left[\omega_{ce} L_n (c\alpha)\right] \left[(1 + \alpha^2)^{1/2} - 1\right]^{1/2} \quad (2)$$

where  $L_n$ , the density scalelength, and  $\alpha = \omega_{pe} / \omega_{ce}$  are evaluated at the UHR layer and  $c$  is the velocity of light. From these equations it can be seen that the B-X conversion efficiency is very sensitive to changes in  $L_n$  at the UHR layer where the wave frequency,  $\omega = \omega_{UHR}$ .

B-X mode conversion is particularly well suited for ST plasmas since the UHR layer for fundamental EBW conversion lies in the scrape off layer outside the last closed flux surface (LCFS) where  $L_n$  can be modified without affecting plasma performance. On NSTX the maximum mode conversion efficiency for fundamental EBWs occurs for  $L_n \sim 0.3 - 0.6$  cm.

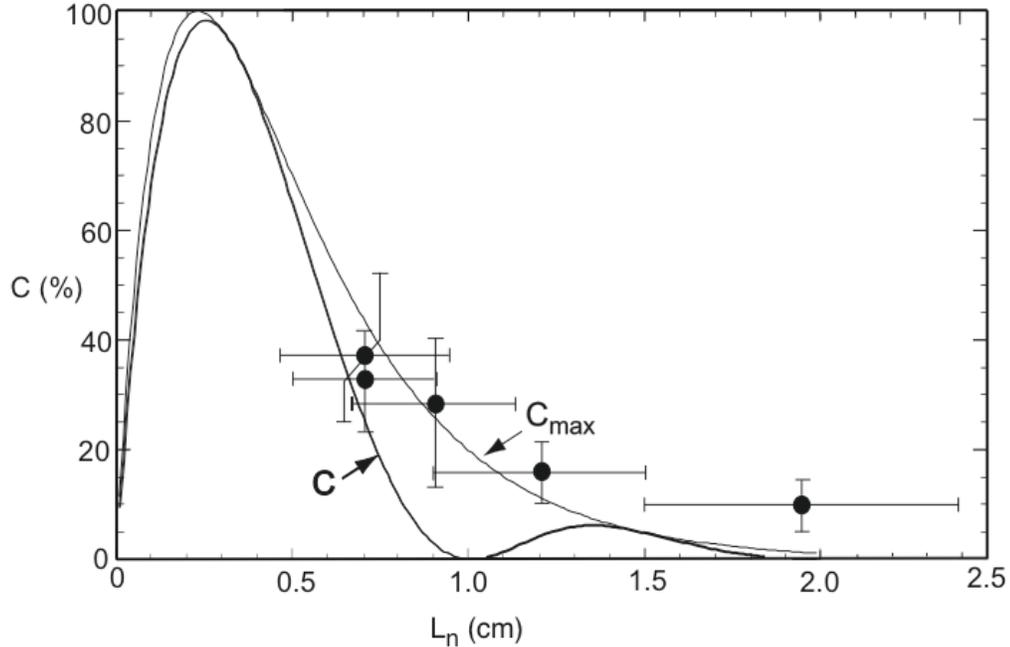


Fig. 2 Plot of theoretically expected B-X mode conversion efficiency for fundamental EBW from the NSTX core versus density scale length ( $L_n$ ) at the B-X conversion layer (lines) and the measured efficiency ( $T_{ebw}/T_e$ ) and attained  $L_n$  measured by X-mode microwave reflectometry in XP-213.

In a previous experiment on NSTX, XP-213, the B-X conversion was increased by a factor of four when  $L_n$  at the mode-conversion layer was shortened from  $\sim 2$  cm to about 0.7 cm (Fig. 2) [4]. In XP-213 the plasma was programmed to run with essentially no gap between the outer edge of the plasma and the Boron nitride limiters in the HHFW antenna. The maximum conversion efficiency approached 50% when the outer gap was zero and  $L_n$  was reduced to 0.7 cm, in agreement with theoretical predictions that used the local  $L_n$  at the B-X conversion layer measured by X-mode reflectometry. To reach  $\geq 80\%$  B-X conversion  $L_n$  needs to be reduced to about 0.3 cm. In XP-213 the minimum attainable  $L_n$  was limited by the connection length along the magnetic field lines between the Boron nitride tiles. The new EBW antenna was designed to have a connection length that can be made short enough to produce  $L_n \sim 0.3$  at the UHR layer.

### References:

- [1] NAKAJIMA, S. and H. ABE, Phys. Rev. A **38**, 4373 (1988).
- [2] SUGAI, H., Phys. Rev. Lett. **47**, 1899 (1981).
- [3] RAM, A.K., and SCHULTZ, S. D., Phys. of Plasmas **7**, 4084 (2000).
- [4] TAYLOR, G., et al., "Enhanced Conversion of Thermal Electron Bernstein Waves to the Extraordinary Electromagnetic Mode on the National Spherical Torus Experiment (NSTX)", PPPL Report 3757 (October 2002).

## 3. Experimental run plan

Dedicated run time for this experiment will be requested only after the new EBW antenna has been fully commissioned with the UCLA O-mode reflectometry operational on the antenna and providing routine measurements of the scrape off density profile. Remote operation of the radially adjustable carbon limiters is also a prerequisite for this experiment. A gas feed is available at the EBW antenna if density is not high enough to make the plasma overdense at the front face of the antennas. The following run plan requires about 20 plasma shots.

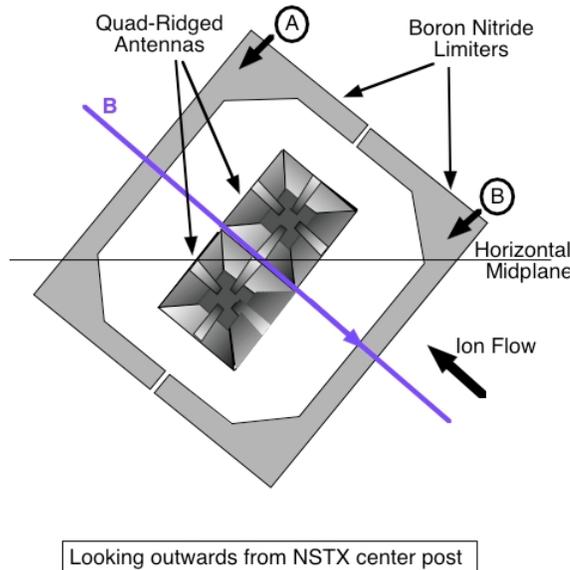
### I. $L_n$ Scan for Optimum B-X Conversion (run EBW radiometer dwelling at one frequency $\sim 13$ GHz (i.e. EBW emission from near the plasma axis):

a) Establish an ohmically-heated, deuterium plasma using the setup from shot 107975, an  $I_p = 800$  kA lower single null plasma, but with  $B_0 = 4.5$  kG, instead of 4 kG. The experiment needs about 150 ms of  $I_p$  flattop without electron density glitches and a well-controlled shape. Five minutes of He GDC will be performed between shots. The experiment will begin with both the B-X antenna limiters A and B retracted (see Fig. 3). Here we define the displacement of A and B limiters as  $\Delta_A$  and  $\Delta_B$ , respectively. Where 0 cm is fully retracted and 3 cm is fully extended towards the plasma. (5 shots)

Repeat same shot until the plasma conditions become reasonably reproducible and without significant MHD. Acquire MPTS  $T_e(R)$  and  $n_e(R)$  profile data during  $I_p$  flattop. Also obtain scrape off density profile at EBW antenna with the UCLA O-mode microwave reflectometer. Measure  $L_n$  at the B-X conversion layer and EBW  $T_{rad}/T_e$ , where  $T_e$  is measured by MPTS. Acquire data on two similar shots. (2 shots)

b) Move limiter B towards the plasma so that  $\Delta_B = 1, 2$  and  $3$  cm, two shots at each position. Limiter B should have the greatest influence on  $L_n$  since it is on the ion flow side of the antenna. Measure  $L_n$  at B-X conversion layer and EBW  $T_{rad}/T_e$ . (6 shots)

c) Leaving  $\Delta_A = 3$ , move limiter B back from plasma so that  $\Delta_B = 2, 1$  and  $0$  cm, two shots at each position. Measure  $L_n$  at B-X conversion layer and EBW  $T_{rad}/T_e$ . (6 shots)



*Figure 3 Schematic showing the EBW B-X antenna with radially adjustable carbon limiters. The two carbon limiters are labeled A and B. Limiter A is on the electron flow side and limiter B is on the ion flow side of the antenna.*

## II. Run EBW radiometer in swept frequency mode (11-18 GHz) at maximum B-X conversion:

Set  $\Delta_A$  and  $\Delta_B$  for maximum B-X conversion and obtain and EBW  $T_{rad}/T_e$  vs radius where  $T_e$  is measured by MPTS on two similar shots. (2 shots)

## III. Use HHFW to Suppress Edge Fluctuations:

It has been noted on NSTX in the past that edge density fluctuations can be reduced or suppressed when HHFW power is coupled to the plasma. Plan to couple 1-2 MW of HHFW power into some of the shots during the last 50 ms of the current flat top to assess the effect of HHFW on edge density fluctuations and EBW B-X conversion. (piggyback).

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

No NBI is required for this experiment. HHFW at  $\sim 2$  MW is required for some discharges. See attached list of required diagnostics and machine parameter requirements. The X-mode EBW radiometer at Bay I/J, MPTS, UCLA O-mode reflectometer at Bay I/J, the ORNL X-mode reflectometer at the HHFW antenna and EFIT equilibrium are essential for this experiment.

**5. Planned analysis**

Compare measured B-X mode transmission efficiency ( $T_{\text{ebw}}/T_e$ ) and the calculated transmission efficiency using  $L_n$  at the B-X conversion layer derived from the UCLA O-mode microwave reflectometer.

**6. Planned publication of results**

PPPL report and perhaps a journal publication if the results warrant it.

# PHYSICS OPERATIONS REQUEST

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Machine conditions (indicate range where appropriate):

**TF:** Flattop (kG) 4.5 Flattop start/stop (s) 0.0 / 0.5

**I<sub>p</sub>:** Flattop (kA) 800 Flattop start/stop (s) 0.2 / 0.35

**Position:** Outer Gap (m) 0-0.04 Z (m) 0 ~~Inner wall/~~ Single null / ~~Double null~~

**Gas:** D (inside gas feed) Puff yes, plus LDGFIS ? n<sub>e</sub>.I programmed to avoid flat-top tearing mode

**NBI:** Power (MW) \_\_\_\_\_ Start / stop (s) \_\_\_\_\_ Voltage (kV) \_\_\_\_\_

**RF:** Power (MW) 2 Start / stop (s) 0.3 – 0.35 Frequency (MHz) 30

**CHI:** Off / Start-up / Ramp-up / Sustainment

If this is a continuation of a previous run or if shots from a previous run are similar to those needed, provide shot numbers for setup

**Setup shot similar to 107975, an I<sub>p</sub> = 800 kA, lower single null plasma, but with B<sub>0</sub> = 4.5 kG, instead of 4.0 kG**

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If shots are new and unique, sketch desired time profiles and shapes. Accurately label the sketch so there is no confusion about times or values. Attach additional sheets as required.

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## DIAGNOSTIC CHECKLIST

Title: Experiment to Optimize the Conversion of EBWs to X-Mode on NSTX

No. 308

Diagnostic system	Need	Desire	Requirements (timing, view, etc.)
Magnetics	✓		
Fast visible camera		✓	
VIPS-1		✓	
VIPS-2		✓	
SPRED		✓	
GRITS		✓	
Visible filterscopes		✓	
VB detector		✓	
Midplane bolometer		✓	
Diamagnetic flux		✓	
Density interferometer (1mm)		✓	
FIReTIP interf'r/polarimeter		✓	
Thomson scattering	✓		Essential for EBW conversion efficiency
CHERS			
NPA			
X-ray crystal spectrometer			
X-ray PHA		✓	
EBW radiometer	✓		Essential at EBW antenna bay I/J location
Mirnov arrays		✓	
Locked-mode detectors			
USXR arrays		✓	
2-D x-ray detector (GEM)		✓	
X-ray tangential camera		✓	
Reflectometer (4 ch.)	✓		Essential at EBW antenna bay I/J location
Neutron detectors			
Neutron fluctuations			
Fast ion loss probe			
Reciprocating edge probe		✓	
Tile Langmuir probes			
Edge fluctuation imaging			
H-alpha cameras (1-D)			
Divertor camera (2-D)			
Divertor bolometer (4 ch.)			
IR cameras (2)			
Tile thermocouples			
SOL reflectometer	✓		Measure edge density fluctuations with/without HHFW