NSTX EXPERIMENTAL PROPOSAL

OP-XP-### : Thermal Electron Bernstein Wave Conversion to O-Mode at 8-40 GHz

1. Overview of Planned Experiment

The goal of this experiment is to measure 8-40 GHz thermal electron Bernstein wave (EBW) emission coupling via the slow extraordinary mode to the ordinary electromagnetic mode (B-X-O emission). The experiment has three objectives; 1) map the coupling efficiency as a function of antenna pointing direction and compare results to theoretical predictions, 2) analyze the polarization of the thermal EBW emission and compare results to theoretical predictions, and 3) measure the electron temperature profile evolution using thermal EBW emission. Experiments will be conducted using two-antenna systems, each with an oblique view at bay G mid-plane. One antenna will measure fundamental (8-18 GHz) emission and the second antenna will measure second harmonic (18-40 GHz) thermal EBW emission. Each antenna is coupled to a dual-channel EBW radiometer at bay G mid-plane.

2. Theoretical/Empirical Justification

The mode conversion and tunneling process between EBWs and the electromagnetic O-mode requires the coincidence of the X-mode and O-mode cutoffs [1-5]. This process has been studied extensively on Wendelstein 7-AS both for heating [6] and as a $T_e(R)$ emission diagnostic [7]. The B-X-O emission leaves the plasma through an angular window at an oblique angle with a transmission function given by [3,5]:

$$T(N_\perp, N_{//}) = \exp\left\{-\pi k_o L_n \sqrt{(Y/2)}\left[2(1+Y)(N_{//,opt} - N_{//})^2 + N_\perp{}^2\right]\right\} \quad (1)$$

where: k_o is the wavenumber, $N_{//,opt}{}^2 = [Y/(Y+1)]$, $Y = (\omega_{ce}/\omega)$, ω_{ce} is evaluated at the cutoff and ω is the wave frequency. For NSTX this B-X-O emission window is located at about 55^o from the direction of the magnetic field. The emission window has a width that increases with decreasing L_n at the O-mode cutoff. For high power EBWCD systems modeling predicts that the resiliency of the coupling efficiency to variations in L_n can be improved by polarization adjustments to the launched microwave power allowing efficient EBW coupling over a broad range of L_n [8].

In a previous experiment on NSTX (XP-514) thermal EBW emission measurements were obtained in the 24-32 GHz frequency range (second harmonic). A single dual-channel radiometer system was manually steered to an alignment location that was optimized for 28 GHz emission measurements. Results from XP-514 and subsequent numerical modeling of the coupling, EBW propagation, and deposition are summarized in Figure 1 for NSTX shot 117970. The central electron temperature profile from Thomson scattering (black dashed line in Figure 1) reaches its peak of ~1 keV at 0.3 s and gradually falls to ~0.35 keV at 0.6 s. The time averaged EBW T_{rad} (blue line in

Figure 1) reaches about 0.3 keV at 0.15 s and then gradually falls to 0.15 keV at 0.6 s. For XP-514, the measured mode conversion efficiency was ~20%.

A numerical 3-D ray tracing model, that utilized the EFIT equilibrium and electron kinetic profiles from Thomson scattering, was used to model the evolution of the 25 GHz thermal EBW emission for shot 117970 (Figure 2). The quad-ridged antenna used in the experiment allowed orthogonal radiation polarizations to be measured simultaneously. Polarization measurements were consistent with the near-circular polarization predicted by the numerical model (Figure 2b).

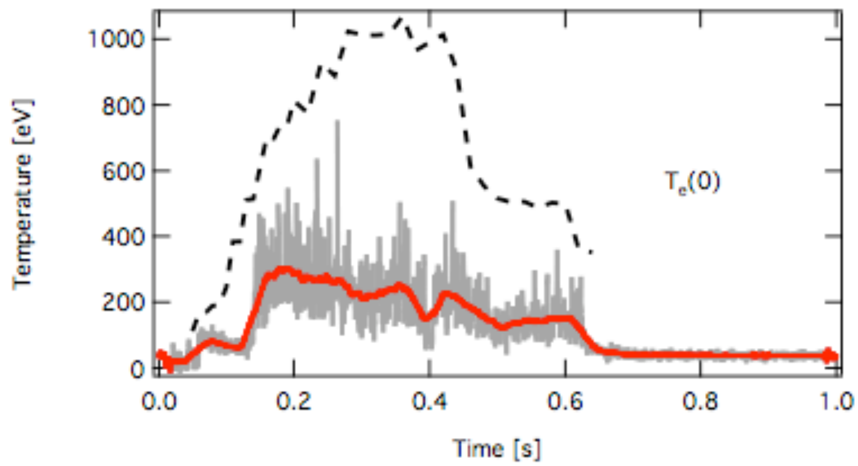

Figure 1. T_{rad} is plotted versus time for NSTX shot 117970. The red trace is the radiation temperature obtained from the absolutely calibrated radiometer for 25 GHz emission. The blue trace is the smoothed T_{rad} data. The black dashed line is the Thomson scattering electron temperature on axis.

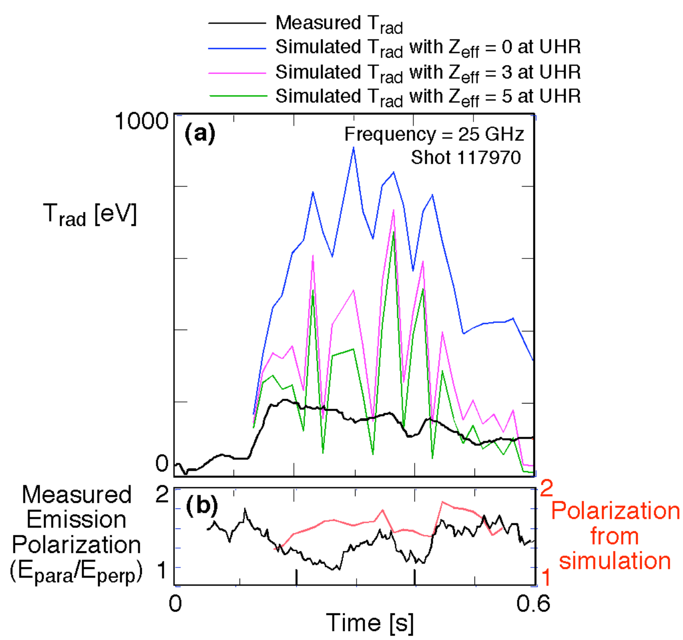

Figure 2. Measured T_{rad} and emission polarization for shot 117970 for 25 GHz. **(a)** T_{rad} vs. time is plotted. The black trace is the time-averaged measured emission. Also plotted is the simulated T_{rad} for shot 117970, the blue trace (Z_{eff}=0) neglects the effects of collisions, the pink (Z_{eff}=3) and green (Z_{eff}=5) include collisional effects. **(b)** The black trace shows the measured emission polarization while the red trace shows the simulated emission polarization.

This numerical modeling predicted that the effective temperature (T_{eff}) of the thermal EBW emission (Figure 2a, blue line) source electrons reaches about 0.8 keV at 0.2 s and then gradually falls to 0.3 keV at 0.6 s. However, the measured effective temperature was 2-4 times smaller than the predicted effective temperature. The measurements for XP-514 were obtained using an H-mode target plasma with an electron temperature near the upper hybrid resonance layer of ~10-30 eV. In this temperature range, collisional losses can be significant. It is hypothesized that these collisional losses are the cause of the low EBW coupling efficiencies measured. A simplistic collisional model was incorporated into the numerical 3-D ray-tracing model to investigate collisional effects on the thermal EBW emission radiated temperature. In Figure 2a, simulated thermal EBW radiation temperatures for shot 117970 including collisional effects for Z=3 (pink) and Z=5 (green) are shown. From these simulations, it is shown that low electron temperatures near the upper hybrid layer can have a significant effect on the measured thermal EBW radiation temperature.

A significant upgrade to the previous dual-channel, 18-40 GHz oblique-viewing, O-mode EBW radiometer will be available for this XP. The 18-40 GHz system will be remotely steerable and can be re-positioned between shots using a PC located in the NSTX control room. A second dual-channel, 8-18 GHz (fundamental frequency) oblique-viewing, O-mode EBW radiometer system (on Bay-G, Figure 3) will also be available for this XP.

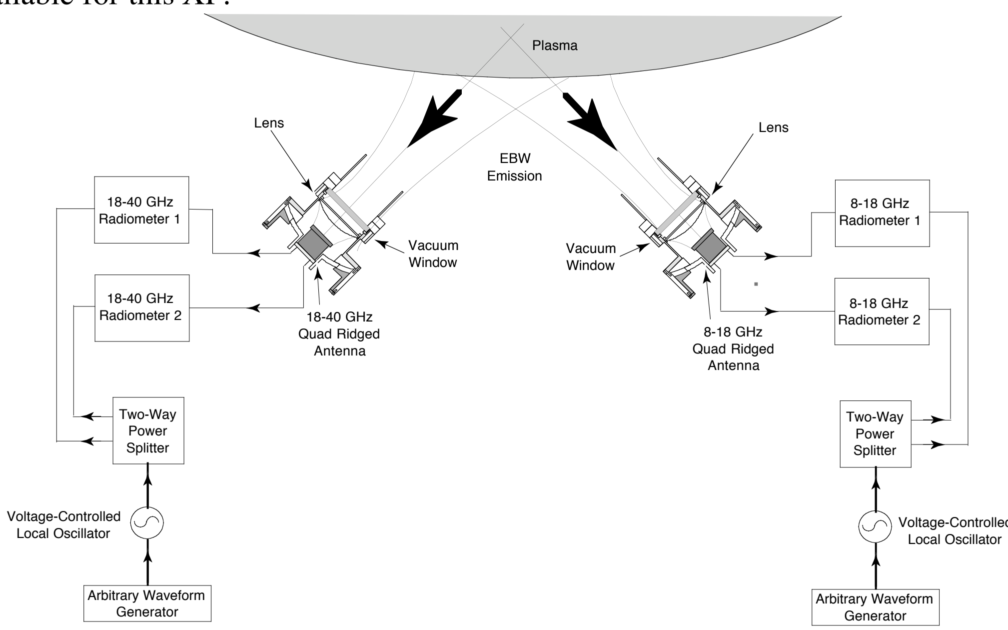

Figure 3. Machine layout of the upgraded remotely-steered EBW emission diagnostic. Each antenna is coupled to a dual channel, absolutely calibrated radiometer system. The 8-18 GHz radiometer will measure O-mode EBW emission is the fundamental frequency range while the 18-40 GHz radiometer will measure emission in the second harmonic frequency range.

The 8-18 GHz system will also be remotely steerable by computer. The remote steering capability will allow a detailed mapping of conversion efficiency as a function of antenna pointing direction to be performed during this XP. Both of the systems will be able to measure two orthogonal polarizations simultaneously. The experiment has three objectives: 1) map the coupling efficiency as a function of antenna pointing direction and compare results to theoretical predictions, 2) analyze the polarization of the thermal EBW emission and compare results to theoretical predictions, and 3) measure the electron temperature profile evolution using thermal EBW emission.

References:

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[7] LAQUA, H.P., *et al*., Phys. Rev. Lett. **81**, 2060 (1998).
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3. Experimental Run Plan

Initially EBW radiometers will acquire measurements during other experiments, in order to debug the new instrument and identify optimum conditions for conducting dedicated experiments. Data will be taken in fast frequency scanning and dwelled frequency mode under various plasma conditions. The experiment would benefit from the use of rtEFIT and a relatively long, 200 - 250 ms, I_p flattop, preferably without significant electron density glitches and a fairly well controlled shape. Both L-mode and H-mode plasmas will be used for the dedicated shots, with shot operating parametrs chosen based on experience gained in analyzing the "piggyback" data from the. This experiment will require at least two half-day runs with 10 reproducible well documented shots each. Thomson scattering $T_e(R)$ and $n_e(R)$ profile data will be acquired during the I_p flattop. Also we will need to obtain the scrape off density profile at Bay C with the ORNL reflectometer and/or at Bay J with the UCLA O-mode microwave reflectometer. EFIT will be essential in order to reconstruct equilibria for numerical modeling with the 3-D EBW ray tracing code and for modeling EBW mode conversion.

There are two main objectives for these experiments on NSTX:

1. **To obtain a mapping of B-X-O mode conversion efficiency for both H- and L-mode plasmas.** This mapping will be achieved by remotely steering the antenna while repeating the same plasma shot.
2. **To investigate collisional effects on mode coupling.** Data analysis from shot 117970 revealed that the predicted effective EBW temperature was a factor of 2-4 lower than the measured effective temperature (figure 2). Gas puffs (at 50, 100, and 165 torr-l/s) will be introduced into the plasma edge to change the effective collision frequency.

Shot List - 2 half-day runs (minimum)

Day 1) H-mode plasma, similar to reference shot #117405

Shots (1-3) Setup and repeat the target plasma shot until the plasma conditions become reasonably reproducible.

Shots (4-13) Repeat best shot from (1-3) and scan antenna pointing direction to obtain a B-X-O mode conversion efficiency mapping.

Shots (14-15) Repeat best shot from (4-13) with a toroidal field sweep during I_p flattop.

Shots (16-18) Repeat best shot from (4-13) and introduce gas puffs from low field side of 50, 100 and 165 torr-l/s at ~0.3 s.

Day 2) L-mode plasma, similar to reference shot #113544

Shots (1-3) Setup and repeat the target plasma shot until the plasma conditions become reasonably reproducible.

Shots (4-13) Repeat best shot from (1-3) and scan antenna pointing direction to obtain a B-X-O mode conversion efficiency mapping.

Shots (14-15) Repeat best shot from (4-13) with a toroidal field sweep during I_p flattop.

Shots (16-18) Repeat best shot from (4-13) and introduce gas puffs from low field side of 50, 100 and 165 torr-l/s at ~0.3 s.

4. Required Machine, NBI, RF, CHI and Diagnostic Capabilities

NBI is required for this experiment in order to provide stable, 200-250 ms, I_p flattop. See attached list of required diagnostics and machine parameter requirements. MPTS, ORNL reflectometer and EFIT equibria are essential for this experiment.

5. Planned Analysis

Compare measured B-X-O mode transmission efficiency (T_{ebw}/T_e) and emission polarization with the calculated coupling efficiency and wave polarization using the density scale length at the electron plasma frequency cutoff, EFIT equilibria, and electron kinetic profiles from laser Thomson scattering.

6. Planned Publication of Results

PPPL report and a journal publication in *Physics of Plasmas*.

PHYSICS OPERATIONS REQUEST

Title: **Thermal Electron Bernstein Wave Conversion to O-Mode at 8-40 GHz** OP-XP-###

Machine conditions (indicate range where appropriate):

TF: Flattop (kG) 4.0 Flattop start/stop (s) 0.0 / 0.5

I_p: Flattop (kA) 800 Flattop start/stop (s) 0.2 / 0.4

Position: Outer Gap (m) 0.05-0.15 Z (m) 0 ~~Inner wall~~ / Single null / ~~Double null~~

Gas: He or D (inside gas feed) Puff yes, plus LDGFIS ? n_e.l programmed to avoid flat-top tearing mode

NBI: Power (MW) ~2 Start / stop (s) ________ Voltage (kV) ______

RF: Power (MW) ______ Start / stop (s) ________ Frequency (MHz) ______

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

Day 1) Setup shot similar to 117405, I_p = 800 kA, B_o = 4.5 kG, final parameters to be determined based"piggback" EBW emission data analysis
Day 2) Setup shot similar to 113544, I_p = 800 kA, B_o = 4 kG, final parameters to be determined based"piggback" EBW emission data analysis

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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.

DIAGNOSTIC CHECKLIST

Thermal Electron Bernstein Wave Conversion to O-Mode at 8-40 GHz OP-XP-###

Diagnostic	Need	Desire	Instructions
Bolometer – tangential array		✓	
Bolometer array - divertor			
CHERS			
Divertor fast camera			
Dust detector			
EBW radiometers (Bay I/J & Bay G)	✓		Needed at bay I/J antenna, desired at Bay G
Edge deposition monitor			
Edge pressure gauges			
Edge rotation spectroscopy			
Fast lost ion probes - IFLIP			
Fast lost ion probes - SFLIP			
Filtered 1D cameras			
Filterscopes		✓	
FIReTIP		✓	
Gas puff imaging			
High-k Scattering			
Infrared cameras			
Interferometer - 1 mm		✓	
Langmuir probes – PFC tiles			
Langmuir probes – RF antenna			
Magnetics - Diamagnetism		✓	
Magnetics - Flux loops	✓		
Magnetics - Locked modes			
Magnetics - Pickup coils	✓		
Magnetics - Rogowski coils	✓		
Magnetics - RWM sensors			
Mirnov coils – high frequency			
Mirnov coils – poloidal array			
Mirnov coils – toroidal array			
MSE			
Neutral particle analyzer			
Neutron measurements			
Plasma TV		✓	
Reciprocating probe		✓	
Reflectometer – FM/CW	✓		Needed for some dedicated shots, but turn off on most dedicated shots to avoid rf interference with radiometers
Reflectometer – fixed frequency homodyne		✓	
Reflectometer –homodyne correlation			
Reflectometer – HHFW/SOL	✓		Needed for density scrape-off data
RF antenna camera			
RF antenna probe			
Solid State NPA			
SPRED		✓	
Thomson scattering - 20 channel	✓		Essential to get Ln for EBW conversion efficiency
Thomson scattering - 30 channel		✓	Desired to get Ln for EBW conversion efficiency
Ultrasoft X-ray arrays		✓	
Ultrasoft X-ray arrays – 2 color		✓	
Visible bremsstrahlung det.		✓	
Visible spectrometers (VIPS)		✓	
X-ray crystal spectrometer - H			
X-ray crystal spectrometer - V			
X-ray PIXCS (GEM) camera			
X-ray pinhole camera		✓	
X-ray TG spectrometer		✓	