Fundamental Investigation of Electron Bernstein Wave Heating and Current Drive at the WEGA Stellarator

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Abstract.
Overdense plasma heating with electron Bernstein waves (EBWs) is of large importance for fusion, since ultra high density operation is a promising fusion scenario for stellarators and heliotrons. The EBW physics is also important for spherical tokamaks (ST). Here the plasma core is inaccessible for standard ECRH with electromagnetic waves. The EBW driven current could help to stabilize MHD-modes and to achieve steady state operation at high beta. The typical EC-frequency range in STs is 10-30 GHz. This paper reports about EBW heating and current drive experiments at frequencies of 2.45 GHz. WEGA is a classical five period l=2 stellarator with a major radius of 0.72 m and an aspect ratio of 7. For the 2.45 GHz the mode conversion could be investigated in detail by hf-probes. The results were consistent with full wave simulations. The short EBW wavelength of < 1mm enabled the calculation of their propagation by a 3D- ray-tracing code. In addition the code predicted an EBW driven current. Both the resonant power deposition and the EBW driven current density profile was measured by power modulation technique with movable probes in the plasma. An agreement between the code results and experimental data was found.

1. Introduction

Plasma heating and current drive with electron Bernstein waves (EBW) have made a remarkable progress in the last decade. High power heating experiments in overdense plasmas at the W7-AS stellarator with 70 and 140 GHz [1], at the TCV tokamak with 82.7 GHz [2] and at the CHS heliotron with 54.5 GHz [3] demonstrated the performance of EBW to achieve high density and high beta operation. Even more at W7-AS efficient EBW current drive in an over-dense plasma was demonstrated [4]. These results are of great importance for the fusion research, since ultra high density operation is a promising fusion scenario for stellarators and heliotrons. The EBW physics is also important for spherical tokamaks (ST). Here, the plasma core is inaccessible for standard ECRH with electromagnetic waves. The EBW driven current could help to stabilize MHD-modes and to achieve steady state operation at high beta. The typical frequency range in STs is 10-30 GHz. At the WEGA stellarator a program for fundamental investigation of EBW physics was established.

1. Experimental set-up

The WEGA is a classical five period l=2 stellarator shown in Fig. 1 with a major radius of 0.72 m and an aspect ratio of 7. The maximum toroidal field is 0.9T, the rotational transform can reach 1. It is also equipped with vertical field coils, which are used for plasma position control and shear variation. The plasma is heated by ECRH for typically 30 s which allows to measure RF-fields and currents in steady state conditions with a high precision. In addition the low temperature plasma enables to measure the current density profile with probes. WEGA is also equipped with an iron OH-transformer with a capability of 440 mVs, which was only used to measure the toroidal plasma current. The device, which was originally build for the development of lower hybrid heating in Grenoble (France), was transferred to Greifswald for fundamental plasma physics research.

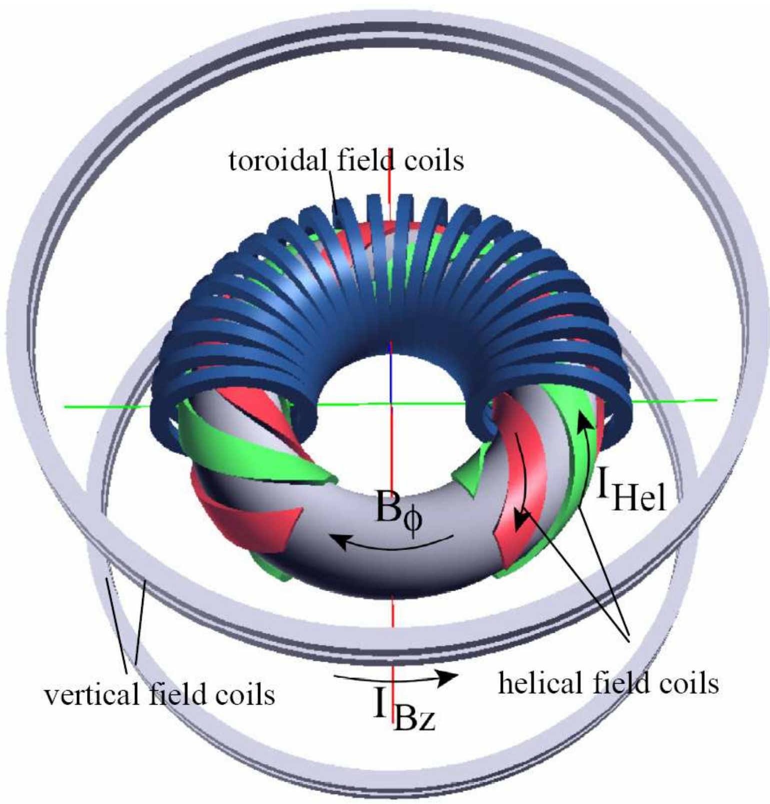

Fig. 1 Coil system of WEGA stellarator

2. EBW heating

EBWs are electrostatic waves. Therefore, they have to be exited by mode conversion from electromagnetic waves. The most favourable scheme is the two step conversion from an ordinary wave (O-wave) into an extraordinary wave (X-wave) and finally into a Bernstein wave. This so called OXB-mode conversion could be investigated in detail using the 2.45 GHz heating system [5]. Here, the cut-off density is very low. As a consequence, the mode conversion region was shifted to the scrape-off plasma outside the separatrix, where the normalised density gradient length $k_0L_n \approx 5$ was favourable for OXB-mode conversion. In addition, the long wavelength provided a unique opportunity to investigate the mode conversion process in detail using radially resolved measurements of the phase and amplitude of the waves involved. A two-dimensional finite-difference time-domain full wave code was developed to compare calculated and measured microwave propagation and mode conversion results. The probe measurements clearly show the transition of the O-wave into the X-wave in the mode conversion region. The EBW heating process itself was investigated by the modulation (12.5 kHz) of a part of the microwave power (26 kW magnetron) and the observation of the concomitant oscillations in the electron temperature and density [5]. Even though the vacuum wavelength for 2.45 GHz is of the same order as the plasma dimensions, the wavelength of the EBWs is below 1 mm. Therefore their propagation could be calculated by a 3D ray-tracing code, which also took into account the antenna coupling efficiency [6]. In

Fig. 2 the EBW rays are shown in the equatorial and poloidal projection. The code calculates the OXB conversion efficiency of the individual ray at the position, where it is generated. Even though the starting N_{II} spectrum is determined by the N_{II} spectrum of the emitting antenna, N_{II} increases to values up to 20 when the rays propagate through the plasma. The calculation could reproduce the strongly Doppler shifted absorption found in the experiments (see Fig. 3). Even though the calculated power deposition is more central the optimum is at 0.65 B_c as in the experiment. B_c is the resonant central magnetic field for 2.45 GHz (87 mT).

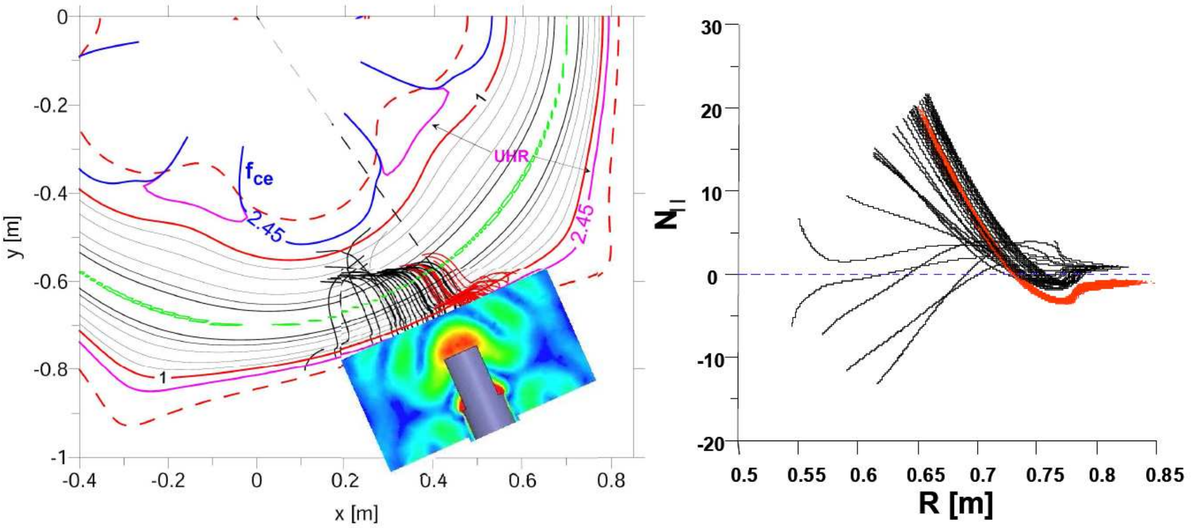

Fig. 2 left) Ray trajectories of EBW's in equatorial projection. right) Development of N_{II} during propagation until absorption for the individual EBW rays calculated by the 3D ray-tracing code.

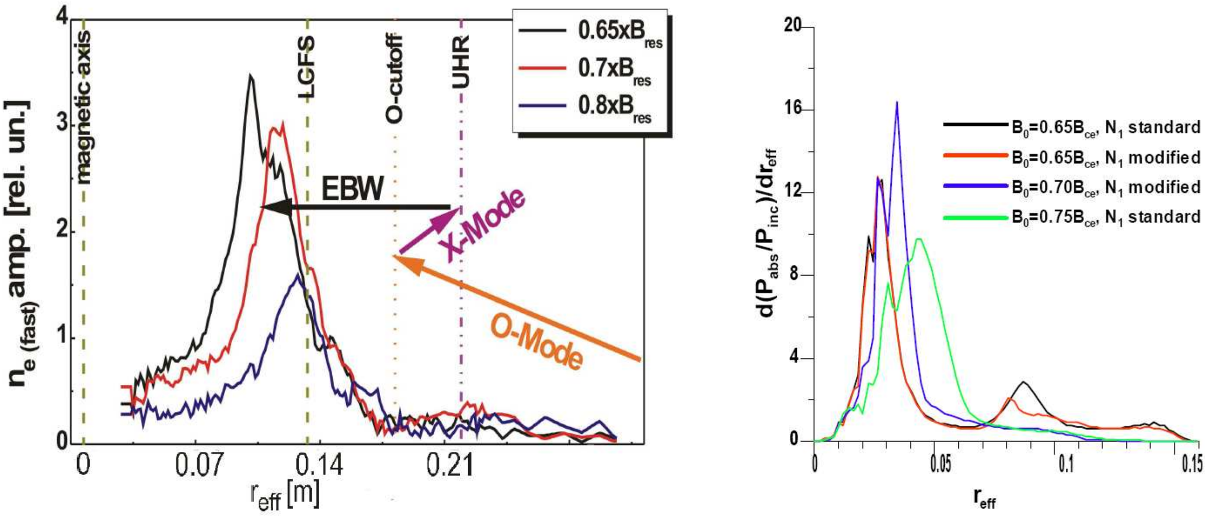

Fig. 3 Power deposition profiles for different magnetic field strength, achieved from probe measurement (left) and ray-tracing calculation (right). In addition in the sensitivity on different profiles of the supra-thermal electrons with a temperature of 150 eV was tested.

4. EBW current drive

The change of N_{II} for the EBWs is mainly due to the magnetic field, which leads to a propagation of nearly all rays into one direction independently whether they have been emitted from the left or right antenna lobe. The asymmetrical development of the N_{II} component generates a toroidal current which is driven by EBWs. This current could be measured by an external Rogowski coil and the short-circuited primary winding of the WEGA transformer coil. A high precision was achieved by making use of the long discharge length, which is possible at the WEGA stellarator. In typically 30 s the 6 kW magnetron power was modulated with 100% amplitude with frequencies between 27 Hz and 90 Hz. A second magnetron was sustaining the plasma with additional 6 kW. Since the plasma was stationary for more than 25 s, an average over all modulation cycles gives a precise measure of the driven current. The highest current was achieved at iota= 0.2 with 45 A for 6 kW modulation and 6 kW constant power. The modelling of the EBW driven current in WEGA turned out to be difficult. Firstly, the profiles of density and temperature are known from probe measurement only, which give some impreciseness due to the plasma perturbation by the probe itself. Secondly, probe measurements indicate that in addition to the thermal electron at 10-20 eV a supra-thermal population of approximately 10 % with an energy of 150-300 eV exists. Those electrons are probably the main source of the driven current. Even more the EBW absorption takes place at the Doppler down shifted first harmonic resonance as well as at the Doppler up-shifted second harmonic resonance. Both processes generate counter-acting currents. In addition collision with the Ions and neutrals should be taken into account, which reduces the current drive efficiency. However, only little influence of the neutral gas pressure on the CD-efficiency was found in the experiments. This was explained by the model, which shows that the electron ion collisions are the dominating process. Further sensitivity studies have been performed. The EBW current rises linearly with the driving power. The dependence on the additional non-modulated power is week, but shows an increase of the current of 20% when the power is varied from 3 kW to 6 kW. Probably, here the higher number of supra-thermal electrons is compensated by the unavoidable density increase with the total power. The Fish-Boozer-mechanism is assumed to be responsible for the EBW driven current. The Okhawa mechanism can be excluded since for large N_{II} the interaction in the phase space takes place far from the trapped particle region. The EBW-current was calculated from the formula in [7]. The knowledge of the total EBW driven current is probably not sufficient to test the modelling, but the low temperature plasma gives access to measurement of the current density directly by current probes, which are moved through the plasma during the discharge. These mini-Rogowski coils consist of a stainless steel tube of 1.3 mm diameter, which forms a loop of 10 mm diameter. Inside the tube there is a coil with typically 500 windings. The tube is covered by insulating ceramics powder. The measured current density profile exhibited two counteracting currents at a magnetic field of 0.65 B_c as shown in Fig. 4. At this magnetic field we found the best heating efficiency. It should be noted that most of the current is driven at the outer radii, thus the total current is negative. But the characteristic positive current contribution could be also predicted by the model. Even more the positive central current vanishes when the magnetic field is increased, which is consistent with the model prediction shown in Fig. 5. The total current of 7.5 A/kW, measured by the ohmic transformer is comparable with the code prediction of 5.6-13 A/kW. The uncertainty of the electron distribution prohibits a more precise prediction. The more spectacular reversal of the total toroidal current due to varying the vertical field could not be explained by the modelling yet. Even though only one control parameter was varied in the experiment the result was a variation of the many plasma parameters like magnetic shear and plasma position in respect to the antenna. As a consequence the mode conversion efficiency was changed. In addition the temperature and density profiles were modified. Therefore this case needs more detailed experimental and theoretical investigation, which is underway.

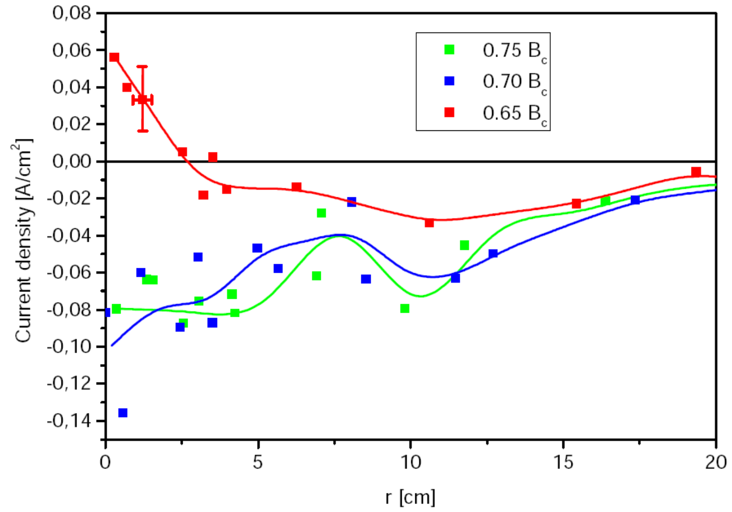

Fig. 4 Experimental current density profiles measured by a movable Rogowski coil for 6 kW injected power.

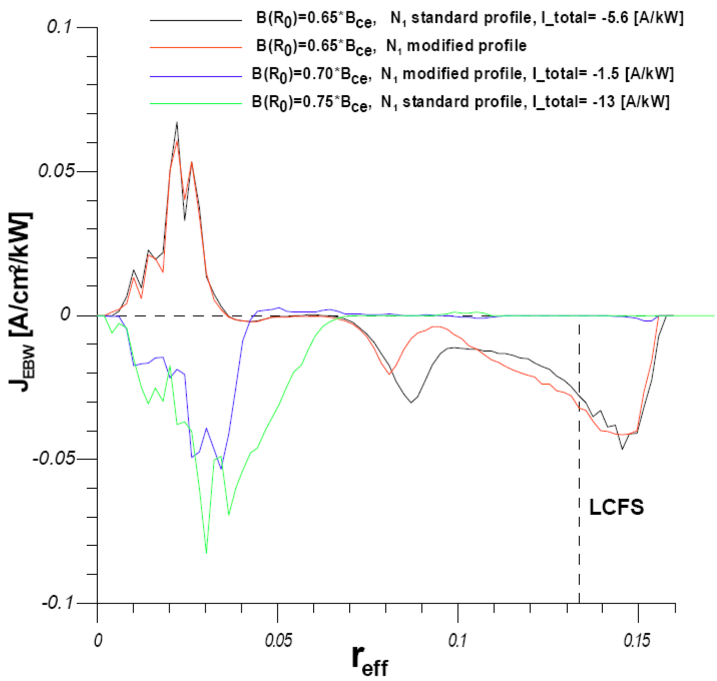

Fig. 5 Calculated current density for different central toroidal field.

4. Conclusions

At the WEGA stellarator detailed investigation of EBW generation and propagation at low frequency (2.45 GHz) has been performed. The mode conversion was simulated with a full wave code. The EBW propagation and absorption were consistent with 3D ray-tracing calculations taking into account a supra-thermal electron distribution. The predicted EBW-current was found experimentally. Even though the detailed modelling of the EBW-current drive turns out to be difficult at WEGA, the different processes and contribution have been identified and sensitivity studies have been performed both in model and in experiment. Thus the magnetic variability of WEGA allows unique tests of modelling EBW propagation as well as their phase space interaction.

5. References

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