J. Plasma Fusion Res. SERIES, Vol.1 (1998) 314–317

Electron Cyclotron Heating beyond the Cutoff Density by O-X-B Mode Conversion in W7-AS

LAQUA Heinrich P.*, ERCKMANN Volker, the W7-AS Team and ECRH-Group[1]
Max-Planck-Institut für Plasmaphysik, EURATOM Ass.
D-85748 Garching, FRG
[1]Institut für Plasmaforschung, Univ. Stuttgart, D-70569 Stuttgart, FRG

(Received: 30 September 1997/Accepted: 22 October 1997)

Abstract

Electron cyclotron heating (ECH) above the plasma cutoff density with electron Bernstein waves (EBW) was successfully demonstrated at W7-AS stellarator. The EBW's were generated via O-X-B mode conversion from O-waves to X-waves and, finally, to electron Bernstein waves. Clear evidences for both mode conversion steps were detected and resonant absorption with a narrow profile was demonstrated.

Keywords:

electron cyclotron heating, electron bernstein waves, mode conversion, o-x-b process

1. Introduction

The accessible plasma density for electron cyclotron heating (ECH) with electromagnetic waves is limited by the plasma cutoff. For the electrostatic electron Bernstein wave (EBW), the third EC-mode which is able to propagate in a hot plasma, no such limit exists. However, since EBW's could not be exited from the outside, they have to be generated via mode conversion from the electromagnetic waves. This can be performed by the O-X-B process which was proposed by J. Preinhaelter and V. Kopecký in 1973 [1]. Here O, X, and B represent the ordinary, extraordinary and the electron Bernstein mode. In a first step an O-wave launched by an antenna is converted into a slow X-wave at the O-wave cutoff layer. This mode conversion requires an oblique launch near an optimal angle, a plasma density above the O-wave cutoff and a frequency above the first cyclotron harmonic in the plasma. In a second mode conversion an EBW is generated from the slow X-wave at the upper hybrid resonance (UHR), where the X-mode branch of the solution of the hot plasma dispersion relation is connected to the electron Bernstein branch. Since for EBW's no density limit exists, they propagate toward the dense plasma center where they are absorbed by cyclotron damping or in the nonresonant case by collisional multiple pass damping. A detailed description of the O-X-B mode conversion process is found in [2, 3]. In this paper the experimental results of the O-X-B mode conversion and EBW heating will be presented.

2. Experimental Results

The experiments were performed at the W7-AS stellarator (major radius $R=2.0$ m, minor radius $a=0.18$ m) with two 70 GHz gyrotrons with 110 kW power each. A detailed description of W7-AS and its 70 GHz ECH system can be found in [4]. The central magnetic field was set between 1.25 T and 2.5 T and the edge rotational transform χ, taken from the magnetic reconstruction, near 0.35 according to the experimental requirements. The central density of the neutral beam injection (NBI) sustained target plasma was up to 1.6×10^{20} m^{-3}, which is more than twice the

*Corresponding author's e-mail: laqua@ipp.mpg.de

70 GHz O-mode cutoff density. Co- and counter-NBI with 360 power each were used to compensate the momentum transfer to the plasma.

2.1 Variation of the launch angle

The launch angle of the incident O-mode polarised wave was varied at fixed heating power (220 kW) at a nonresonant magnetic field. The increase of the total stored plasma energy (from the diamagnetic signal) depends strongly on the launch angle (see Fig. 1), which is typical for the O-X-conversion process, and fits well to the calculation. Here the power transmission function given by [5] was normalised to the maximum energy increase. The central density was 1.5×10^{20} m^{-3} and the central electron temperature was 500 eV. Heating at the plasma edge could be excluded since at the nonresonant magnetic field of 1.75 T no electron cyclotron resonance existed inside the plasma. Due to technical limitation of the maximum launch angle, only the left part of the transmission function could be proved experimentally. The plasma energy content increased by about 1.5 kJ compared to a similar discharge with neutral beam injection (NBI) only as shown in Fig. 2. Here two 70 GHz beams in O-mode polarisation (110 kW power each) were launched with an angle of 40° with respect to the perpendicular launch into a NBI (720 kW) sustained target plasma with a central density of 1.6×10^{20} m^{-3} and a central temperature of 560 eV. More than 70% of the heating power was found in the plasma if the power scaling of the energy confinement

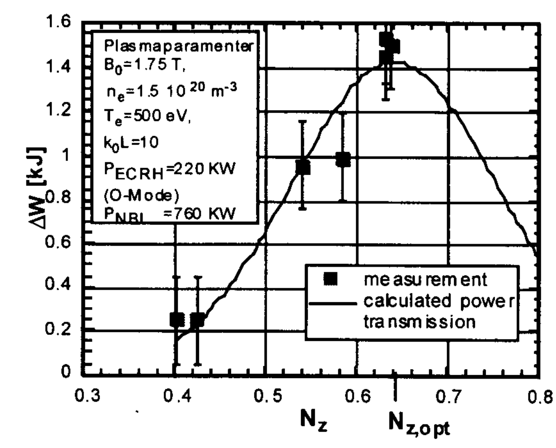

Fig. 1 Increase of the plasma energy content by O-X-B-heating versus the longitudinal vacuum refractive index N_z=cosφ of the incident O-wave (φ: launch angle). The solid line is the calculated transmission function multiplied by the maximum energy increase.

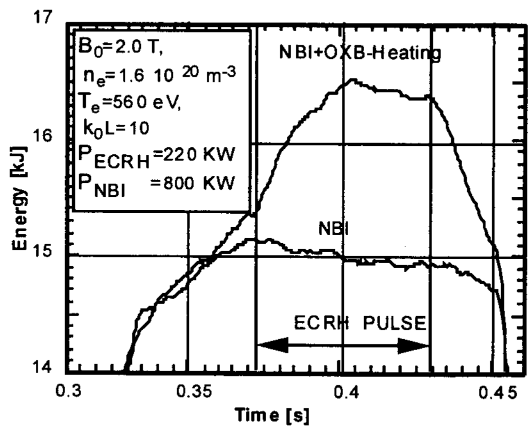

Fig. 2 Energy content (diamagnetic signal) of a NBI-discharge with and without O-X-B-heating.

($P^{-0.6}$) was taken into account. Thus O-X-B-heating turned out to be efficient.

2.2 Density variation and parametric instability (PI)

In these experiments, it should be demonstrated, that a density threshold (O-cutoff) for the O-X-conversion exists and that the parametric decay process which is a footprint of the X-B conversion takes place. For this the plasma was build up by one 70 GHz gyrotron in X-polarisation in a resonant central magnetic field of 1.25 T. Then the density was slowly ramped up to density above the O-cutoff. In parallel as shown in Fig. 3 a second 70 GHz beam O-mode polarised with the optimal launch angle and modulated with 20% amplitude was launched into the plasma. During the plasma build up thermal EC emission (ECE) was detected. As soon as the cutoff density is reached ECE vanished and O-X-B heating started, which caused an increase of the plasma energy and central soft-X emission shown in Fig. 3. Simultaneoulsy the PI at the X-B-conversion process generated a decay spectrum, whose high frequency part could be measured with the ECE-detector. The modulation amplitude strongly exceeded that of the pump wave, what clearly demonstrated the nonlinear character (power threshold) of the PI. Figure 4 shows the high frequency decay spectrum. Two red shifted and one blue shifted lines can be recognised. Their spectral distances to the 70 GHz pump wave, which was suppressed by a Notch filter, are multiples of the lower hybrid resonance (LHR) frequency (~900 MHz). The spectrum of the LHR oscillation itself could be detected by a loop antenna. The LHR oscillation shows a high degree of correlation with the high frequency decay waves.

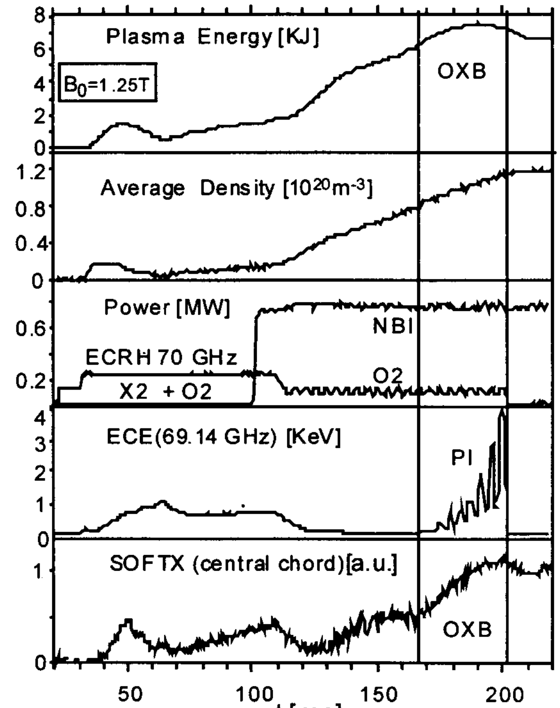

Fig. 3 Temporal development of some plasma parameter during a O-X-B heated discharge. From the top: plasma energy estimated from the diamagnetic signal, average density from the interferometric measurement, heating power, intensity of ECE and PI, central soft X signal. The markers show the O-X-B heating interval.

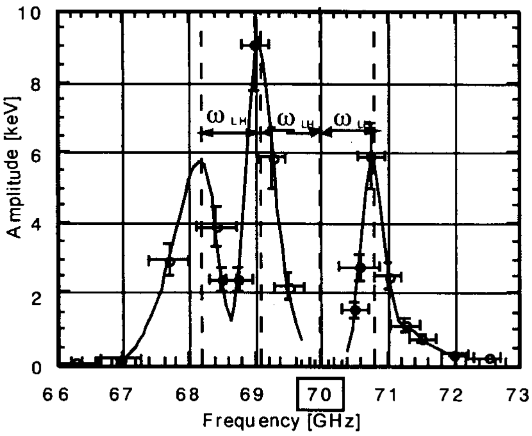

Fig. 4 High frequency spectrum of the parametric decay waves generated in the X-B-process. The incident wave frequency is 70 GHz and the LH frequency is about 900 MHz.

2.3 Resonant cyclotron absorption

Here the central magnetic field was varied between 2.0 T and 2.5 T to show resonant absorption of the EBWs. In the equatorial plane the magnetic field as a function of the effective radius $r_{\rm eff}$ is approximately given by the following relation: $B(r_{\rm eff})=B_0A/(A+r_{\rm eff}/a)$ with $A=10.5$. The power deposition was estimated from the change of the temperature profile at the power switch-off. Since the density was far above the ECE cutoff, the temperature profiles were calculated from the soft-X emission and the Thomson scattering diagnostic. The central temperature was 500 eV. The X-ray emission was monitored by an array of 36 silicon detectors with a 25 μm beryllium filter. To obtain the radial X-ray emission profile the signals were inverted to the magnetic flux co-ordinates. The time resolution was 0.1 ms and the radial resolution was about 1 cm. In Fig. 5 the absorption profiles for different magnetic fields are shown. The absorption is strongly Doppler shifted due to the oblique launch and moves from the high field side at 2.0 T through the center (2.2 T) to the low field side at 2.3 T with increasing magnetic field, which clearly demonstrates the propagation and the local cyclotron absorption of the EBW's for the first time.

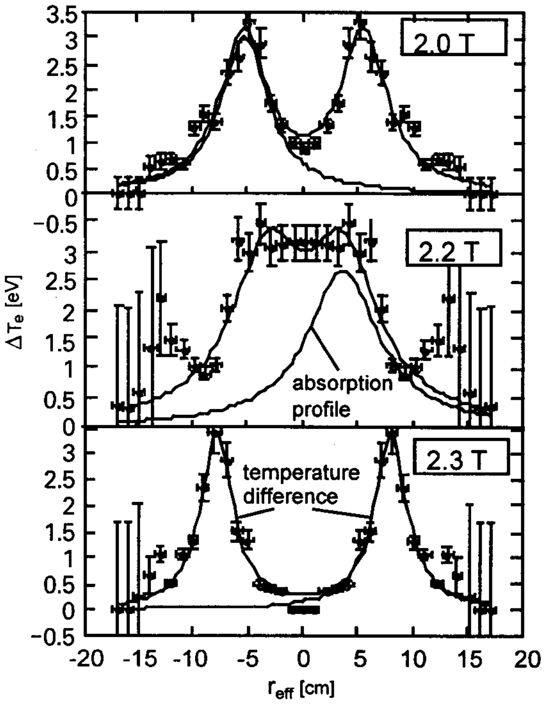

Fig. 5 Changes of temperature 3 ms after O-X-B heating switch-off and the related ECRH absorption profiles different central magnetic fields.

3. Conclusions

ECH of an overdense plasma with 70 GHz electron Bernstein waves was clearly demonstrated at W7-AS. The EBW's were generated via mode conversion in the O-X-B process. Both, the angular dependence of the O-X-conversion and the parametric instability which is typical for X-B-conversion could be experimentally verified. The position of the narrow absorption profile, estimated from the soft-X emission, could be changed by a shift of the cyclotron resonance layer. Thus generation, propagation and local resonant cyclotron absorption of EBW's was shown, which is an excellent test of hot plasma wave theory.

References

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

[2] T. Meakawa *et al.*, Phys. Rev. Let. **20** (1978).

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

[4] H. Renner *et al.*, Plasma Phys. and Control. Fusion, **31**, 1579 (1989).

[5] E. Mjølhus, J. Plasma Phys. **31**, 7 (1984).