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Electron Bernstein Wave Research on NSTX and CDX-U

by

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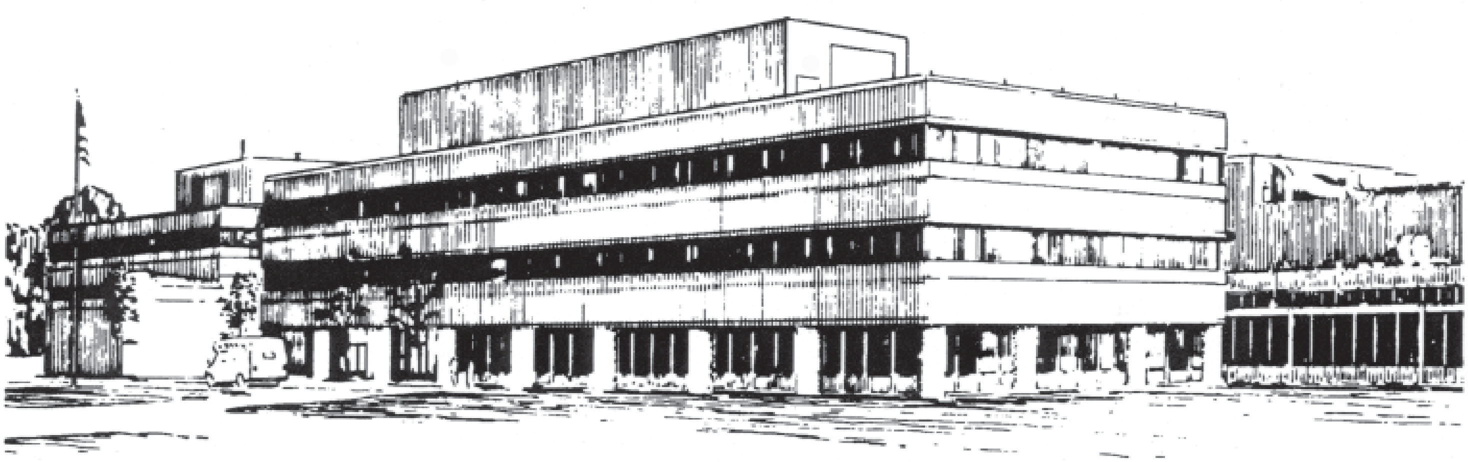

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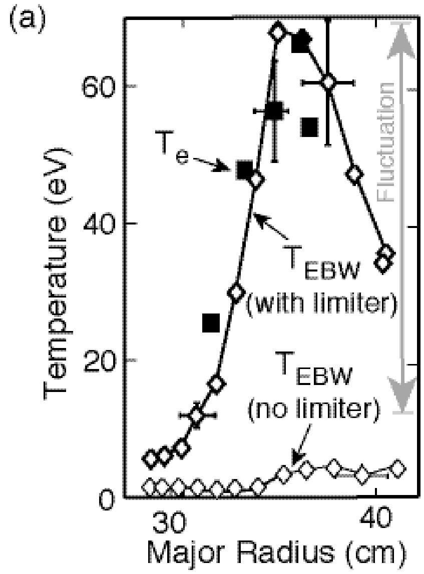
Abstract. Studies of thermally emitted electron Bernstein waves (EBWs) on CDX-U and NSTX, via mode conversion (MC) to electromagnetic radiation, support the use of EBWs to measure the T_e profile and provide local electron heating and current drive (CD) in overdense spherical torus plasmas. An X-mode antenna with radially adjustable limiters successfully controlled EBW MC on CDX-U and enhanced MC efficiency to ~ 100%. So far the X-mode MC efficiency on NSTX has been increased by a similar technique to 40-50% and future experiments are focused on achieving ≥ 80% MC. MC efficiencies on both machines agree well with theoretical predictions. Ray tracing and Fokker-Planck modeling for NSTX equilibria are being conducted to support the design of a 3 MW, 15 GHz EBW heating and CD system for NSTX to assist non-inductive plasma startup, current ramp up, and to provide local electron heating and CD in high β NSTX plasmas.

INTRODUCTION

CDX-U [1] and NSTX [2] are high β spherical tori that contain overdense ($\omega_{pe} >> \omega_{ce}$) plasmas that are not accessible to low harmonic electron cyclotron waves, and hence preclude the use of established technologies such as ECRH and ECCD. Since electron Bernstein waves (EBWs) propagate in overdense plasmas and absorb strongly at electron cyclotron resonances, they may be used for local electron temperature measurements, electron heating (EBWH) and current drive (EBWCD). Coupling to EBWs is possible via mode conversion (MC) of electromagnetic waves in the vicinity of the plasma edge [3,4]. Recent studies of thermally emitted EBWs via MC have evaluated the EBW MC physics both to develop a local electron temperature diagnostic and, as a result of the symmetry of the MC process [5], to support the development EBWH and EBWCD.

EBW MODE CONVERSION MEASUREMENTS

Optimized EBW MC has been demonstrated on CDX-U, with almost complete conversion of thermally emitted EBWs to X-mode electromagnetic radiation, in agreement with theoretical predications using the measured density scale length (L_n) at the MC layer [6]. A local, radially scanned, limiter surrounding a quad-ridged antenna produced controlled steepening of L_n from > 3 cm to 7 mm in the vicinity of the EBW to X-mode MC layer, resulting in an order of magnitude increase in the MC efficiency of fundamental EBW emission, so that $T_{rad} \sim T_e$, measured by Thomson scattering (Fig. 1(a)).



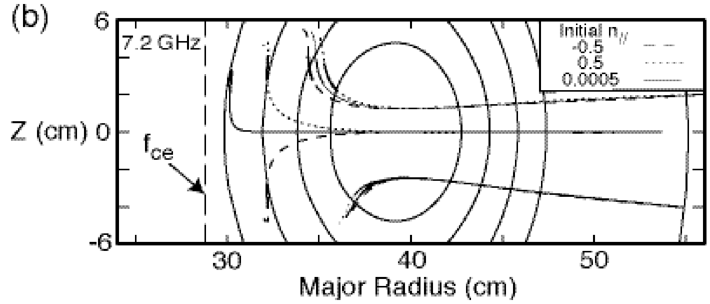


Figure 1. **(a)** Radiation temperature of MC EBW emission with and without a local limiter on CDX-U. When the limiter shortens L_n to 7 mm at the EBW MC layer, the EBW T_{rad} and T_e profiles are similar. The EBW T_{rad} exhibits large amplitude fluctuations (vertical grey arrows). **(b)** GENRAY calculation showing significant displacement for EBW rays near the midplane resulting from 1-2 cm vertical shifts in the plasma column causing large fluctuations in measured T_{rad}.

Large fluctuations in EBW MC efficiency were observed on CDX-U (vertical grey arrows in Fig. 1(a)) and, while these were fairly strongly correlated with L_n fluctuations at the MC layer, GENRAY [7] ray tracing calculations (Fig. 1(b)) indicate that vertical plasma oscillations of only 0.3 cm could account for oscillations in T_{rad} of 20-80 eV, or about half the observed T_{rad} fluctuation. Detailed analysis of the CDX-U EBW MC experiments is presented elsewhere [8]. Since the NSTX plasma is much larger and better controlled than CDX-U, fluctuations in EBW emission due to refraction on NSTX are expected to be considerably smaller. Initial studies of EBW emission during NSTX plasmas showed $\Delta T_{rad}/T_{rad}$ ~ 20%, confirming this expectation. These initial EBW emission measurements also indicated MC efficiency < 5% for L-mode discharges and ~ 15% during H-modes, consistent with theoretical calculations using the measured L_n at the MC layer [9].

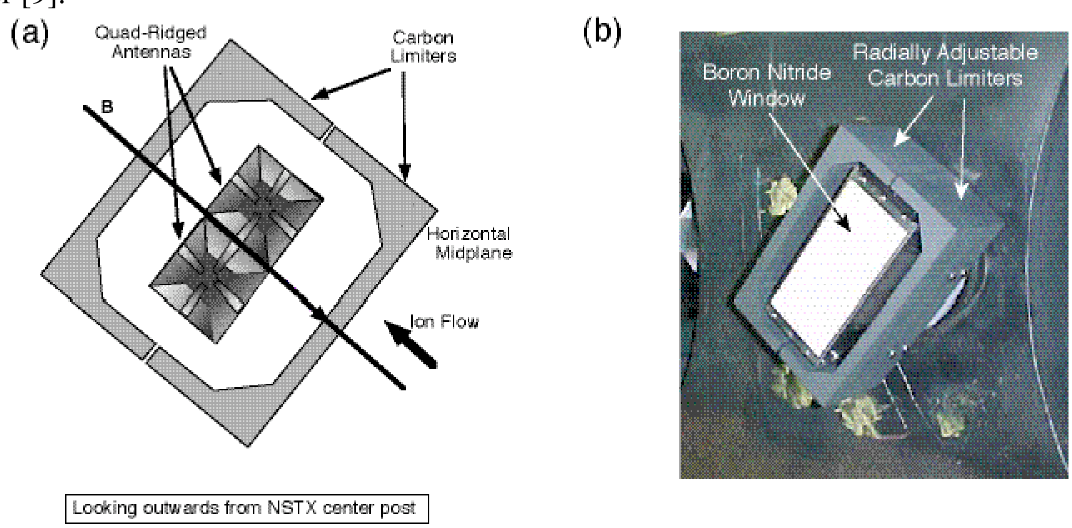


Figure 2. **(a)** Schematic diagram showing the layout of the X-mode EBW antenna installed on NSTX. Two carbon limiters surround a pair of quad-ridged antennas used for X-mode EBW radiometry and O-mode reflectometry. **(b)** Photograph of the antenna installed near the mid-plane of NSTX.

Recently, EBW MC experiments on NSTX, that use the HHFW antenna limiters to steepen L_n at the MC layer, have demonstrated 40-50% EBW MC [10]. The maximum MC efficiency was limited by the connection length between the antenna limiters which constrained the shortest achievable L_n at the MC layer to ~ 7 mm. An X-mode EBW antenna with a local limiter calculated to achieve L_n ~ 3 mm has been installed in NSTX (Fig. 2). An O-mode reflectometer integrated into the antenna will measure the local L_n at the MC layer. This antenna is predicted to achieve better than 80% EBW MC.

EBW HEATING AND CURRENT DRIVE

While the EBW MC studies on CDX-U and NSTX were motivated by the need to develop a fast electron temperature profile diagnostic for high β, overdense plasmas, they also validate the MC physics for EBWH and EBWCD [5]. EBWH and EBWCD can help optimize the magnetic equilibrium and suppress deleterious MHD in ST plasmas that might otherwise prevent access to high β operation [11]. Deposition at r/a > 0.8 may be required for MHD suppression in NSTX. Placing the EBW launcher well above or below the mid-plane on the low field side may have several benefits; large uni-directional $n_{//}$ shifts, needed for efficient CD, can result even with an $n_{//}$ ~ 0 launch [12], trapped particle effects that significantly reduce the EBWCD efficiency near the mid-plane can be minimized, and the launcher can be located where there is generally less competition for vacuum vessel access.

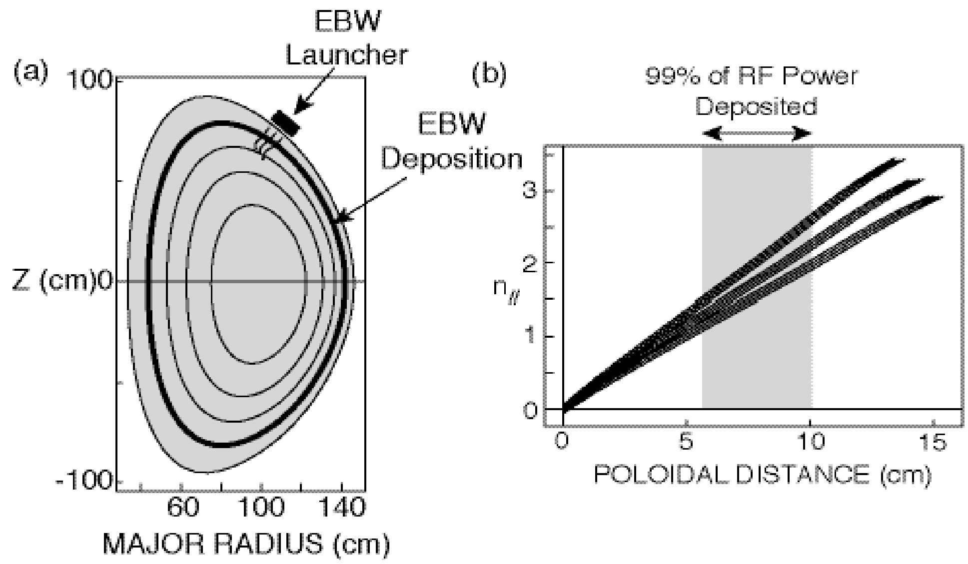


Figure 3. (a) GENRAY ray tracing calculation for 15 GHz EBWs launched from a location at a poloidal angle 85 degrees above the mid-plane of NSTX for a β = 30% plasma equilibrium. 12 rays are launched with $n_{//}$ from - 0.1 to + 0.1. EBW rays are projected on to a poloidal cross-section. **(b)** Plot of $n_{//}$ versus poloidal projected distance along the ray show a significant shift in $n_{//}$ within 5-10 cm of the plasma edge.

Figure 3(a) shows a GENRAY [7] calculation for a bundle of 15 GHz EBW rays launched from 85 degrees above the mid-plane with a range of $n_{//}$ between – 0.1 and + 0.1. Figure 3(b) shows the significant $n_{//}$ upshift that occurs during the first 5-10 cm the rays travel into the plasma. 99% of the EBW power is deposited at the Doppler-shifted second harmonic resonance within 6-10 cm from the plasma edge, shown by the thickened flux surface line in Fig. 3(a) and the grey shaded region in Fig. 3(b).

Modeling of the EBWCD was performed with the CQL3D bounce-averaged Fokker-Planck code [13] for the case shown in Fig. 3. CQL3D results for 1 MW of launched EBW power are shown in Fig. 4. The EBW power is locally deposited near r/a = 0.8 (Fig. 4(a)) and the resulting CD profile is shown in Fig. 4(b). The CD efficiency for this case is 0.06 A/W, assuming 100% MC between the injected RF power and the EBW. Since T_e = 0.6 keV and $n_e = 1.6\text{x}10^{19}\text{m}^{-3}$ at the CD location which has a major radius of 1 m, this corresponds to a dimensionless current drive efficiency, $\zeta_{ec} = 0.53$ [14]. This is about three times the value of ζ_{ec} obtained with the same plasma with CD at r/a = 0.8 near the mid-plane, is similar to the value obtained for EBWCD near the magnetic axis [15] and is about 2-3 times the ζ_{ec} for ECCD in DIII-D [16].

The EBW deposition profile and CD efficiency can be modified by changes in the density and temperature profile, a sensitivity study is being conducted to investigate this and an EBW launcher design is being developed that will allow control of $n_{//}$ and the polarization of the electromagnetic launch wave for optimum coupling to the EBW. A single steerable mirror launcher combined with a rotatable reflective grating polarizer is being considered, since it provides the greatest flexibility for optimizing EBW coupling and control of the EBW power deposition. The launch frequency that provides the widest radial access to NSTX, which typically operates at 0.35 to 0.45 T, is about 15 GHz. Presently, no high power RF sources with pulse durations of about 1 s exist at this frequency. MIT has proposed the development of an 800 kW 15 GHz gyrotron tube, a 3 MW EBW system using this tube is being considered for NSTX to assist non-inductive plasma startup, current ramp up, and to provide local electron heating and CD in high β NSTX plasmas.

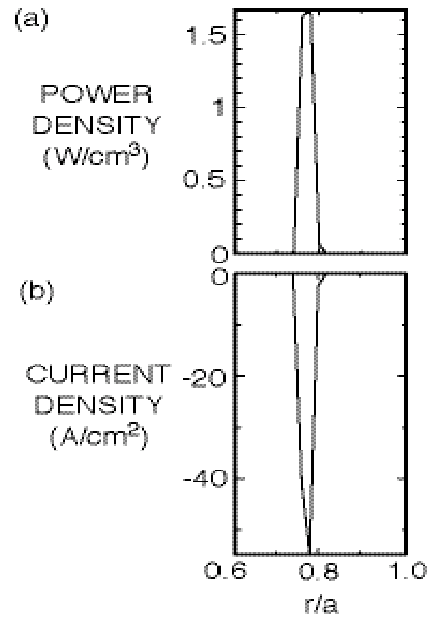


Figure 4. (a) The EBW power deposition profile and **(b)** EBWCD current density profile for the case in Fig.3 for 1 MW of RF power.

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REFERENCES

[1] Menard, J., *et al.*, *Phys. Plasmas,* **6**, 2002-8 (1999).
[2] Ono, M., *et al.*, Proc. 17th IAEA Fus. Energy Conf. (IAEA, Vienna, 1999), **3**, p. 1135.
[3] Preinhaelter, J., and Kopécky, V., *J. Plasma Phys.* **10**, 1-12 (1973).
[4] Ram, A.K., and Schultz, S.D., *Phys. Plasmas* **7**, 4084-4094 (2000).
[5] Ram, A.K., Bers, A., and Lashmore-Davies, C.N., *Phys. Plasmas* **9**, 409-418 (2002).
[6] Jones, B., *et al.*, *Phys. Rev. Lett.*, **90**, 165001 (2003).
[7] Smirnov, A.P., and Harvey, R.W., Bull. Am. Phys. Soc. **40**, 1837 (1995).
[8] Jones, B., PhD. Thesis, Princeton University (2002).
[9] Taylor, G., *et al.*, *Phys. Plasmas,* **9**, 167-170 (2002).
[10] Taylor, G., *et al.*, *Phys. Plasmas,* **10**, 1395-1401 (2003).
[11] Efthimion, P.C., *et al.*, "Applications of Electron Bernstein Wave Heating and Curent Drive in High β Plasmas", Paper IAEA-CN-94/EX/P2-12, 19th IAEA Fus. Energy Conf., Lyon, France, October 2002.
[12] Forest, C.B., *et al.*, *Phys. Plasmas*, **7**, 1352-1355 (2000).
[13] Harvey, R.W., and McCoy, M.G., *Proc. IAEA. Com. on Advances in Simulation and Modeling of Thermonuclear Plasmas*, Montreal, Quebec (IAEA, Vienna, 1993) p. 489.
[14] Luce, T.C., *et al.*, *Phys. Rev. Lett.*, **83**, 4550-4553 (1999).
[15] Taylor, G., *et al.*, "Mode-Converted Electron Bernstein Wave Emission Research on CDX-U and NSTX", *Proc. 12th Joint Workshop on ECE and ECRH*, edited by G. Giruzzi, World Scientific, Singapore, 2003, pp. 151-160.
[16] Petty, C.C., *et al.*, "Electron Cyclotron Wave Experiments on DIII-D", *Proc. 14th Topical Conference on Radio Frequency Power in Plasmas*, edited by T.K. Mau and J. deGrassie, AIP Conf. Proc. 595, Melville, New York, 2001, pp. 275-281.

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