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HEATING AND CURRENT DRIVE BY ELECTRON BERNSTEIN WAVES IN NSTX AND MAST-TYPE PLASMAS

A. K. Ram and S. D. Schultz
Plasma Science & Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA

C. N. Lashmore-Davies
Euratom – UKAEA Fusion Association
Culham Science Centre
Abingdon, Oxon OX14 3DB U.K.

R. A. Cairns
University of St. Andrews
St. Andrews, Fife KY16 9SS U.K.

P. C. Efthimion and G. Taylor
Princeton Plasma Physics Laboratory
Princeton, New Jersey 08543 USA

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Heating and Current Drive by Electron Bernstein Waves in NSTX and MAST-Type Plasmas

A. K. Ram, A. Bers, S. D. Schultz
Plasma Science & Fusion Center, M.I.T., Cambridge, MA, 02139, U.S.A.

C. N. Lashmore-Davies
Euratom – UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom

R. A. Cairns
University of St. Andrews, St. Andrews, Fife, KY16 9SS United Kingdom

P. C. Efthimion, G. Taylor
Princeton Plasma Physics Laboratory, Princeton, NJ, 08543, U.S.A.

E-mail contact of main author: abhay@psfc.mit.edu

Abstract. The high β operating regime of spherical tokamaks (ST), such as in NSTX and MAST, make them attractive fusion devices. To attain the high β's, there is a need to heat and to drive currents in ST plasmas. While ST plasmas are overdense to conventional electron cyclotron (EC) waves, electron Bernstein waves (EBW) offer an attractive possibility both for heating and for driving plasma currents. We consider techniques for the excitation of EBWs on NSTX and MAST-type plasmas. Emission of EBWs from inside the plasma and its conversion to the conventional EC modes at the plasma edge are also considered.

1. Introduction

In STs like NSTX and MAST, $f_{pe}/f_{ce} >> 1$ over most of the plasma cross section (f_{pe} and f_{ce} are the electron plasma and cyclotron frequencies, respectively). Consequently, in the frequency regime for which the ordinary O-mode and the extraordinary X-mode damping is appreciable inside a plasma, these modes are cutoff at the plasma edge. However, EBWs, which have no density limits, can propagate into the plasma core for frequencies above f_{ce}, and damp effectively on electrons near the Doppler-shifted electron cyclotron resonance or its harmonics [1]. The localized, strong absorption of EBWs also makes their emission from the electron cyclotron resonance, or its harmonics, a possible means for diagnosing the electron temperature profile [2]. Since EBWs are not vacuum modes, the coupling of power to EBWs is indirectly through mode conversion of the slow X-mode (SX) to an EBW at the upper hybrid resonance (UHR). The coupling to the SX-mode is either through the fast X-mode or the O-mode, which can be directly excited from outside the plasma. The former is referred to as the X-B mode conversion process and the latter as the O-X-B mode conversion process. Results from theoretical and computational studies on mode conversion coupling to EBWs, and the emission of X- and O-modes via EBWs, are summarized below.

2. Theoretical Modelling of Mode Conversion

From an analytical treatment of wave propagation in an inhomogeneous, cold plasma [1], we find that the mode conversion efficiency is dependent on an effective tunneling parameter η given by:

$$\eta \approx \frac{\omega_{ce} L_n}{c\alpha} \left[\sqrt{1+\alpha^2} - 1\right]^{1/2} \tag{1}$$

where all the quantities on the right-hand side are evaluated at the location of the UHR, $\omega_{ce} = 2\pi f_{ce}$, L_n is the density scalelength, $\alpha = f_{pe}/f_{ce}$, and c is the speed of light. For $\alpha \sim 1$:

$$\eta \approx \frac{1}{2}\left[\frac{\omega_{ce} L_n}{c}\right] \approx 293.5 \left| B L_n \right|_{UHR} \tag{2}$$

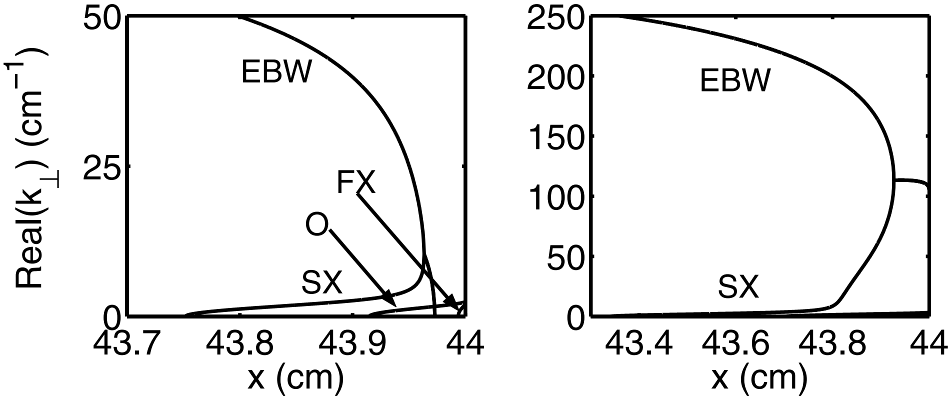
where B is the local magnetic field in Tesla and L_n is in meters.

For maximum X-B mode conversion, the X-mode should be propagating essentially across the magnetic field (i.e., $n_\parallel \ll 1$ where $n_\parallel$ is the wave index parallel to the magnetic field). Then, for a given plasma configuration, the maximum power mode conversion efficiency (at $n_\parallel \approx 0$) is:

$$C_{\max} = 4e^{-\pi\eta}(1 - e^{-\pi\eta}) \tag{3}$$

For $C_{\max} \gtrsim 0.5$, we require that $0.05 \lesssim \eta \lesssim 0.6$; for $\eta \approx 0.22$, $C_{\max} = 1$ giving complete mode conversion.

The O-X-B mode conversion is most efficient when the O-mode cutoff coincides with SX-mode cutoff. This occurs at a critical $n_\parallel$ [3]: $(n_\parallel)_{\text{crit}} = 1/\sqrt{1+\alpha}$. However, in addition, one requires $\eta > 1$ in order to avoid coupling appreciable power to the outgoing fast X-mode [4]. From these conditions, we find that the X-B and the O-X-B mode conversion processes optimize in different regions of frequency and $n_\parallel$ space.



(a) (b)

Figure 1: *(a)* $f_{UHR} < 2f_{ce}$, *(b)* $f_{UHR} > 2f_{ce}$.

For NSTX-type plasmas the wave frequency has to be such that the UHR frequency $f_{UHR} \approx 2f_{ce}$ for optimum X-B mode conversion. For optimum O-X-B mode conversion $f_{UHR} \approx 4f_{ce}$. The dispersion characteristics of the EBW change significantly as the f_{UHR} is changed from below $2f_{ce}$ to above. This is illustrated in Figures 1(a) and 1(b) for NSTX-type parameters [1] where the fully kinetic dispersion characteristics of the various electron cyclotron modes are plotted as a function of the radial distance along the equatorial plane; $x = 44$ cm is the outside edge of the plasma ($x = 0$ is the magnetic axis). The UHR is located at $x \approx 43.96$ cm in the first case and at $x \approx 43.82$ cm in the second case. In the second case, the SX mode propagates through the UHR and then near the edge of the plasma it turns into an EBW with a much shorter wavelength than in the first case.

The results of Eq. (2) can also be used to determine the required density scalelengths for optimum mode conversion for a fixed frequency. Such would be the case, for instance, for MAST where sources and couplers at 60 GHz are already installed on the machine. For MAST-type parameters with an edge magnetic field of $0.37\,T$ and an edge density of $4 \times 10^{19}\,\mathrm{m}^{-3}$, complete mode conversion (for $n_{\|} = 0$) is possible if $L_n \approx 1.7 \times 10^{-3}\,\mathrm{m}$ at the UHR. This corresponds to a density profile of the form $(1 - r^2/a^2)^{0.25}$. For optimizing the O-X-B mode conversion, a scale length of $L_n \approx 6 \times 10^{-2}\,\mathrm{m}$ and a critical $(n_{\|})_{\mathrm{crit}} \approx 0.4$ are required. These conditions also ensure that $\eta > 1$.

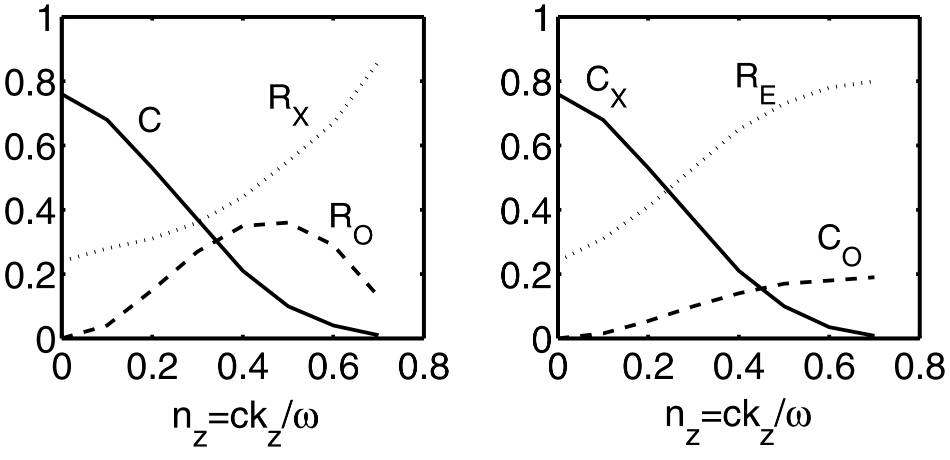
3. Mode Conversion and Emission

We have developed a numerical code that solves for mode conversion in an inhomogeneous slab plasma with a sheared magnetic field [1]. The code uses an approximate kinetic (Maxwellian) plasma model in which the EBW can be clearly identified. This is a sixth order ordinary differential equation and the mode conversion coefficient is determined from the actual power flowing in EBW. This code can also be used to determine the emission of EBWs from the electron cyclotron resonance. The emitted EBWs would mode convert to the X-mode and/or O-mode radiation at the UHR and be detected in the vacuum region of a plasma device.

Figures 2(a) and 2(b) show the results obtained from this numerical code for the cases of mode conversion heating and emission, respectively, for NSTX-type parameters [1] for a frequency of 14 GHz. In Fig. 2(a) we assume that the power is coupled into the plasma through the X-mode. Then C is the fraction of this power that appears in EBW, and R_X and R_O are the fractional powers being reflected back out on the X and O modes, respectively. These fractional powers are plotted as a function of the normalized toroidal mode numbers. (The poloidal mode number is set to zero.) In Fig. 2(b) we assume that the EBW is emitted inside the plasma and propagates out towards the edge. Near the UHR the EBW can couple to the X- and O-modes and can also be reflected. C_X and C_O are the fractions of the input EBW power that are mode converted to X and O modes, respectively. R_E is the fraction of the input power that is reflected back into the plasma along the EBW.

4. RF Current Drive With Bootstrap Current

Steady state operations of tokamaks will require non-inductive current generation. RF current drive in combination with the bootstrap current may achieve this goal; RF driven current also offers a means to control the current profile. We have initiated a study on the self-consistent interaction of RF current drive with bootstrap current in a toroidal plasma. The RF quasilinear diffusion coefficient is included in the relativistic



(a) (b)

Figure 2: *(a) X-B mode conversion heating, (b) emission from EBW*

neoclassical drift-kinetic equation for plasma transport. The formulation is limited to the thin banana regime of electrons. A numerical code FASTFP-NC [5] in two-dimensional momentum space for solving the drift kinetic equation has been developed. We find that synergistic effects increase the total current beyond the linear combination of RF generated current and bootstrap current. Bootstrap current in the presence of lower hybrid current drive or electron cyclotron current drive has been calculated numerically and with analytical approximations. The scaling of the synergistic effects with plasma parameters and with the bootstrap current are obtained from the analytical formulation and are in reasonable agreement with the numerical results. The effect of EBW current drive on bootstrap current will be incorporated in the near future.

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6. References

[1] A. K. Ram and S. D. Schultz, to appear in Phys. Plasmas (October 2000); A. Bers, A. K. Ram, and S. D. Schultz, in Proc. 2nd Europhysics Topical Conf. on RF Heating and Current Drive of Fusion Devices (EPS, Petit-Lancy, 1998), Vol. 22A, pp. 237–240.
[2] G. Taylor et al., Princeton Plasma Physics Laboratory Report PPPL-3476 (July 2000); to appear in Rev. Sci. Instr. (2000).
[3] J. Preinhaelter and V. Kopecky, J. Plas. Phys. **10**, 1 (1973).
[4] S. D. Schultz, A. K. Ram, and A. Bers, paper IAEA-F1-CN-69/CDP/13, in Proc. 17th IAEA Fusion Energy Conference (1998).
[5] S. D. Schultz, Ph.D. thesis, Department of Physics, M.I.T., Cambridge, MA 02139 USA. (1999).