Princeton Plasma Physics Laboratory
NSTX Experimental Proposal

Title: Thermal Electron Bernstein Wave Conversion to O-Mode at 20-40 GHz

OP-XP-514	**Revision: 3**	Effective Date: February 22, 2005 *(Ref. OP-AD-97)* Expiration Date: February 22, 2007 *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Authors: G. Taylor, P. Efthimion, J. Wilgen, J.Caughman	Date
ATI-ET Group Leaders: E. Fredrickson & J.R. Wilson	Date
RLM - Run Coordinator: J. Menard	Date

Responsible Division: Experimental Research Operations

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

NSTX EXPERIMENTAL PROPOSAL

OP-XP- 514: Thermal Electron Bernstein Wave Conversion to O-Mode at 20-40 GHz

1. Overview of Planned Experiment

The goal of this experiment is to measure 20-40 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) to measure the electron temperature profile evolution by utilizing thermal EBW emission, 2) to analyze the polarization of the thermal EBW emission to benchmark theoretical predictions, and 3) to demonstrate >80% coupling of thermal EBW emission to electromagnetic waves at emission frequencies ~ 28 GHz; a prerequisite for proceeding with installation of a 28 GHz megawatt-level EBW current drive (EBWCD) system on NSTX. Experiments will be conducted using a dual-channel, 20-40 GHz oblique-viewing, O-mode 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]:

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

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° 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-405), >80% coupling of 16-18 GHz thermal EBWs was measured via B-X-O conversion [9]. Results from XP-405 and subsequent numerical modeling of the coupling, EBW propagation, and deposition are summarized in Fig. 1 for NSTX shot 113544. For these earlier experiments the alignment and focusing of the EBW radiometer quad-ridged antenna were not optimized for the angular coupling window defined in equation 1. Also the focusing of the antenna pattern was constrained by the relatively small diameter of the viewport used for these experiments. This may explain the rapid fluctuations on the measured EBW radiation temperature (T_{rad}) at 16.5 GHz (thin solid line) shown in Fig. 1. The central electron temperature

($T_e(0)$) measured by Thomson scattering (triangles) reaches almost 2 keV at 0.3 s, $T_e(0)$ then gradually falls to about 0.7 keV at 0.5 s. The time-averaged EBW T_{rad} (thick solid line) reaches about 1.1 keV at 0.3 s and then gradually falls to 0.6 keV at 0.5 s.

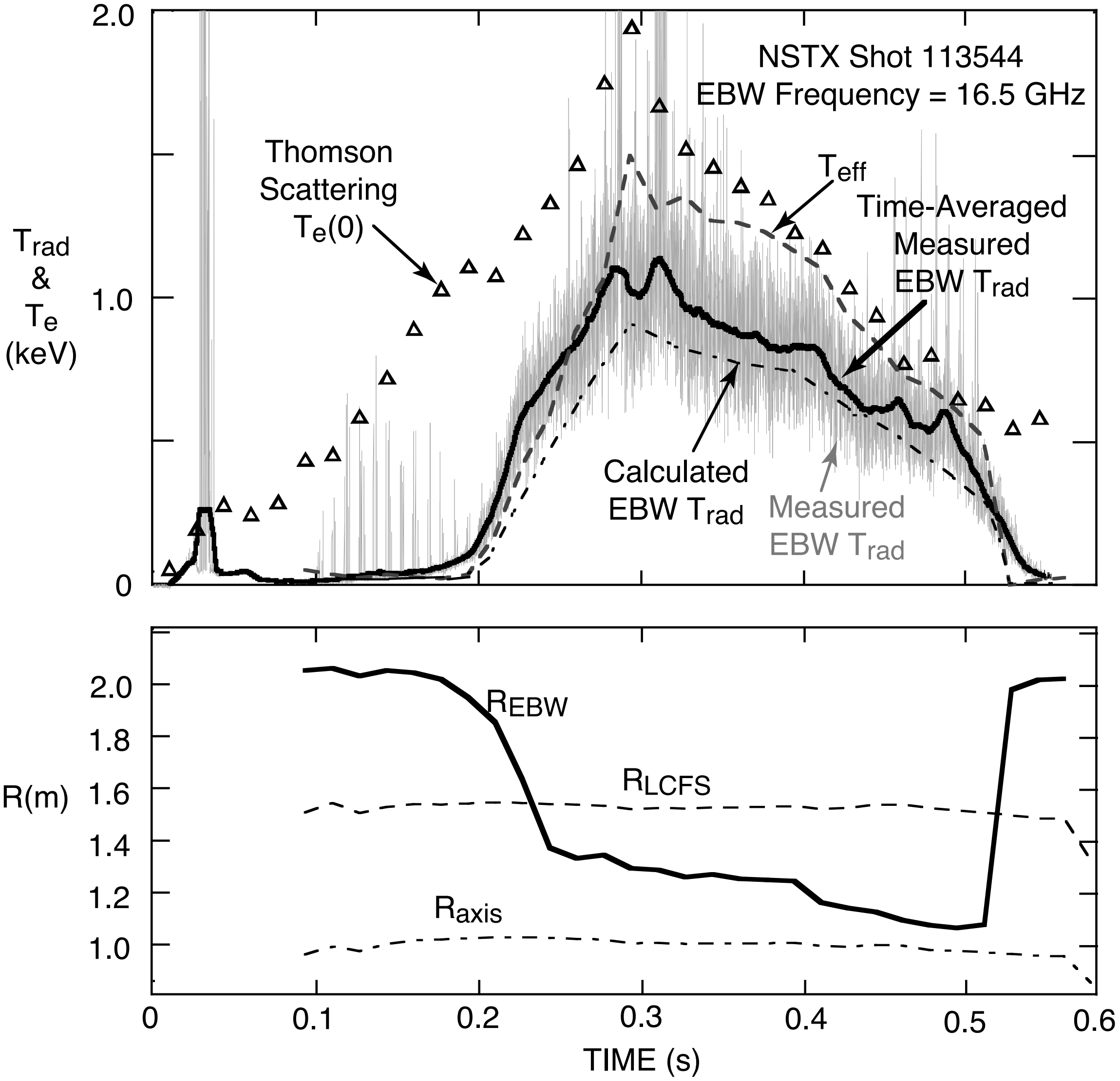

Figure 1: *Time evolution of $T_e(0)$ measured by Thomson scattering (triangles), the radiation temperature (thin solid line) and its time average (thick solid line) measured by the EBW radiometer at 16.5 GHz, the effective temperature of the thermal EBW radiation source electrons (long dashed line) and the calculated EBW radiation temperature (short dashed line) for NSTX shot 113544. The lower figure shows the time evolution of the mean major radius of the electrons contributing to the thermal EBW emission at 16.5 GHz (thick solid line), the major radius of the last closed flux surface (long dashed line) and the major radius of the magnetic axis (dash-dot line) from EFIT.*

A numerical 3-D ray tracing model, that utilized the EFIT equilibrium and electron kinetic profiles from Thomson scattering, predicted that the effective temperature (T_{eff}) of the thermal EBW emission source electrons (long dashed line) reaches about 1.3 keV at 0.3 s and gradually falls to 0.7 keV at 0.5 s. The average major radius of the EBW emission source (R_{EBW}) is plotted in Fig. 1, before 0.23 s it lies outside the last closed flux surface (LCFS) and then moves inwards to about 1.2 m at 0.3 s. By 0.5 s the R_{EBW} has moved into 1.1 m, close to the magnetic axis, located at 1.0 m and $T_{eff} \sim T_e(0)$. The numerical modeling calculates the expected EBW T_{rad} measured by the radiometer, it was somewhat lower than the measured EBW T_{rad}. The predicted EBW coupling efficiency, T_{rad} / T_{eff} , ranges between 0.62 at 0.3 s and 0.67 at 0.5 s, whereas the measured coupling efficiency T_{rad} / T_{eff} is 0.8±0.2 at both 0.3 s and 0.5 s. Assuming the same antenna pattern used in the experiment, but with the antenna aligned for optimum EBW coupling, the numerical model predicts about 90% EBW coupling could have been achieved in XP-405. 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.

The proposed experiment will be similar to XP-405, except that it will measure EBW emission and coupling over a higher frequency range and the emission spectrum will be measured with better time resolution. A new dual-channel, 20-40 GHz, EBW radiometer has been installed on an enlarged oblique-viewing vacuum window at Bay G. The instrument has a much faster response time (~ 1 μs) than the radiometer used in XP-405 (~ 50 μs), allowing for better time resolution of the fluctuations in EBW T_{rad}, and the relative timing of the fluctuations between the orthogonally polarized signals. The higher EBW emission frequency and enlarged viewport will allow better antenna focusing. Provision is also being made to allow alignment of the antenna axis with the optimum B-X-O angular coupling "window". In addition to measuring two orthogonal polarizations simultaneously between 20 and 40 GHz, provision will also be made for installing a quarter wave plate optimized for operation ~ 28 GHz in front of the antenna for more detailed polarization analysis. As in XP-405, the new antenna can be rotated by 45 degrees about its axis to quantify the polarization ellipticity. The experiment has three objectives; 1) measure $T_e(R,t)$ via thermal EBW emission, 2) analyze EBW emission polarization to benchmark numerical modeling predictions, and 3) demonstrate >80% EBW coupling at ~ 28 GHz to support planning for a megawatt-level EBWCD system on NSTX.

References:

[1] PREINHAELTER, J. and KOPÉCKY, V., J. Plasma Phys. **10**, 1 (1973).
[2] WEITZNER, H. and BATCHELOR, D.B., Phys. Fluids **22**, 1355 (1979).
[3] MJØLHUS, E., J. Plasma Phys. **31**, 7 (1984).
[4] NAKAJIMA, S. and ABE, H., Phys. Lett. A **124**, 295 (1987).
[5] HANSEN, F.R., *et al.*, J. Plasma Phys. **39**, 319 (1988).
[6] LAQUA, H.P., *et al.*, Phys. Rev. Lett. **78**, 3467 (1997).
[7] LAQUA, H.P., *et al.*, Phys. Rev. Lett. **81**, 2060 (1998).
[8] IGAMI, H., *et al*, Plasma Phys. And Cont. Fusion **46**, 261 (2004).
[9] TAYLOR, G., *et al.*, "*Efficient Coupling of Thermal Electron Bernstein Waves to the Ordinary Electromagnetic Mode on the National Spherical Torus Experiment (NSTX)*" to be published in Phys. Plasmas **12** (May 2005). PPPL Report 4047 (February 2005).

3. Experimental Run Plan

Initially the 20-40 GHz radiometer measurements will be made in "piggyback" mode, in order to debug the new instrument and identify optimum conditions for conducting dedicated experiments. Data will be taken in fast frequency scanning mode to acquire the EBW emission spectrum between 20 and 40 GHz every 10μs, under various plasma conditions. Dedicated experiments will probably use plasma parameters similar to NSTX shot 113544. This shot had an I_p = 800 kA, B_o = 4 kG and about 2 MW of neutral beam heating. 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. L-mode is not essential for this experiment. A decision to use L-mode or H-mode plasmas for the dedicated shots will be based on experience gained in analyzing the "piggyback" data from the 20-40 GHz radiometers. This experiment will require at least 10 dedicated shots, less than half a run day. 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.

Shot List

1) Setup and repeat shot similar to 113544 until the plasma conditions become reasonably reproducible. Run EBW radiometer in swept frequency mode between 20 and 40 GHz. (2-3 shots)
2) Set radiometer receive frequency at ~ 28 GHz (1 shot)
3) Increase outer gap of plasma over sequence of shots in 5 cm steps from ~5 cm to ~ 15 cm, at each gap setting take radiometer at ~ 28 GHz receive frequency and in 20-40 GHz swept mode (4 shots)
4) In controlled access, rotate antenna by 45 degrees, then run plasma with outer gap from step 3 that provided maximum thermal EBW coupling, then take radiometer data at ~ 28 GHz and in 20-40 GHz swept mode (2 shots)
5) In controlled access, insert quarter wave plate in front of antenna, then take radiometer data at ~ 28 GHz and in 20-40 GHz swept mode (2 shots)

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 20-40 GHz** **OP-XP-514**

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

Setup shot similar to 113544, I_p = 800 kA, B_o = 4 kG, final parameters to be determined based“piggback” EBW emission data analysis

---

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 20-40 GHz OP-XP-514

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		✓	