EBW H&CD Potential for Spherical Tokamaks

J. Urban, J. Decker, Y. Peysson, J. Preinhaelter, V. Shevchenko et al.

Citation: AIP Conf. Proc. **1406**, 477 (2011); doi: 10.1063/1.3665018
View online: http://dx.doi.org/10.1063/1.3665018
View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1406&Issue=1
Published by the American Institute of Physics.

EBW H&CD Potential for Spherical Tokamaks

J. Urban,[a] J. Decker,[b] Y. Peysson,[b] J. Preinhaelter,[a] V. Shevchenko,[c] G. Taylor,[d] L. Vahala,[e] G. Vahala[f]

[a] EURATOM/IPP.CR Association, 182 00 Prague, Czech Republic
[b] EURATOM-CEA, Cadarache, France
[c] EURATOM/CCFE Fusion Association, Abingdon, OX14 3DB, UK
[d] Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA
[e] Old Dominion University, Norfolk, VA 23529, USA
[f] College of William & Mary, Williamsburg, VA 23185, USA

Abstract. Spherical tokamaks (STs), which feature relatively high neutron flux and good economy, operate generally in high-ß regimes, in which the usual EC O- and X- modes are cut-off. In this case, electron Bernstein waves (EBWs) seem to be the only option that can provide features similar to the EC waves—controllable localized heating and current drive (H&CD) that can be utilized for core plasma heating as well as for accurate plasma stabilization. We first derive an analytical expression for Gaussian beam OXB conversion efficiency. Then, an extensive numerical study of EBW H&CD performance in four typical ST plasmas (NSTX L- and H-mode, MAST Upgrade, NHTX) is performed. Coupled ray-tracing (AMR) and Fokker-Planck (LUKE) codes are employed to simulate EBWs of varying frequencies and launch conditions. Our results indicate that an efficient and universal EBW H&CD system is indeed viable. In particular, power can be deposited and current reasonably efficiently driven across the whole plasma radius. Such a system could be controlled by a suitably chosen launching antenna vertical position and would also be sufficiently robust.

Keywords: Fusion, tokamak, heating, current drive, electron Bernstein wave, EBW.
PACS: 52.35.Hr, 52.50.Sw, 52.55.Fa.

INTRODUCTION

Spherical tokamaks (STs) feature relatively high neutron flux and good economy at the same time. For these reasons, ST is a candidate for component test facility [1, 2] and appears in fusion-fission concepts [3]. ST's typical low magnetic field has a major impact on the propagation of electron cyclotron (EC) waves in the plasma. This frequency range is of crucial importance for auxiliary H&CD systems in present and future tokamaks. Typically, in STs, the electron plasma frequency $\omega_{\mathrm{pe}}^2 \equiv n_{\mathrm{e}} e^2 / (m_{\mathrm{e}} \varepsilon_0)$ is much greater than the electron cyclotron frequency $\omega_{\mathrm{ce}} \equiv eB / m_{\mathrm{e}}$. In this so called overdense regime, the O- and X-mode EC waves are cut-off and cannot propagate inside the overdense plasma. However, the electron Bernstein wave (EBW) [4]—a quasi-electrostatic kinetic EC mode—can propagate and be strongly absorbed in the overdense plasma.

EC waves are extremely useful because they can be launched far from the plasma and feature highly localized and controllable H&CD capabilities. The application of the overdense mode—the EBW—is, however, complicated by its electrostatic nature. First, EBWs must be excited by appropriately launched O- or X-mode via the so called OXB or XB mode conversion schemes. The excited EBW can subsequently propagate inside the overdense plasma; however, because of its dispersion characteristics, the propagation strongly depends on plasma parameters and the wave vector can change considerably in various ways.

In this paper, we pursue an overall study of EBW H&CD on spherical tokamaks by means of numerical ray-tracing and Fokker-Planck simulations. Two coupled codes—AMR

Radio Frequency Power in Plasmas
AIP Conf. Proc. 1406, 477-480 (2011); doi: 10.1063/1.3665018

(Antenna, Mode-conversion, Ray-tracing) [5] and LUKE [6]—are employed. A large number of cases with different injection parameters is simulated in four different ST conditions: two experimental discharges of the NSTX tokamak [7], an ST-CTF-like MAST-Upgrade H-mode scenario [8] and an NHTX scenario [7].

GAUSSIAN BEAM O-X-B CONVERSION

We derive here an analytic formula for the so called O-X-B (O-mode to X-mode to EBW) mode conversion, which is the most promising candidate for EBW H&CD applications. The *E*-field of a Gaussian beam in Fourier space is

$$E \propto \exp\left(-\frac{w_0^2}{4}\left(k_x^2+k_y^2\right)\right) \tag{1}$$

where w_0 is the beam waist radius and the beam propagates in the z-direction. Using Parseval's theorem, the beam conversion efficiency can be calculated as

$$\frac{P_{\mathrm{OX}}}{P_0}=\frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^2 C_{\mathrm{OX}}\mathrm{d}k_x\mathrm{d}k_y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^2 \mathrm{d}k_x\mathrm{d}k_y}. \tag{2}$$

For C_{OX} we now use the analytical mode conversion efficiency of a plane wave, derived by Preinhaelter [9] and Mjølhus [10], and assume a uniform magnetic field in the mode conversion region. Maximum conversion can be achieved when the central beam wave vector is incident at optimum angle, which implies

$$\mathbf{B}/B=\left(0,\pm\sqrt{1-N_{\|,\mathrm{opt}}^2},N_{\|,\mathrm{opt}}\right),\quad N_{\|\mathrm{opt}}^2=\left(1+\omega/\omega_{\mathrm{ce}}\right)^{-1}. \tag{3}$$

Under these conditions and after some algebra, the optimum beam conversion efficiency is

$$\frac{P_{\mathrm{OX}}}{P_0}=\left(1+3\frac{\kappa}{z_{\mathrm{R}}}+2\frac{\kappa^2}{z_{\mathrm{R}}^2}\right)^{-\frac{1}{2}},\quad \kappa\equiv\pi L_n\sqrt{\omega_{\mathrm{ce}}/2\omega}. \tag{4}$$

Here, $z_{\mathrm{R}}\equiv\pi w_0^2/\lambda_0$ is the Rayleigh range and L_n is the electron density scale length. In Fig. 1 and 2 we plot the optimum Gaussian beam conversion efficiency for typical parameters of NSTX, MAST-U and NHTX.

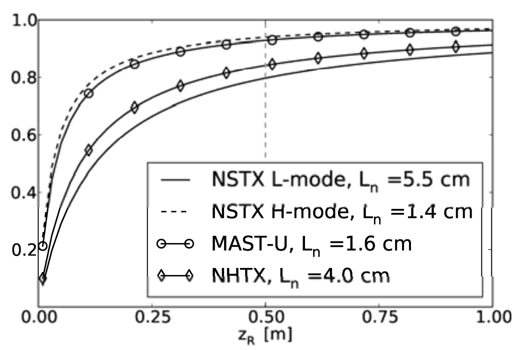

FIGURE 1. Gaussian beam maximum conversion efficiency (4) dependence on z_{R}. Average L_n in the mode conversion region is used. $\omega_{\mathrm{ce}}/\omega=0.5$.

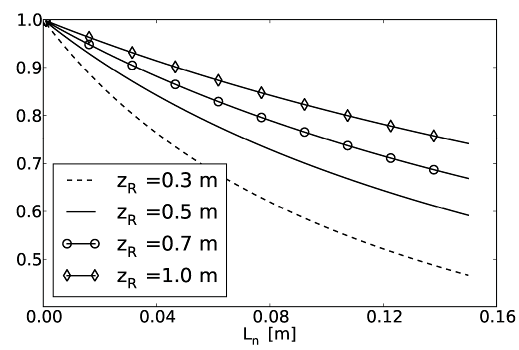

FIGURE 2. Gaussian beam maximum conversion efficiency (4) dependence on L_n, $\omega_{\mathrm{ce}}/\omega=0.5$.

EBW H&CD FOR SPHERICAL TOKAMAKS

We have performed ray-tracing and Fokker-Planck (AMR + LUKE) simulations for 4 different ST scenarios: NSTX L- and H-modes, MAST-U and NHTX. (For details see [11].) Shown here are results for NSTX L-mode (Fig. 3) and NHTX (Fig. 4). We show the normalized CD efficiency $\zeta \cong 3.27 I R_0 n_e / P T_e$ [12]; the absolute efficiency $\eta \equiv I / P$ can be easily calculated from the plotted η / ζ conversion factor. The classification of the current drive mechanism is performed automatically by calculating the average $N_{\|}$ of the rays and subsequently comparing the LUKE-calculated current direction to Ohkawa and Fisch-Boozer current directions. In certain cases, this leads to ambiguous results, either because the rays have mixed signs of $N_{\|}$ or they are absorbed at different harmonics.

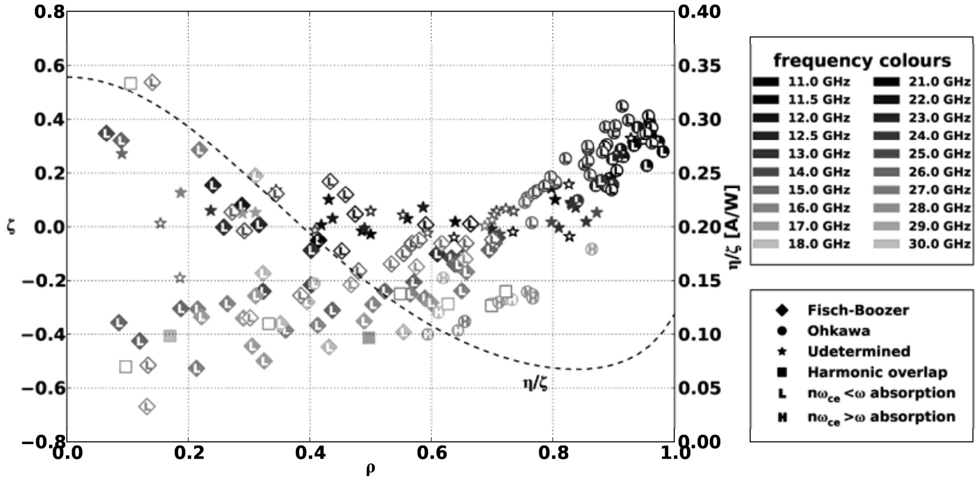

FIGURE 3. Current drive efficiency ζ (symbols) and η / ζ conversion factor (dashed line) versus ρ, NSTX L-mode first (full symbols) and second (open symbols) harmonics, all simulated frequencies and vertical launch positions, 1 MW incident power. B_0=0.5 T, I_p=0.6 MA, n_{e0}=2.6×10^{19} m^{-3}, T_{e0}=2.9 keV, Z_{eff}=2.

As can be seen, by changing the frequency and/or the vertical launch position, the power deposition location and the CD efficiency can be selected. In the NSTX L-mode case, $|\zeta|$ up to at least 0.4 can be reached across the whole plasma and the absolute efficiency is quite high due to low collisionality, particularly in the center. NHTX features a higher magnetic field, higher collisionality and a magnetic field bump, caused by strong edge currents. There properties make EBW CD less efficient and flexible. The magnetic field bump screens the plasma center—EBWs are often absorbed at the higher harmonic at the edge, driving mostly Ohkawa current. Generally, we find that in the central plasma regions EBWs drive a Fisch-Boozer current while Ohkawa current in edge regions. Higher harmonic absorption, i.e., absorption on the n^{th} harmonic with $n\omega_{ce} > \omega$, favors the Ohkawa mechanism.

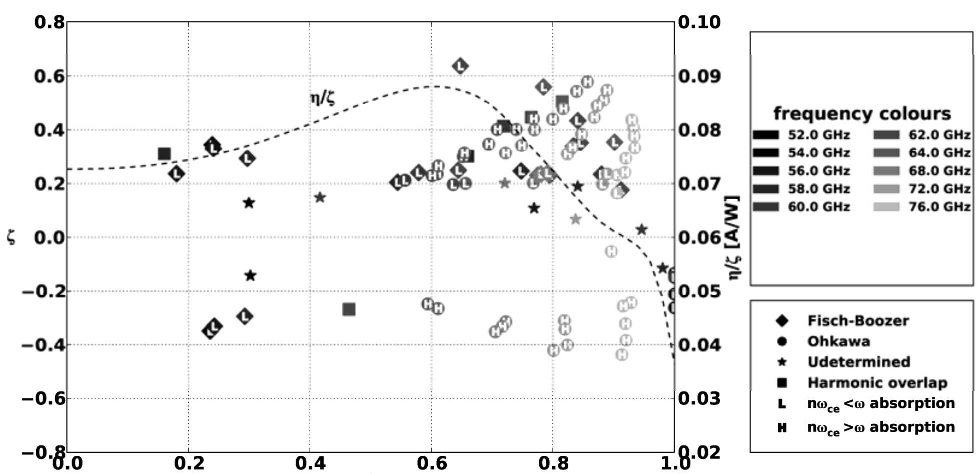

FIGURE 4. Same as Fig. 3 but for NHTX. B_0=2 T, I_p=3.5 MA, n_{e0}=2×10^{20} m^{-3}, T_{e0}=2.9 keV, Z_{eff}=2.

In [11] we show that NSTX H-mode is very similar to the L-mode except that the absolute CD efficiency is considerably lower because of higher n_e and lower T_e. MAST-U results are more like NHTX results—central plasma is blocked by a magnetic field bump and $|\zeta| \sim 0.3$ across the plasma. However, the 1st and the 2nd harmonics can be both used in MAST-U, which results in a better flexibility compared to NHTX. We also show that the CD efficiency does not generally depend on $N_{\parallel}$ at the absorption. Z_{eff} and quasilinear effects must be taken into account. We have also analyzed the robustness of EBW H&CD with respect to n_e, T_e and B-field changes. Overall, the intrinsic performance (CD efficiency ζ) is not very sensitive to n_e and T_e changes, while it is more sensitive to B-field changes.

CONCLUSIONS

We have shown the potential of EBWs as a H&CD system for STs. First, the O-X-B conversion efficiency of Gaussian beams is investigated, showing that the beam divergence, expressed via the Rayleigh range, is a crucial parameter, together with the electron density scale length.

On an extensive set of EBW launch scenarios with varying frequency, vertical antenna position and toroidal injection angle, we show that EBWs can be absorbed at almost arbitrary radius and that EBWs can drive current with efficiencies comparable to electron cyclotron O- or X-modes. Moreover, the efficiency does not change with radius, while typically the efficiency of X- and O-modes decreases with radius. Best results in terms of efficiency and flexibility are achieved in NSTX plasmas, where the electron cyclotron frequency radial profiles are monotonic.

ACKNOWLEDGMENTS

This work was supported by the grant no. 202/08/0419 of Czech Science Foundation, AS CR #AV0Z20430508, MSMT #7G10072, Euratom under EFDA, and US DoE.

REFERENCES

[1] Y. K. M. Peng *et al.*, Plasma Phys. Control. Fusion **47**, B263 (2005).
[2] G. M. Voss *et al.*, Fusion Eng. Des. **83**, 1648 (2008).
[3] M. Kotschenreuther *et al.*, Nucl. Fusion **50** (2010).
[4] I. B. Bernstein, Phys. Rev. **109**, 10 (1958).
[5] J. Preinhaelter *et al.*, Plasma Phys. Control. Fusion **51**, 125008 (2009).
[6] J. Decker, and Y. Peysson, (EURATOM-CEA, Cadarache, 2004).
[7] D. A. Gates *et al.*, Nucl. Fusion **49**, 104016 (2009).
[8] D. Stork *et al.*, in 23rd IAEA Fusion Energy Conference (IAEA, Daejon, Korea, 2010), pp. ICC/P5.
[9] J. Preinhaelter, Czech J Phys **25**, 39 (1975).
[10] E. Mjølhus, J. Plasma Phys. **31**, 7 (1984).
[11] J. Urban *et al.*, ArXiv e-prints, 1103.4484 (2011).
[12] C. C. Petty *et al.*, Nucl. Fusion **42**, 1366 (2002).