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Electron Cyclotron Wave Experiments at the WEGA Stellarator

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The WEGA stellarator (see P 2.145) is a classical five period l=2 stellarator with a major radius of 0.72 m and an aspect ratio of 6. The device is used for student education, test of diagnostics and machine control for W7-X. It also continues with the traditions of basic plasma research of our institute. This paper reports about experiments with electron cyclotron wave heating at a frequency 2.45 GHz and 28 GHz.

For the 2.45 GHz frequency the cut-off density is very low ($7.5 \cdot 10^{16} m^{-3}$), therefore an electron Bernstein wave heating (EBW) with OXB-mode conversion [1,2] was implemented. The mode conversion region was shifted to the scrape-off plasma outside the separatrix, where the normalised density gradient length of $k_0 L_n \approx 5$ is favourable for OXB-mode conversion. The long wavelength provided a unique opportunity to investigate the mode conversion process in detail with radially resolved measurements of the phase and amplitude of the waves involved. The EBW heating process itself was investigated by 12.5 kHz modulation of typically 50% of the microwave power (12 kW) and observation of the concomitant oscillations in electron temperature and density [3]. The waves were launched by a double-slot TE11 antenna, which was designed to emit a **k**-spectrum optimized for the O-X conversion. A two-dimensional

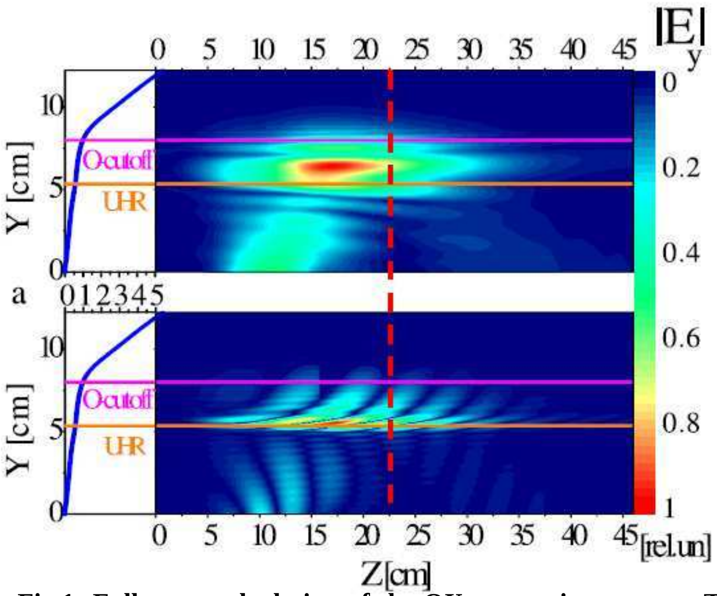

Fig.1 Full-wave calculation of the OX conversion process. Time averaged (a) and instantaneous (b) y-component of the wave E-field distribution.

finite-difference time-domain full wave code was developed to compare calculated and measured microwave propagation and mode conversion results. In Fig.1 the calculated wave field at the O-X-B conversion region near the antenna is shown. The wave field could be measured with a movable array of small HF-probes (loop and electrostatic antennas), which were sensitive to the different polarisations of the involved modes. Both, the amplitude and the phase of the X- and O-mode could be measured with a heterodyne receiver. In addition the local density was measured by Langmuir probes. The O-mode amplitude drops near the O-cutoff, while the X-mode amplitude is increasing, which represents the O-X conversion. The appearance of the upper hybrid resonance (UHR) could be clearly demonstrated by the phase jump and an amplitude peak of the X-wave. The measurements reproduce the simulation results. The EBW´s itself could not be detected by

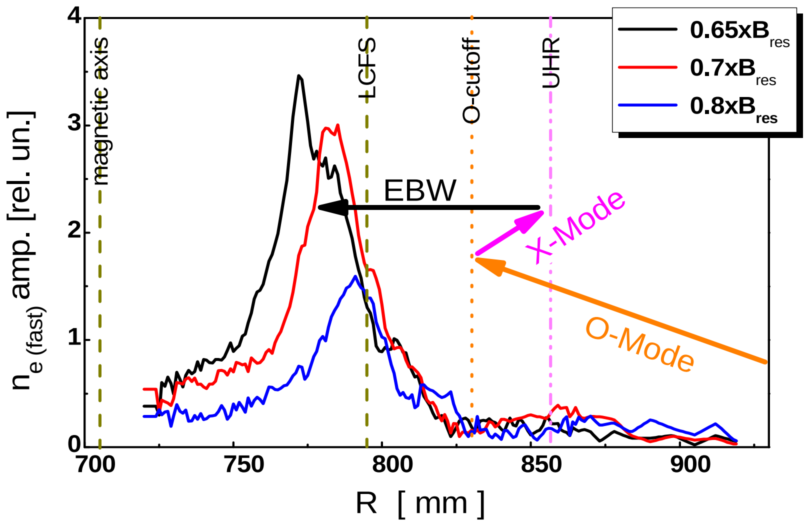

Fig.2 Power deposition profiles for different magnetic field strength, achieved from probe measurements.

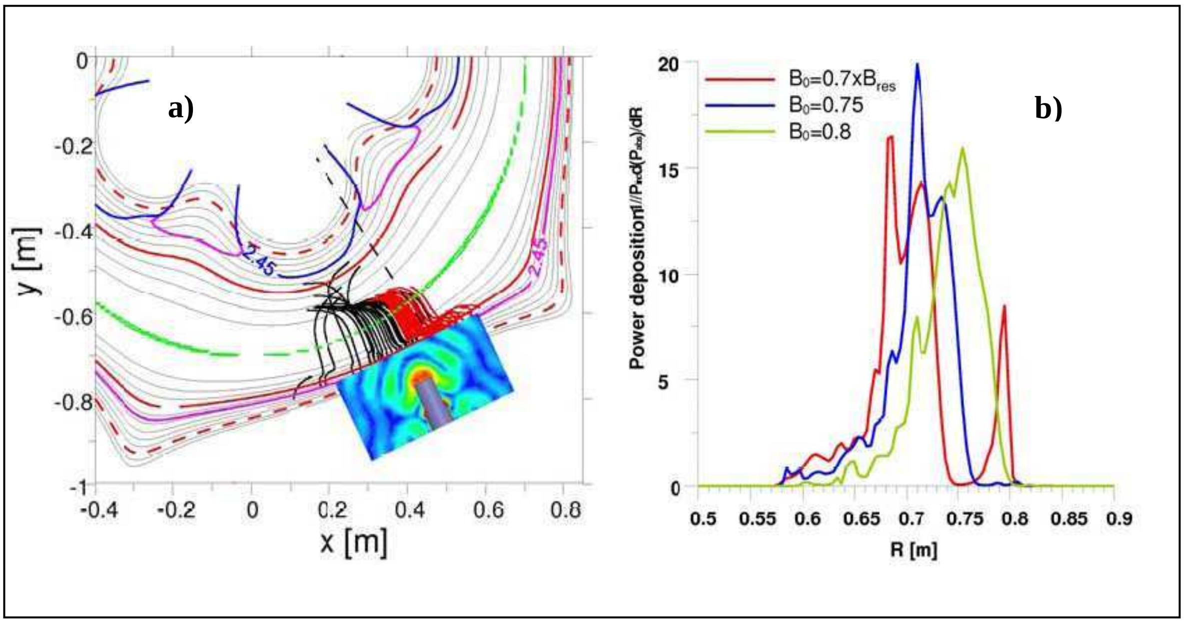

Fig.3 a) Ray trajectories of EBW's in equatorial projection b) Power deposition calculated with O-X-EBW conversion efficiency and ray-tracing simulation code.

RF-antennas directly, since their wave length is of the order of the electron gyro radius (≈0.1 mm). However their deposited power could be found by fast power modulation experiments (12 kHz) and coherent detection by Langmuir probes. The deposition profile was located well inside the confined plasma. This bulk plasma was highly, up to 12 times, over-dense and not accessible for the electromagnetic waves. The deposition is strongly dependent on the magnetic field and the highest plasma pressure could be achieved at $0.65 \times B_{res}$. In Fig.2 the shift of the power deposition profiles for different magnetic fields is shown. The results were confirmed by 3D ray tracing calculations for EBW´s in the WEGA magnetic field using the experimental density and temperature profiles [4]. The mode conversion was simulated by using the pattern of the double-slot antenna. Typical coupling efficiencies of up to 30 % were found. In Fig. 3a) the ray trajectories are shown. The strongly Doppler-shifted absorption could be reproduced by the ray tracing calculation taking into account a supra-thermal electron distribution, which was expected due to the resonant EC-interaction interaction. Fig. 3b) shows the calculated deposition profiles as a function of the magnetic field strength. It is remarkable that the EBW propagation is not dependent on their incident $N_{||}$ value generated by the antenna, but is strongly affected by the magnetic configuration. In Fig.3 most of the rays propagate in the direction of the magnetic field vector. The resulting EBW driven current is directed counter to **B**. The current was detected by a Rogowski coil on the plasma vessel and a current measurement at the short-circuited 32 turn primary winding of the WEGA transformer. A sensitivity of 0.5 A could be achieved by power switching with 37 Hz and averaging over 150 modulation cycles. The current amplitude and its polarity strongly depend on the magnetic configuration, as shown in Fig.4. A maximum current of 45 A was achieved. The resulting normalized current drive efficiency fit well to those found at higher frequencies in [5,6] .

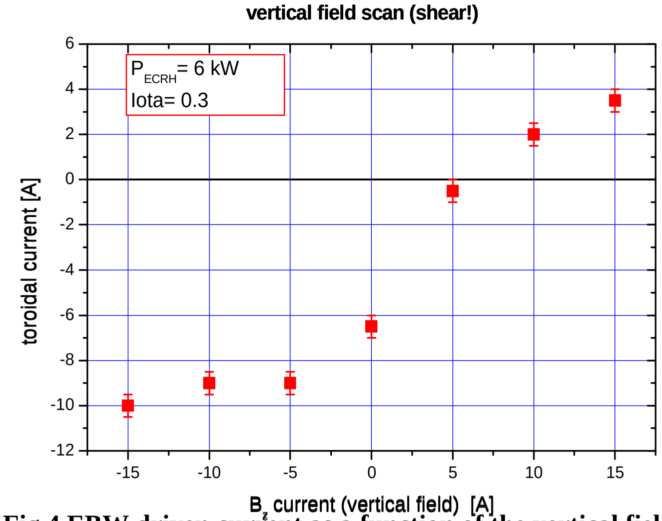

Fig.4 EBW driven current as a function of the vertical field coil current. Vertical field changes the radial plasma position and the shear.

$$\zeta = \frac{e^2 I_{CD} n_e R_0}{\varepsilon_0^2 P_{HF} T_e} = 0.48 \pm 0.2 \left(\frac{I_{CD}}{P_{HF}} \left[\frac{kA}{kW} \right], \frac{n_e R_o}{T_e} \left[\frac{1}{m^2 eV} \right] \right)$$

Here we have assumed that the 30% of the microwave power (6 kW) was converted into EBW’s. The temperature dependence is rather uncertain, since there are some evidences that beside the measured 12 eV bulk temperature a supra-thermal component is existing. Further modelling of the EBW current drive is under way.

In the experiments with the 28 GHz frequency we concentrated on the second harmonic X-mode heating at a magnetic field of 0.5 T. An efficient transmission line was build-up, which converts the TE02 output mode of a 10 kW cw gyrotron into a HE11 mode launched by a quasi-optical antenna system into the plasma [7]. The transmission line was upgraded by a quasi optical antenna, which focuses the beam into the plasma center with a beam waste diameter of 2 cm. The WEGA vacuum vessel with circular cross-section is used as a focusing reflector, which provides several well focused passes through the plasma center. Typically 8 kW could be coupled into the plasma. The ray tracing calculation with multiple reflections indicates that about 80% of the power is deposited in the plasma center. This is supported by sniffer probe measurement of the non-absorbed ECRH stray radiation at the opposite torus position. During the high power heating the stray radiation signal vanishes above a power level of 6 kW. A well localized power deposition was found by probe measurements at a high neutral gas density. For low density hydrogen plasmas at $n_e = 1 \cdot 10^{18}$ m^{-3} the temperature is expected to be above 100 eV . An ECE system is in preparation.

Summary and conclusions

The WEGA stellarator is an unique test bed for the investigation of EBW generation and the EBW current-drive at low frequency. The 0.5 T 28 GHz operation has started successfully. Localized multi-pass absorption in the plasma center could be demonstrated.

References:

[1] J. Preinhaelter, and V.Kopecký, J. Plasma Phys. 10 (1973) 1;

[2] H. P. Laqua, et al., Phys. Rev. Lett. **78**, 3467 (1997).

[3] Y.Y. Podoba, H. P. Laqua, G. B. Warr, M. Schubert, M. Otte, S. Marsen, F. Wagner and E. Holzhauer, Phys. Rev. Lett. **98**, 255003 (2007)

[4] J. Preinhaelter, J. Urban, H. P. Laqua, Y. Podoba, L. Vahala, G. Vahala, submitted for publication in AIP Proc. of the 17th Topical Conference on Radio Frequency in Plasmas

[5] H. P. Laqua, H.Maassberg, N.B. Marushchenko, F. Volpe, W.Kasparek, A. Weller, Phys. Rev. Lett. **90,** 075003 (2003);

[6] V. Shevchenko et al., Phys. Rev. Lett. **89**, 265005 (2003)

[7] G. B. Warr et al. Europhysics Conference Abstracts Vol. 30I, p2.122 (2006)