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Current Drive and Plasma Heating by Electron Bernstein Waves in MAST

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Abstract. Electron Bernstein waves (EBW) have the potential to provide highly localized heating and current drive (CD). EBWs are predominantly electrostatic and they damp on electrons near electron cyclotron harmonics without momentum injection into the plasma. These features represent a powerful tool for understanding transport and stability phenomena by locally perturbing the plasma and providing complementary CD methods in addition to neutral beams. The Mega-Ampere Spherical Tokamak (MAST) has a large cylindrical vacuum vessel and we have taken advantage of this to consider a number of launcher positions for RF power injection. The feasibility of EBW in the extended parameter space of MAST has been explored. Modelling was conducted with the EBW&BANDIT code package using a "steady state" reference scenario with near zero loop voltage. Clear heating and CD effects have been identified for different launch configurations and frequencies.

Keywords: Electron Bernstein waves, plasma heating, current drive, spherical tokamak.
PACS: 52.55.Fa, 52.35.Hr

INTRODUCTION

In the present work we explore the potential of EBW heating and CD on MAST over a range of parameters. A new centre column together with additional poloidal field coils and new power supplies for toroidal and poloidal fields are planned for MAST, subject to resources availability [1]. They will provide a longer pulse capability at higher toroidal magnetic field. Together with the increased NBI power these upgrades move MAST toward fully non-inductive operation at high beta. EBW may provide highly localised near-axis and off-axis heating and CD without any momentum transfer to the plasma. EBW heating and CD are based on resonant absorption near EC harmonics. Hence they must be optimized for every particular application in a given magnetic configuration. EBW can be an efficient tool providing local profile control capability. Also highly localised controllable electron temperature perturbations can be beneficial in plasma transport studies.

The ordinary-extraordinary-Bernstein (O-X-B) mode conversion scheme (MC) is studied here because the plasma is typically well overdense in MAST, i.e. ($\omega_{pe} >> \omega_{ce}$) where ω_{ce} and ω_{pe} are the electron cyclotron and plasma frequencies. Analysis is focused on 3 main tasks: a) optimisation of launch parameters and launch frequency to achieve maximum efficiency for near-axis counter-CD; b) achievement of efficient

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off-axis EBW CD; and finally c) achievement of efficient near central EBW heating with close to zero EBW CD effects.

EBW & FOKKER-PLANCK MODELLING

MAST has a large cylindrical vessel 4 m in diameter and 4.4 m in height [2]. Poloidal field coils are located inside the vacuum vessel and they represent a major constraint for the RF launcher positioning. Taking into account the large aperture ~300mm required for the launcher there are only 3 possible vertical Z ranges for its location: -0.2m < Z < 0.2m with respect to the midplane and 0.55m < |Z| < 0.7m above and below the midplane. The radial position of the launcher is at R=1.75 m for any vertical location. The RF beam is assumed to be Gaussian with a waist radius of 150 mm at the last mirror for all frequencies. Plasma parameters are restricted to low ($3.5\cdot10^{19}$ m^{-3}) and high ($8.8\cdot10^{19}$ m^{-3}) density scenarios at fixed plasma current (I_p=1.2 MA) and toroidal field of 0.78 T. Relevant profiles and magnetic equilibria have been obtained from TRANSP modeling. The scrape-off layer plasma is described analytically with an exponential density decrease in the scale of a few centimeters.

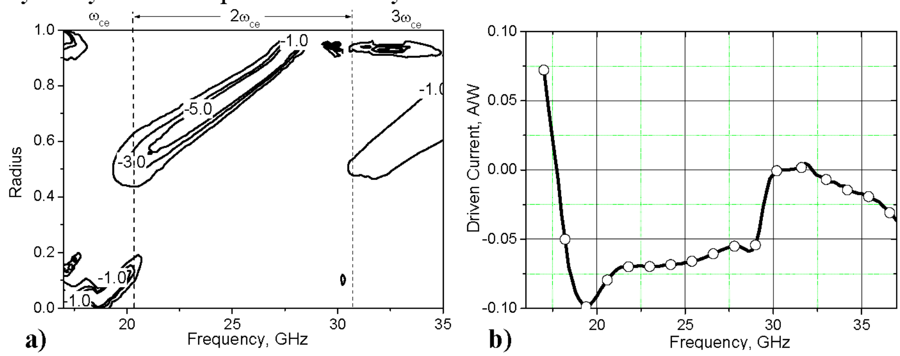

FIGURE 1. EBW & Fokker-Plank modeling results in the range of the first three EC harmonics. The launcher position is 55 cm below the midplane, right polarization. **a)** Driven current density distribution across normalised radius, a. u. **b)** Total EBW driven current integrated over the radius.

The modeling has been conducted using an EBW & Fokker-Planck code [3]. First, a few frequency scans within the range of the first 3 EC harmonics have been done for every possible launch position at optimal launching angles. The results for the -55 cm launch are illustrated in Fig. 1. There are three separate frequency ranges corresponding to different EC harmonics in Fig. 1a. At $3\omega_{ce}$ absorption is very peripheral with low CD efficiency while the radial location of absorption at the $2\omega_{ce}$ harmonic can be in the range of normalized radii r/a = 0.5 – 0.9 depending on the RF frequency chosen. The highest CD efficiency of -0.1 A/W is achievable at the fundamental resonance at 19.4 GHz with the driven current localized within r/a ~0.1 (see Fig. 1b). This launch configuration is the best solution for the task a). All currents except for a small fraction at 17 GHz are in the counter-direction. Due to poloidal asymmetry the same currents can be driven in the co-direction if the launch position is switched to 55 cm *above* the midplane with *left* polarization.

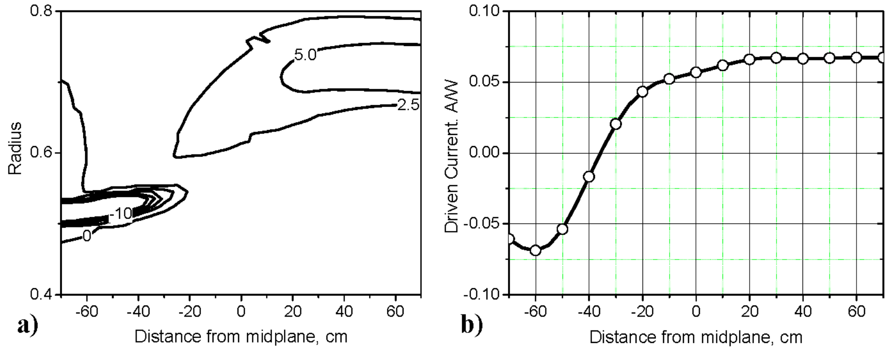

FIGURE 2. EBW CD against vertical position of the launcher, 25 GHz, left polarization. **a)** Driven current density across normalised radius, a. u. **b)** Total EBW driven current integrated over the radius.

From Fig. 1 it is clear that the $2\omega_{ce}$ range is very attractive for task b). For stability of high beta plasmas normalized radius of ~0.7 is advantageous. This requires a frequency of about 25 GHz. Obviously in the $2\omega_{ce}$ range the radial location of RF power deposition and CD can be varied by appropriate variation of toroidal magnetic field. Vertical optimization of the launcher position has been done with vertical scaning at a fixed frequency of 25 GHz (see Fig. 2a). The CD efficiency is almost constant over the range of 55 – 70 cm (Fig. 2b) with good radial localisation. As seen from Fig. 2a the driven current can be switched to the opposite localized around r/a=0.52 if the RF is launched from $-70 < Z < -55$ cm.

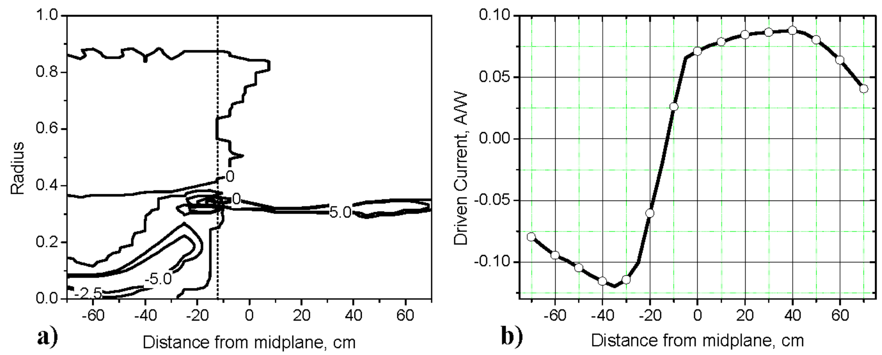

FIGURE 3. Same as in Fig. 2 simulated for 19.4 GHz, right polarisation. Note co- and counter – CD compensation at the launcher position of 12.5 cm below midplane.

The third task c) can be satisfied at the same frequency of 19.4 GHz as the task a) with close to midplane launch where co- and counter-driven currents compensate each other providing pure heating (Fig. 3). EBWs drive current in the co-direction at a radius r/a ~ 0.33 when RF was launched from *above* the midplane then the current switched to the counter-direction when RF was launched from *below* the midplane (Fig. 3a). At the launch position -12.5 cm the total driven current is zero as seen in Fig. 3b. The RF power is deposited around r/a = 0.25 as required by task c).

Finally the sensitivity of O-X-B MC has been studied for various launch positions against pitch angle variations in the MC layer. Fig. 4a represents MC windows calculated for 3 values of the magnetic pitch angle at 19.4 GHz and Z = -12.5 cm launch position. It shows a gradual shift of the MC maximums and decrease of the MC window width with pitch angle increase. Surprisingly the same launcher at the same frequency but located far off-midplane at Z = -55 cm appears to be less sensitive to the pitch angle variations as seen in Fig. 4b.

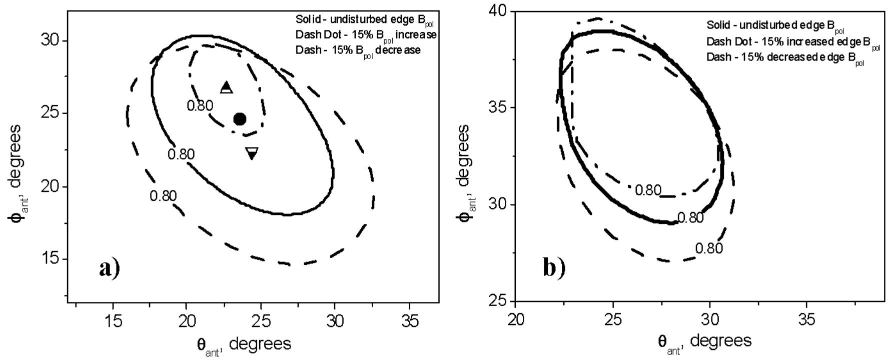

FIGURE 4. Sensitivity of the O-X-B mode conversion to magnetic pitch angle variations. MC windows in angular coordinates for undisturbed magnetic field and 15% variations of the poloidal component. **a)** MC window contours of 80% coupling and their maxima for 19.4 GHz, right polarisation and launch from 12.5 cm below midplane. **b)** 80% contours of MC window for 19.4 GHz, right polarisation and launch from 55 cm below midplane.

CONCLUSIONS

For the specified magnetic equilibrium and plasma parameters the optimum frequency for near axis counter-CD is ~19.4 GHz. It can provide up to 0.1 A/W CD efficiency with localisation r/a < 0.1. Near central heating (with zero CD effect) can be achieved at the same frequency of 19.4 GHz with Z = -12.5 cm launch. Efficient off-axis EBW CD can be achieved at a higher frequency of 25 GHz at the $2\omega_{ce}$ harmonic or with 19.4 GHz at reduced toroidal field. CD efficiency up to 0.075 A/W is achievable near r/a ≈ 0.5 and r/a ≈ 0.7. MC coupling is found to be less sensitive to pitch angle variations for far off-midplane launch.

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