

Electron Cyclotron Heating and Current Drive Approach for Low-Temperature Startup Plasmas Using O-X-EBW Mode Conversion

D. B. Batchelor and T. S. Bigelow

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-8071

Abstract. A mechanism for heating and driving currents in very overdense plasmas is considered based on a double-mode conversion: Ordinary mode to Extraordinary mode to electron Bernstein wave. The possibility of using this mechanism for plasma buildup and current ramp in the National Spherical Torus Experiment is investigated.

RECEIVED

JUN 17 1997

OSTI

INTRODUCTION

To eliminate or minimize the inductive current drive (CD) system would be very attractive for advanced tokamaks. Particularly in spherical torus (ST), for which it is highly desirable to eliminate the Ohmic solenoid from the center stack, non-Ohmic techniques for plasma initiation, buildup, and current ramp are needed. However, the modest density and low electron temperature obtained in non-inductive plasma initiation provide small optical depth for most wave heating and CD techniques. This problem is particularly exacerbated in ST because of the weak magnetic field in which even startup plasmas tend to be highly overdense, $\omega_{pe} \gg \Omega_e$. An approach to heating overdense plasmas was proposed by Preinhaelter and Kopecky (1) in which an Ordinary mode (O-mode) wave is totally converted to an Extraordinary mode (X-mode) at the $\omega = \omega_{pe}$ layer. The analysis was generalized by Weitzner and Batchelor (2) to an arbitrary angle of incidence and to account for gradient in magnetic field. The theory was generalized by Mjølhus (3) to allow for the magnetic field to be at an angle with respect to the direction of stratification. The converted X-mode wave is reflected from a linear ray turning point at nonzero k_{\perp} and returns to the upper hybrid resonance where it is converted to an electron Bernstein wave (EBW) (3). This process has been experimentally demonstrated on W7-AS (4). An analysis will be presented for the National Spherical Torus Experiment (NSTX).

RESONANCE AND CUTOFF STRUCTURE IN 1D

In tokamaks an indication of wave behavior can be gained by assuming perpendicular plasma stratification (i.e., $n_e = n_e(x)$, $B = B(x)$, $k_x = k_x(x)$, $k_z = \text{const.}$). Then the cold plasma dispersion relation yields three cutoffs and one resonance: (1) $\omega_{pe}^2 = \omega^2$ plasma cutoff - O-mode branch; (2) $\omega_{pe}^2 / \omega^2 = (1 - \Omega_e / \omega)(1 - n_z^2)$ right-hand X-mode; and (3) $\omega_{pe}^2 / \omega^2 = (1 + \Omega_e / \omega)(1 - n_z^2)$, which can lie on the X-mode or O-mode branch depending on plasma parameters. For the specific n_z given by

$$n_z^2 = n_{z \text{ crit}}^2 = \frac{\Omega_e / \omega}{1 + \Omega_e / \omega} \quad (1)$$

Cutoff (3) coincides with the O-mode cutoff $\omega_{pe}^2 = \omega^2$, and complete conversion of O-mode incident from the low-density side to X-mode occurs. The converted

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

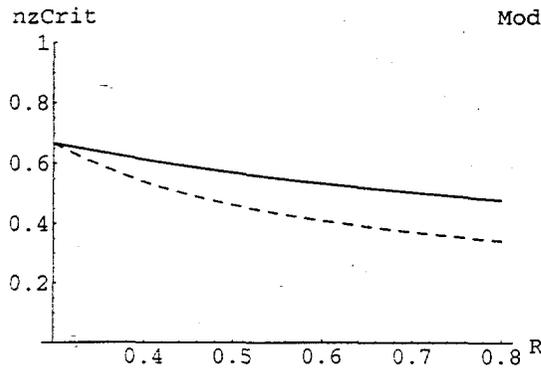


FIGURE 2. Variation of $n_{z \text{ incident}}$ (dashed line) and $n_{z \text{ crit}}$ (solid line) with radial location of cutoff layer.

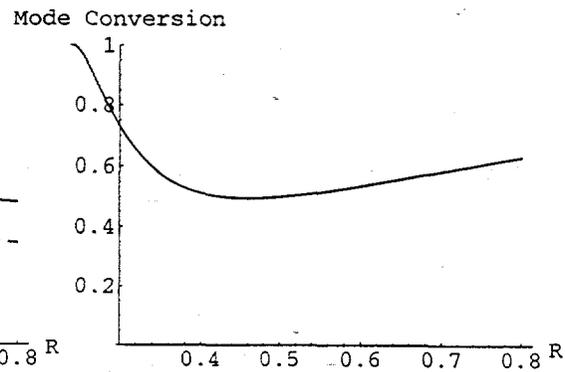


FIGURE 3. Variation of O-X mode conversion coefficient with location of plasma center.

DISCUSSION

This looks promising as a plasma startup and current ramp approach for NSTX. A similar calculation was done for a conventional tokamak, similar to DIII-D, with a highly overdense profile: $R_{\text{maj}} = 167$ cm; minor radius $r_{\text{min}} = 68$ cm; and magnetic field on axis of $B_0 = 1.9$ T, $n_{e0} = 3 \times 10^{20}$, $f = 110$ GHz. Again, if the beam is perfectly aimed at the initial conversion point, a wide range of cutoff positions is possible with high conversion efficiency. Additional confidence in this technique exists because the technique has been demonstrated experimentally, first on Heliotron DR (6) and recently on W7-AS (4).

Clearly, this investigation is preliminary. Work is in progress to investigate the 3-D effects associated with finite beam divergence, plasma shape, and wave refraction. It is also of interest to calculate the propagation of the converted EBW and to determine the CD. It will also be important to estimate the effects of density fluctuations, which were found to be important in the studies on W7-AS.

ACKNOWLEDGMENTS

This work is sponsored by Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

REFERENCES

- (1) Preinhaelter and V. Kopecky, *J. Plasma Phys.* **10** (1973)1.
- (2) Weitzner, H., and D. B. Batchelor, *Phys. Fluids* **22** (1979), 1355.
Batchelor, D. B., et al., *IEEE Transactions on Plasma Science*, **PS-8**, (1980), 78.
- (3) Mjølhus, E., *J. Plasma Phys.*, **31**, (1984), 7.
- (4) Laqua, H. P., et al., *Phys. Rev. Letters* (accepted for publication).
- (5) Forrest, C. B., et al., *Phys. Plasmas*, **1** (1994), 1568.
- (6) Morimoto, S., et al., *Nucl. Fus.* **29** (1989), 1697.

Here $k_0 = \omega/c$ is the free space wave number, and L_n, L_B are the density and magnetic field gradient scale lengths, respectively. Note that this expression is somewhat different from that given by Mjølhus (3) because it includes the gradient in B . If ∇n_e and ∇B both have the same sign (e.g., both profiles are radially decreasing), then the tunneling length is shorter and conversion is higher than if only ∇n_e is included.

APPLICATION TO NSTX

NSTX is an ultralow aspect ratio tokamak under construction at the Princeton Plasma Physics Laboratory, having major radius $R_{maj} = 80$ cm, minor radius $r_{min} = 64$ cm, and magnetic field on axis of $B_0 = 0.3$ T. Use of two gyrotrons with a total power of 400 kW at 28 GHz is being proposed. At this frequency the fundamental electron cyclotron resonance appears on the inside plasma edge at $R = 24$ cm. For the proposed mechanism to operate an overdense plasma is required, $n_e = 9.7 \times 10^{18}$ at $f = 28$ GHz. Many tokamaks have used electron cyclotron heating (ECH) in a pure toroidal field to breakdown and produce plasma exceeding the critical density. In both CDX-U and DIII-D, ECH was used to produce overdense plasmas and self-generated (5) plasma current. On DIII-D the pressure-driven plasma current ($I_p > 22$ kA) was sufficient to form closed flux surfaces. We assume the capability to produce such a target plasma in NSTX.

Assuming the existence of a small volume of overdense plasma with cutoff not far outside the fundamental cyclotron layer, the critical n_z given by Eq. (1) will be $n_z \sim 1/\sqrt{2}$. This is easy for beam aiming and is a favorable angle for CD. The main issue is the variation of the conversion efficiency as the plasma is built up and moved toward the magnetic axis so that the angle of incidence of the launched O-mode wave is no longer precisely at the critical value. If the ECH beam is stationary, the angle of incidence deviates from the optimum as the plasma moves out. Figure 2 shows the variation of $n_{z,incident}(R)$ neglecting ray refraction (dashed line) and $n_{z,crit}(R)$ (solid line) as the location of the plasma cutoff moves out in major radius. We see that although the angle of incidence drops because of geometrical effects, $n_{z,crit}(R)$ is also decreasing because of the dependence on $|B|$. Once the cutoff layer passes about 0.6 m, there is little additional mismatch in n_z .

As shown in Eq. (3), the conversion efficiency depends on the density and magnetic field profile scale lengths as well as the magnetic field strength and n_z mismatch. For concreteness we assume a $1/R$ dependence of B and a simple parabolic n_e profile centered at $R = R_p$ with width w extending to the inside wall, $w = R_p - (R_{maj} - r_{min})$. For a startup scenario, we assume initial plasma with $n_0 = 2 \times n_{cutoff} = 2 \times 10^{19}$ centered at $R_p = R_{res}$ with width $w = R_p - R_{inner}$. This then moves out with constant peak density until $R_p = R_{maj}$ and $w = R_{min}$. The O-mode cutoff then is at the half maximum point, so $r_{cutoff} = w/\sqrt{2}$, and $L_n = -w/2\sqrt{2}$. We also assume the beam to be perfectly aimed at initial configuration: $n_z = n_{z,crit0}$, $n_z = 0$. Figure 3 shows the variation of $|C|^2$ as R_p and w increase. We see that $|C|^2$ does indeed decrease from unity but does not go below about 50%. As R_p increases beyond 0.45 m, $|C|^2$ actually begins to increase again because n_z , $n_{z,crit}$ and Ω_e/ω are decreasing although L_n, L_B and the n_z mismatch are increasing.

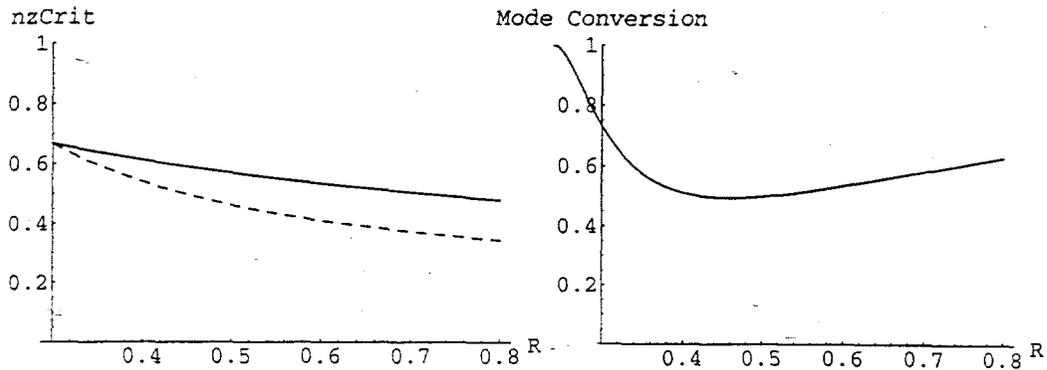


FIGURE 2. Variation of $n_{z \text{ incident}}$ (dashed line) and $n_{z \text{ crit}}$ (solid line) with radial location of cutoff layer.

FIGURE 3. Variation of O-X mode conversion coefficient with location of plasma center.

DISCUSSION

This looks promising as a plasma startup and current ramp approach for NSTX. A similar calculation was done for a conventional tokamak, similar to DIII-D, with a highly overdense profile: $R_{\text{maj}} = 167$ cm; minor radius $r_{\text{min}} = 68$ cm; and magnetic field on axis of $B_0 = 1.9$ T, $n_{e0} = 3 \times 10^{20}$, $f = 110$ GHz. Again, if the beam is perfectly aimed at the initial conversion point, a wide range of cutoff positions is possible with high conversion efficiency. Additional confidence in this technique exists because the technique has been demonstrated experimentally, first on Heliotron DR (6) and recently on W7-AS (4).

Clearly, this investigation is preliminary. Work is in progress to investigate the 3-D effects associated with finite beam divergence, plasma shape, and wave refraction. It is also of interest to calculate the propagation of the converted EBW and to determine the CD. It will also be important to estimate the effects of density fluctuations, which were found to be important in the studies on W7-AS.

ACKNOWLEDGMENTS

This work is sponsored by Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

REFERENCES

- (1) Preinhaelter and V. Kopecky, *J. Plasma Phys.* **10** (1973)1.
- (2) Weitzner, H., and D. B. Batchelor, *Phys. Fluids* **22** (1979), 1355.
Batchelor, D. B., et al., *IEEE Transactions on Plasma Science*, **PS-8**, (1980), 78.
- (3) Mjølhus, E., *J. Plasma Phys.*, **31**, (1984), 7.
- (4) Laqua, H. P., et al., *Phys. Rev. Letters* (accepted for publication).
- (5) Forrest, C. B., et al., *Phys. Plasmas*, **1** (1994), 1568.
- (6) Morimoto, S., et al., *Nucl. Fus.* **29** (1989), 1697.