RESONANT ELECTRON BERNSTEIN WAVE HEATING VIA MODE CONVERSION IN W7-AS

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Abstract

Electron cyclotron resonance heating (ECRH) above the plasma cutoff density with electron Bernstein waves (EBW) was investigated and successfully demonstrated at W7-AS stellarator. The EBW's were generated via O-X-B mode conversion heating from an O-wave to an X-wave and, finally, to an electron Bernstein wave. A narrow power deposition profile could be determined from a careful analysis of the soft-X emission at the power switch-off. The deposition could be shifted by changing the position of the cyclotron resonance layer.

Introduction

ECRH with electromagnetic waves is a very efficient method to heat magnetically confined fusion plasmas. However, the accessible plasma density is limited by a critical density (cutoff density). On the other hand, the prospected large stellarator W7-X will have operational regimes above the cutoff density of the proposed ECRH heating system. A possibility to overcome the density limit is the O-X-B mode conversion process proposed by J.Preinhaelter and V.Kopecký [1] in 1973. This process is a general physics phenomenon of EC-waves propagating in hot magnetised plasmas, such as ionospheric or fusion plasmas. Here O, X, and B represent the ordinary, extraordinary and electrostatic mode, the so called electron Bernstein mode. The essential part of this scheme is the conversion of an O-wave launched by an antenna from the low field side into an X-wave at the O-wave cutoff layer. This mode conversion requires an O-wave oblique launch near an optimal angle. The transverse refractive indices N_x of the O-wave and X-wave along a wave trajectory in a density gradient are connected at the optimal launch angle with a corresponding longitudinal (parallel B_0) index $N_{z,opt}^2=(Y/(Y+1))$ with $Y=\omega_{ce}/\omega$ (ω is the wave frequency, ω_{ce} is the electron cyclotron frequency) without passing a region of evanescence ($N_x^2<0$). Therefore power can be transmitted through the plasma cutoff and a fast X-wave is generated. At the upper hybrid resonance (UHR), where the X-mode branch is connected to the electron Bernstein branch, EBW's are generated and propagate, since for EBW's no density limit exists, toward the dense plasma center. A detailed description of the O-X-B mode conversion experiments at W7-AS is found in [2]. In this paper the propagation and cyclotron absorption of the EBW's in W7-AS was investigated and successfully demonstrated.

Ray tracing

Ray tracing calculations were performed in order to get a more detailed insight into the O-X-B-scheme and to show the propagation and absorption of the EBW's. Density, temperature and magnetic field profiles similar to that of a typical neutral beam sustained W7-AS plasma were used for model calculations in a torus. We use the nonrelativistic hot dielectric tensor with a correction for electron ion collisions given by [3] and an isotropic electron temperature. The ray trajectories in the equatorial plane are shown in Fig. 1. The beam is launched from the low field side and propagates through the cutoff, where it is converted into an X-mode. Then it moves back to the UHR-layer, where the X-B-conversion takes place. The EBW's are absorbed near the cyclotron resonance at the plasma centre. A small fraction of the beam power is lost at the UHR due to finite plasma conductivity. The power deposition zone for resonant heating strongly depends on the magnetic field and electron temperature as shown in Fig.1.

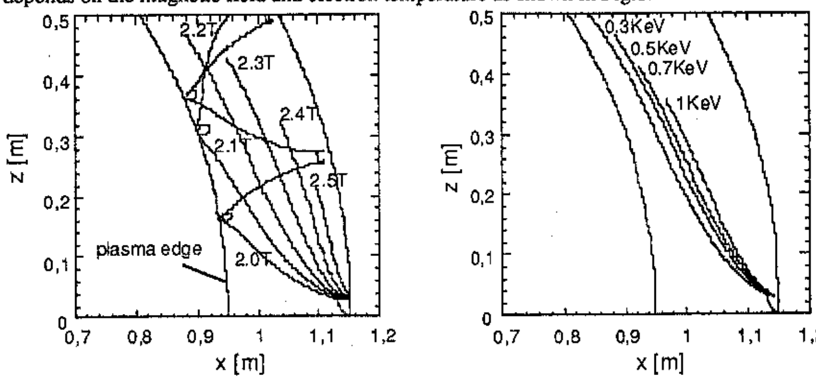

Fig.1 Results of ray tracing calcultions.
Left picture: Ray trajectories of 70 GHz EBW's in a plasma torus for different magnetic fields. The central density was 1.5 $10^{20}m^{-3}$ and the central temperature was 500 eV. In the resonant case the trajectory was calculated until 99% of the power was absorbed.
Right picture: Ray trajectories for different central plasma temperatures at a central magnetic field of 2.2 T and a density of 1.5 $10^{20}m^{-3}$.

EBW's experience a cutoff layer ($N \rightarrow 0$) at the UHR surface, which in the nonresonant or higher harmonic ($\omega_{ce}/\omega < 1$) field totally encloses the inner plasma. The radiation is then trapped inside the plasma like in a hohlraum. The EBW's are either reflected at the UHR surface in the case of an oblique angle of incidence or are back converted to X-waves which are converted again to the EBW's at their next contact with the UHR. Radiation can only escape through the small angular window for O-X- and X-O-conversion, respectively. In the absence of an electron cyclotron resonance in the plasma the EBW's may be absorbed due to finite plasma conductivity after some reflections at the UHR-layer. In the resonant case due to the nonvanishing parallel component $N_{\parallel} \approx N_{z,opt}$ of the refractive index in the oblique launch the cyclotron absorption is strongly Doppler shifted.

Experimental set-up

The experiments were performed at the W7-AS stellarator (major radius R= 2.0m , minor radius a= 0.18m) with two 70 GHz gyrotrons with 170 KW power each. A detailed description of W7-AS and its 70 GHz ECRH system can be found in [4]. The central magnetic field was set between 2.0 and 2.5T and the edge rotational transform ι, 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 1.5 10^{20} m^{-3}, which is more than twice the 70 GHz O-mode cutoff density. The NBI power was 360 KW in co-injection. At the ECRH launch position the stellarator plasma has an elliptical shape similar to D-shaped tokamak. In the equatorial plane the magnetic field as a function of the effective radius r_{eff} is approximately given by the following relation: $B(r_{eff}) = B_0 A / (A - r_{eff} / a)$ 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 1cm.

Experimental results

The soft-X intensity I_{SX} at the detector is approximately given by the following formula:

$$I_{sx}(T_e) = c_{fit}\, n_e^2 Z_{eff} \sqrt{T_e} \exp\left(-\frac{E_{filter}}{T_e} \right),$$

where n_e is the electron density, which we take from the Thomson scattering diagnostic, T_e is the temperature, and E_{filter} is the cutoff energy of the filter (1keV for 25 μm Be). Z_{eff} is assumed to be constant over the radius. At the time of Thomson scattering the linearity of this relation was checked with the Thomson temperature over the full temperature range and a proportionality factor c_{fit} was estimated. Assuming that n_e and Z_{eff} do not change during the ECRH power switch-off the temperature difference is then

$$\Delta T_e = \left(\frac{dI_{sx}}{dT_e} \right)^{-1} \Delta I_{sx}.$$

Since for small time scales the radial heat transport is low, the difference of two soft X-ray profiles with Δt=3ms immediately after the ECRH switch-off represents the upper limit of the relative ECRH absorption profile. The local power deposition was estimated from the heat wave at the power switch-off taking into account the radial symmetry of the temperature profile. In Fig.2 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 2.0T through the center (2.2T) to the low field side at 2.3T with increasing magnetic field, which clearly demonstrates the propagation and the local cyclotron absorption of the EBW's for the first time. In comparison with the ray tracing results the experimental absorption is more Doppler shifted than the calculated one, which may be related to an only rough modelling of the stellarator magnetic field geometry in the ray tracing code.

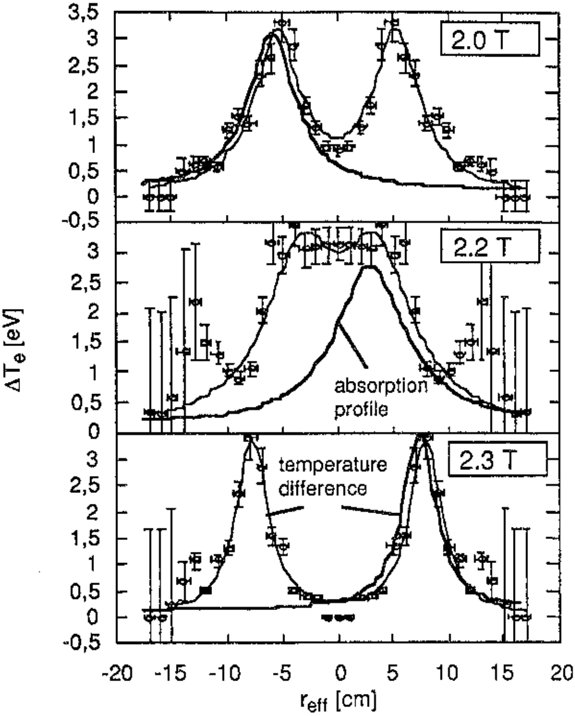

Fig.2
Changes of temperature 3ms after O-X-B heating switch-off and the related ECRH absorption profiles different central magnetic fields.

Conclusions

ECRH of an overdense plasma with 70 GHz electron Berstein waves was clearly demonstrated in W7-AS. The EBW's were generated via mode conversion in the O-X-B process. 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 the propagation and the local resonant cyclotron absorption of EBW's was shown, which is an excellent test of hot plasma wave theory.

References

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