Electron Bernstein Wave Heating and Diagnostic

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Abstract

This article gives a review on the experiments with electron Bernstein waves (EBWs) in fusion devices. The different methods of EBW generation are described and compared with experimental results. The influence of density fluctuation and parametric instability on the conversion efficiency is discussed. The related experiments are reported. The EBW propagation is calculated ray-tracing codes. The results are used to analyse EBW emission (EBE), heating and current drive experiments in Stellarators and Tokamaks. With high power microwave sources EBWs have been excited over a wide range of frequencies for plasma heating and current drive. The experimental results demonstrated that EBW can efficiently heat over-dense plasmas. The local power deposition allows the generation of heat waves for transport studies. Due to their electrostatic character, EBWs can achieve parallel refractive indices ($N_\parallel$) larger than 1, which is favourable for efficient current drive. This could be confirmed by first current drive experiment. The EBWs express also a strong cyclotron damping, which enabled efficient heating at higher harmonics in several experiments.

Content:

1 Introduction

Waves in plasmas have been investigated for many years. The Nobel price for Hannes Alfven was an appreciation of the scientific relevance of this topic. In this article we will deal with wave in the high frequency limit, the so called electron cyclotron (EC) waves. A special kind of EC waves are the electron Bernstein waves, which are short wavelength electrostatic waves in a magnetised “hot” plasma. The interest on electron Bernstein waves (EBW) in fusion plasma physics has strongly grown in the last years. There are several reasons responsible for this. Although many of the theoretical and experimental fundamentals had been set in the years 1960-1980, the application of EBWs was limited by the availability of the appropriate mm-wave technology. First, for heating by EBWs (EBH) no high power microwave sources were on the market. Second, the plasma parameters, which were achieved in fusion experiments at that time were not adequate for a useful application of EBH and EBW-emission (EBE) temperature diagnostics. The development of powerful microwave sources in the frequency range of 28-160 GHz and a power above 100 kW as well as the possibility of over-dense plasma operation in advanced Stellarator, Heliotrons, reversed field pinches and spherical Tokamaks initiated a large number of new experiments. Especially in overdense plasmas operation, where the plasma is inaccessible for the electromagnetic EC waves, EBWs are used for plasma heating, current drive and for temperature measurement.

This review article describes experiments with EBWs in fusion plasmas only. Theoretical papers will only be cited where a deeper understanding of the physics background is desirable and if they are necessary for the interpretation of the experimental results. The large number of table-top fundamental experiments will not be considered here. Only selected papers will be cited in the introduction. The author is aware of the fact the there is no clear cut separation between fusion and non-fusion plasma experiments. Therefore the choice of EBW references for this review was made with the subjective criterion of fusion relevance.

1.1 Physics of electron cyclotron waves

For the treatment of electron cyclotron wave (EC-waves) in fusion plasmas it is generally adequate to describe the wave propagation with the well-known WKB-approximation. Here it is assumed that the typical scale lengths the plasma parameters are large compared with the wavelength and the temporal variation is slow compared with the frequency. In the high frequency limit of the WKB approximation we assume that the ions are immobile and only guarantee the quasi-neutrality, therefore ion motion is neglected. For the electromagnetic type of waves outside the vicinity of a resonance, one can use the “cold” dielectric tensor **K** with the so called “Stix”-parameters S, P and D [1] and neglect the thermal electron motion (cold plasma approximation).

$$\mathbf{K} = \begin{bmatrix} S & D & 0 \\ -D & S & 0 \\ 0 & 0 & P \end{bmatrix} \tag{1.1}$$

$$D = i\frac{\omega_c}{\omega}\frac{\omega_p^2}{\omega^2-\omega_c^2}, \; P = 1-\frac{\omega_p^2}{\omega^2}, \; S = 1-\frac{\omega_p^2}{\omega^2-\omega_c^2}$$

Here ω_c is the cyclotron frequency and ω_p is the plasma frequency. The dispersion relation is obtained from the wave equation.

$$(N \times (N \times E)) + \mathbf{K}E = 0\,, \qquad (1.2)$$

where N is the refractive index vector.
The solvability condition

$$Det\left[(N \times (N \times E)) + \mathbf{K}E\right] = 0 \qquad (1.3)$$

shows the well-known solutions, namely the ordinary mode (O-mode) and the extraordinary mode (X-mode) in case of a propagation perpendicular to the magnetic field.

$$N_o^2 = P\,, \qquad N_x^2 = \frac{S^2 - D^2}{S}$$

For the propagation parallel to the magnetic field the solutions are the R-wave and the L-wave with $N_R^2 = S + D$ and $N_L^2 = S - D$.
For low field experimental devices with EC-frequencies below 30 GHz the typical density scale length reaches the order of the wavelength and the description has to be extended towards a full wave analysis, since the assumptions for WKB are no longer valid.

1.2 *Electron Bernstein waves*

The validity of the WKB-approximation gets lost in case the wave hits the cut-off were the refractive index goes to zero. Here the wavelength is no longer negligible in comparison with the scale length of the relevant plasma parameters. It will be shown later, that this point is important for the excitation of EBWs by mode conversion.
In the case of a resonance, where the refractive index becomes infinite, the cold plasma approximation breaks down, if the wavelength reaches the size of the electron gyro (Larmor) radius. Here the so called finite Larmor radius effects have to be taken into account. Let us therefore introduce the finite Larmor parameter $\mu = 0.5\,k_\perp^2 v_{th}^2 / \omega_c^2$ and the normalised electron thermal velocity $\beta = v_{th}/c$. Here $k_\perp$ represent the k-vector in any direction perpendicular to the magnetic field. We could choose the magnetic field pointing into the z-direction, without loosing the generality. We assume a Maxwellian velocity distribution function and neglect relativistic effects. Finally we express the frequency distance from the nth cyclotron harmonic resonance by $\zeta_n = (\omega + n\omega_c)/\left(|\,k_z\,|\,v_{th}^2\right)$. k_z represents the wave vector components in z-direction. The dielectric tensor can be rewritten as [1]

$$\mathbf{K} = \mathbf{1} + \frac{\omega_p^2}{\omega^2}\zeta_0 \sum_{n=-\infty}^{\infty} \begin{bmatrix} \frac{n^2}{\mu}\tilde{I}_n Z_n & in\tilde{I}_n' Z_n & -n\sqrt{\frac{2}{\mu}}\tilde{I}_n(1+\zeta_n Z_n) \\ -in\tilde{I}_n' Z_n & \left(\frac{n^2}{\mu}\tilde{I}_n - 2\mu\tilde{I}_n'\right) Z_n & i\sqrt{2\mu}\tilde{I}_n'(1+\zeta_n Z_n) \\ -n\sqrt{\frac{2}{\mu}}\tilde{I}_n(1+\zeta_n Z_n) & -i\sqrt{2\mu}\tilde{I}_n'(1+\zeta_n Z_n) & 2\zeta_n\tilde{I}_n(1+\zeta_n Z_n) \end{bmatrix} \qquad (1.2.1)$$

Here the abbreviation $Z_n = Z(\zeta_n)$ and $\tilde{I}_n = e^{-\mu} I_n(\mu)$ are used, where I_n is the nth order modified Bessel function and Z is the plasma dispersion function

$$Z(\zeta_j) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-s^2}}{s - \zeta_j} ds\,.$$

The so called “hot” dielectric tensor expresses several new features for the wave propagation in comparison with the “cold” dielectric tensor. Now, the dielectric tensor is not only a function of ω_c and ω_p, but also a function of the temperature and the wave vector $\vec{k}$. This leads to a new kind of solutions of the dispersion relation, the electrostatic modes. For the first understanding we restrict ourselves to perpendicular propagation ($N_z = 0$). The quantity ζ_n diverges, $1+\zeta_n Z_n$ approximates $-1/2\zeta_n^2$. The solvability condition takes the form:

$$Det\begin{bmatrix} \Lambda_{xx} & \Lambda_{xy} & 0 \\ -\Lambda_{xy} & \Lambda_{yy} & 0 \\ 0 & 0 & \Lambda_{zz} \end{bmatrix} = 0$$

The eigenvectors of the dielectric tensor K are the possible modes of wave propagation. One Eigenvector is immediately obtained from $\Lambda_{zz} = 0$ and has only a z component, i.e. E is parallel to the externally produced B_0. This is a generalization of the ordinary mode, with dispersion relation $N^2 = K_{zz}$. The two other eigenmodes, which have a polarization perpendicular to the incident magnetic field, satisfy the dispersion relation:

$$Det\begin{bmatrix} \Lambda_{xx} & \Lambda_{xy} \\ -\Lambda_{xy} & \Lambda_{yy} \end{bmatrix} = 0$$

Without loosing generality, one can restrict the propagation into the y-direction. Then the dispersion relation becomes:

$$N^2 = \left(K_{xx}K_{yy} + K_{xy}^2\right)/K_{xx}$$

In contrast to the cold plasma approximation the components of ***K*** are function of the unknown *N*, now. Moreover the sum over the Bessel functions gives rise to a large number of possible roots for a given *N*. These new waves are named electron Bernstein waves in honour of Ira. B. Bernstein and of his fundamental article of 1958 [2]. They are harmonics of the electron Bernstein mode. The other solution is the well known extraordinary mode (x-mode). For the approximation of large $\mu = \frac{1}{2}k_\perp^2\frac{v_{th}^2}{\omega_c^2}$, which means short wavelength or large gyro radius, the two modes decouple and an analytical formula for the EBW dispersion relation can be found. It makes us of the asymptotic behaviour of

$$.\ \tilde{I}_n = \frac{1}{\sqrt{2\pi\mu}}\left(1 - \frac{4n^2-1}{8\mu} + \ldots.\right) \qquad (\mu >> 1).$$

The dispersion relation for this so called electrostatic approximation (*E*||*N*) is:

$$\mu = \frac{\omega_p^2}{\omega^2}\sum_{n=-\infty}^{\infty}\frac{n^2\tilde{I}_n(\mu)}{1+n\dfrac{\omega_c}{\omega}}$$

Here also the approximation $Z_n \cong -\frac{1}{\zeta_n}$ was used.

EBWs are characterized by wavelength of the order of four times the electron gyro radius. They are longitudinal waves, which are generated by a coherent motion of electrons around

their guiding center. In that case, as shown in the Figure 1, periodic charge accumulations propagate in the direction of the wave vector. Even though the electric field is perpendicular to the magnetic field the electrons will not express any E×B drift since $\omega \geq \omega_c$ and thus the average electric field will chancel during a gyro motion.
For perpendicular wave propagation with respect to the magnetic field, the imaginary part in the dispersion relation vanishes, which results in an un-damped wave propagation, except in the vicinity of the cyclotron resonance. Close to every cyclotron harmonic resonance (ω=n ω_c) the refractive index becomes infinite and the wave are strongly cyclotron damped as shown in Figure 2 ([3])

It is also remarkable and very useful for plasma application that the propagation of EBWs is not limited by a cutoff density as shown in Figure 3. ere the wave vector remains real with increasing normalised density $(\omega_p/\omega)^2$ .The electrostatic approximation is no longer valid at the upper hybrid resonance (UHR, $f_{UH} = \sqrt{f_p^2 + f_c^2}$), where the X-wave adopts also an electrostatic character. Its refractive index becomes large and the longitudinal electric field dominates. Finally the roots merge and both the X- and EBW-modes coincide; the X-wave is coupled into an EBW and vice versa. In a full wave view the X-wave expresses a longitudinal polarisation which becomes dominant when the X-wave reaches the UHR. In the vicinity of the UHR the phase velocity is strongly reduced until it approximates the thermal velocity. Here the wavelength reduces down the order of the electron gyro radius and an EBW is excited.

1.3 First Experiments with EBWs.

The experimental verification of the EBWs had been demonstrated by Crawford et al. [4] in 1964. Later on, many experiments were performed to measure the transmission and emission of EBW in linear low temperature plasmas devices [5,6]. An overview of these basic experiments is given by Crawford [4]. The author would like to select two representative examples. In the experiments of Landauer [5] the strong EC interaction was demonstrated. There the EBW were excited by an unstable electron distribution function. Landauer could observe emission even at the 20th harmonic. In addition the theoretically expected polarisation dependence was shown. In the experiments of Leuterer [6] the EBW excitation and detection was done by small antennas at the plasma edge. Leuterer could demonstrate forward and backward wave propagation. With the measurement of the phase difference between emitter and detector the dispersion relation could be estimated.
The basic understanding and the experimental verification of the EBW physics initiated plans for using EBWs for fusion plasma heating and for temperature diagnostics. The motivation to use EBWs was, that the well established plasma heating methods and temperature diagnostics with electromagnetic EC-waves have the drawback of the non-accessibility of over-dense plasmas, whereas for EBWs this density limit does not exist. They have a high cyclotron absorption in addition, which offer the possibility for plasma heating at higher (>2) harmonic resonant frequencies, while for electromagnetic EC-waves plasma heating is only useful for frequencies at the first harmonic ordinary and extra-ordinary mode and the second harmonic extra-ordinary mode. Only for special high temperature conditions higher harmonic heating is applicable.

1.4 The Wendelstein-AS Stellarator

The major part of the experimental results, which are presented in this review had been achieved at the Wendelstein7-AS stellarator (W7-AS). Therefore we dedicate a separate chapter to its description.

Stellarators do not suffer from a density limit caused by MHD instability, which make them an ideal tool for investigation of wave physics in over-dense plasmas. Their three-dimensional magnetic configuration offers a higher experimental flexibility. In addition, due to their possibility of current-less operation, even small RF-driven currents can be measured precisely. The Wendelstein7-AS (W7-AS) was a partially optimised Stellarator with modular non-planar coils [7]. Its major plasma radius was 2 m and the minor plasma radius was 0.2 m yielding a plasma volume of about 1 m^3. One of its optimisation criteria was the reduction of the so called Shafranov shift, which is the shift of the plasma center towards the edge at high normalised plasma pressure β. In combination with a powerful neutral beam heating system (NBI) of up to 4 MW extremely high densities of up to 4 10^{20} m^{-3} were attainable. The steep density gradients at the plasma edge, which are typical for stellarators, were even steepened in the region of strong plasma elongation and reached values of up to 5 10^{22} m^{-4}. In addition, at W7-AS, the high confinement mode (H-mode) could be established, which reduced the density fluctuation at the plasma edge. The W7-AS was equipped with a powerful and flexible ECRH system [8]. Both, the polarisation and the launch angle could be adjusted for the different heating scenarios. At the beginning of the EBW-experiments in 1995 W7-AS was equipped with two 70 GHz gyrotron with 180 kW power each, and three 140 GHz gyrotrons with a total power of up to 1.5 MW. In the last experimental campaign the ECRH system was upgraded to one 70 GHz gyrotron with 450 KW power and four 140 GHz gyrotrons with a total power of 2.1 MW. In addition, W7-AS was equipped with magnifold diagnostics, which made possible the observation of the individual processes of the OXB-heating scheme.

2 The excitation of Bernstein waves

EBWs are space charge waves. They do not exist in vacuum, but require a magnetised plasma for propagation. Therefore their excitation is only possible inside the plasma. In the table top experiments described in chapter 1 the EBWs were excited by electrostatic antennas, which were inserted into the plasma. This is not useful for millimetre waves which are necessary in high temperature fusion plasmas, since the antenna structures have to be of the order of the electron gyro radius (<0.1 mm). Such structures cannot survive in the high temperature fusion plasma environment. Therefore only mode conversion from electromagnetic waves is the adequate method to produce EBWs in fusion plasmas. Three schemes, which had been proposed, will be discussed next.

2.1 High field side launch

High field side launch is possible with the first harmonic X-wave only. In contrast to higher harmonics the UHR is not screened by the X-mode right-hand cutoff (R-cutoff) evanescent layer completely, but can be reached by crossing the EC-resonance from the high field side. The slow X-waves approaches the upper hybrid resonance (UHR) were they are converted to EBWs. Since the plasma has to be transparent for the X-waves, this scheme is of interest for plasma start-up and EBW current drive (EBCD). Once the density is above the left-hand cutoff (L-cutoff) no X-wave propagation is possible anymore. Therefore this scheme cannot be used for over-dense plasma heating and will not be treated in detail in this review. High field side launch experiments have already been reported by many authors. The experiment of McDermott et al. [9] at the Versator 2 Tokamak and that of Wilhelm et. al. [10] at the Wendelstein7-A Stellarator should be mentioned, exemplarily. In both experiments the X-B conversion was accompanied by a parametric wave decay, which will be treated in more details in chapter 2.7. At the LATE Tokamak the Doppler shifted power deposition could be measured [11]. Further on, the high field launch was also used to drive current with Bernstein waves [12], which will be treated in chapter 4.2.

2.2 *Direct XB-conversion*

Another method to excite EBWs is to launch an X-wave from the vacuum into a plasma, which has a steep density gradient with a density scale length is of the order of the vacuum wave length of the incident wave. The fast X-mode tunnels through the evanescent region between the R-wave cutoff and the UHR and couples to the slow X-mode which, in turn, mode converts to EBWs at the UHR. This is referred as the X-B mode conversion process. This process involves the R-wave cutoff, located towards the low-density side of the UHR, the UHR, and the L-wave cutoff of the slow X-mode, located towards the high-density side of the UHR. Simply speaking the two cutoffs exhibit an interferometer, such that the wave phases at the UHR are optimal for XB-conversion. In [13] a theory of X-B conversion was derived and shown that the X–B conversion can be efficient over a broad range of frequencies and launch angles.

The power mode conversion coefficient is

$$C = 4e^{-\pi\eta}\left(1-e^{-\pi\eta}\right)\cos^2\left(\frac{\phi}{2}+\theta\right), \qquad (2.2.1)$$

where θ represents the phase of the Gamma function $\Gamma(-i\eta/2)$, ϕ is the phase difference between the slow X-mode propagating toward the *L*-cutoff and the reflected component propagating toward the UHR, and η is the Budden [14] parameter which is obtained by expanding the wave potential around the UHR, to find the location of ξ_R (position of the R-cutoff). In the case that L_B (scale length of magnetic field) >> L_n ($L_n = n_e/(\partial n_e/\partial x$, density scale length), this procedure leads to

$$\eta \approx \frac{\omega_c L_n}{c\alpha}\left[\sqrt{1+\alpha^2}-1\right]^{\frac{1}{2}} \quad \text{with } \alpha = \left.\left(\frac{\omega_p}{\omega_c}\right)\right|_{UHR} \qquad (2.2.2)$$

The mode conversion coefficient consists of a phase independent part

$$C_{\max} = 4e^{-\pi\eta}\left(1-e^{-\pi\eta}\right),$$

which represents the envelope of $C(\eta,\phi)$. Maximum possible power conversion, C=1, can only be obtained, if $(\phi/2+\theta)$ is any multiple of π and $e^{-\pi\eta} = 0.5$, i.e., $\eta \approx 0.22$. The phase factors ϕ and θ, which result from the phasing of the waves in the cavity created by the R- and L-cutoff and are also a function of L_n, can be calculated numerically following [15] and [16]. The phase factors can significantly modulate C as a function of L_n.

Assuming $\alpha \approx 1$, high coupling efficiency is achievable for $\frac{\omega_c L_n}{c} = k_0 L_n \approx 0.3$,

which can only be fulfilled in fusion plasmas for low frequencies (< 20 GHz). This means that the X-B conversion is applicable for low magnetic field, high β devices like spherical Tokamaks, reversed field pinches and for high β stellarators experiments at low magnetic field only. In addition the required adjustment of the phase factor makes the X-B conversion very sensitive to density fluctuation. In

Figure 4 $C_{\max}$ is plotted as a function of the frequency for the spherical Tokamak NSTX [17].

Experiments on this mode conversion scheme have been performed at the CDU-X [18] and NSTX [15] Tokamaks and at the MST reversed pinch [19].

It is more convenient to use the thermal emission of EBWs to measure the conversion efficiency, than to couple the wave into the plasma.

On CDU-X, which is a small spherical Tokamak (R_0= 0.35 m, R_0/a= 1.5, B_0= 0.21 T), the BX-emission was measured by a quadratic wave-guide antenna in perpendicular direction to the magnetic field. The naturally occurring density scale length of L_n=3-6 cm in the scrape-off layer, where the XB-conversion takes place, was too large for efficient mode conversion. Therefore an additional local limiter was positioned in front of the antenna, which created L_n=0.66 cm in front of the antenna. An array of Langmuir probes allowed to measure L_n in the mode conversion region in front of the antenna, so that the conversion efficiency C could be calculated. These probes could be swept to measure T_e or biased negatively to measure electron density n_e. Using these density profiles, the UHR frequency was calculated as a function of major radius. An EBW of a given frequency mode converts when the outgoing wave reaches the radial position at which $f = f_{UH}$. With the local limiter present, the mode conversion for 4–12 GHz occured in the few-centimeter-wide region between the limiter and antenna. The effect of the local limiter on the EBW emission is seen in Figure 5. With the antenna at R =68 cm so that the mode conversion occurs in a region with long L_n, the fundamental emission is observed at a low level (triangles). With the local limiter near the last closed flux surface (LCFS) so that the mode conversion occurs in a region of short L_n, the emission increased by an order of magnitude (diamonds, solid line). For comparison also the second harmonic T_{rad} (diamonds, dashed line) is plotted in Figure 5. There was god agreement with Thomson scattering (squares) and Langmuir probe (circle) T_e data for both fundamental and second harmonic mode-converted EBW emission with L_n shortened by the local limiter.

This was also in agreement with the theory of B-X mode conversion. Here the theoretical mode conversion efficiency C, which was calculated from the n_e profile data from the probes predicts nearly 100% for the observed frequency range in the case of the short L_n produced by the local limiter.

On NSTX, which is a medium size spherical Tokamak (R_0= 0.89 m, R_0/a=1.26, B_0= 0.3T) the variation of L_n was realised by moving the plasma towards a fixed limiter. The change in L_n was detected with a reflectometer system. The antenna was oriented to receive predominantly emission that had the electric field normal to the edge magnetic field during the plasma current flat top. EBW emission was acquired with an 8–12 GHz, frequency-swept, heterodyne radiometer. The EBW ray-tracing calculations showed that the 11.6 GHz EBW emission has its source near the magnetic axis. The ray-tracing calculation used the n_e and T_e profiles measured by Thomson scattering. The T_e profile was relatively flat over a region extending about 40 cm in major radius about the magnetic axis, therefore it was reasonable to use the core T_e when calculating the inferred B–X conversion efficiency, T_{rad} / T_e , at 11.6 GHz. The theoretical B–X conversion efficiency, C, was calculated from the equation 2.2.1. Figure 6 shows a plot of both C and $C_{\max}$ vs L_n. The maximum value of C reaches 98% when L_n falls to

2.5–3 mm. The inferred B–X conversion efficiencies derived from the EBW T_{rad}/T_e measured in the experiment are also plotted in Figure 6 (closed circles). L_n attained in this experiment was about a factor of 2 longer than is needed for ~100% B–X conversion. Note that the error bars actually represent the standard deviation of the fluctuations in T_{rad}/T_e and L_n within the analysis time window, not the uncertainty in these quantities. The measured EBW mode conversion efficiency was in reasonable agreement with the theoretical value of $<C_{\max}(t)>$. The fact that T_{rad}/T_e did not express the $<C(t)>$ behaviour was explained by the broad antenna pattern, which averaged over the different phase factors for different $N_{\parallel}$-components. Although these experiments demonstrated that a high X-B conversion efficiency is achievable by fine adjustment of L_n, they did also show that the conversion efficiency is strongly sensitive on density fluctuations in the conversion region. This will be discussed in more detail in chapter 2.6.

Direct X-B conversion was also detected by measurement of EBE at the MST reversed field pinch [19]. The emission was measured by a broadband double-ridge horn antenna (aperture 5 cm×5 cm), with an antenna gain of 3–17 dB ($\Delta N_{\parallel} = \pm 0.34 - \pm 0.22$) over the bandwidth 3.8–8.2 GHz. The antenna viewed the plasma radially (perpendicular to **B** with $N_{\parallel} = 0$) and was rotatable to receive radiation with $\mathbf{E}_{\mathrm{rad}} \| \mathbf{B}$ or $\mathbf{E}_{\mathrm{rad}} \perp \mathbf{B}$ corresponding to O-mode and X-mode emission from the plasma edge. The emission was detected by a 16 channel homodyne radiometer. Figure 7 shows the radiation temperature measured by the radiometer (T_{EBE}) mapped to plasma radius (r). Ray tracing calculations were used to determine the emission location and include the Doppler shift from the cold EC resonance. By comparing the temperature as measured by Thomson scattering (T_{Thomson}) with T_{EBE} the mode-conversion efficiency could be inferred from the ratio $T_{\mathrm{EBE}}/T_{\mathrm{Thomson}}$ at a given position/frequency. For example, at f=4.0 GHz which corresponds to r=37 cm, $T_{\mathrm{EBE}}/T_{\mathrm{Thomson}}=0.4$. The mode conversion efficiency appeared to increase with frequency. For frequencies higher than 5.75 GHz, harmonic overlap occured, which means that core emission from the fundamental resonance was absorbed at the second harmonic near the edge. The observed levels of emission were consistent with emission from the second harmonic at the edge. The plotted uncertainty represents both the statistical variation associated with the inherent fluctuation levels and the systematic error associated with calibration. The difference between the radiation temperatures for the two polarizations was attributable to the differences in the mode conversion efficiencies from EBW to O-mode and X-mode, the dependence of the mode conversion efficiencies on angle, and the antenna pattern. The viewing geometry used in these experiments was not optimised for coupling to the O-mode. The antenna received only linear polarization while the polarization of the X- and O-modes became elliptical for oblique propagation. For obliquely propagating O-mode the power in X-mode polarization is less than 10% of the power in O-mode polarization taking into account the antenna gain. Therefore it was concluded that radiation received with $\mathbf{E}_{\mathrm{rad}} \perp \mathbf{B}$ is primarily coming from the X-mode.

2.3 *OXB-conversion*

The key problem in generation of EBWs is to produce a slow X-wave, which propagates towards the UHR. This has been demonstrated succesfully in the high field lauch scheme in chapter 2.1 but it is limited for the first harmonic EBWs to low densities only. For higher harmonics the UHR is completelly enclosed by the R-cutoff for the X-waves. Preinhealter proposed a scheme based on two mode conversions [20]. First an O-wave is launched from the outside with an oblique angle of incidence or a non-vanishing parallel refractive index $N_{||}$, respectively. For an optimal value $N_{||,opt}$ there is a coincidence of O-mode and X-mode at the critical plasma density (cut-off), where $\omega = \omega_p$ as shown in Figure 8. This mean that both modes have the same phase and group velocities and the power is transferred without reflections. For the "slab" geometry Preinhealter found an analytical solution for the ray trajectories in the "cold" plasma approximation.

The optimal launch angle can be derived from the dispersion relation for oblique wave propagation as reported in [21].

$$N^2 = 1 - \frac{2X(1-X)}{2(1-X) - Y^2\sin^2\theta \pm \Gamma}$$
$$\Gamma = \sqrt{Y^4\sin^4\theta + 4(1-X)^2 Y^2\cos^2\theta}$$

Here X and Y represent the normalised plasma frequency $X = \omega_p^2/\omega^2$ and cyclotron frequency $Y = \omega_c/\omega$ respectively. The propagation angle with respect to the magnetic field is θ. The upper "+" belongs to the O-mode and the lower "-" to the X-mode. It is seen that for Γ=0 both modes coincide. This happens if θ=0 and X=1. Let us further assume a plasma "slab" with B in z-direction and grad n_e in x-direction. Due to symmetry N_z remains constant. Further, θ =0 is equivalent with N_x and N_y =0 at the critical density X=1. The dispersion relation can be reduced to

$$N_z^2 = \frac{1-X \pm Y}{1 \pm Y}\, for\, X < 1 \text{ and } N_z^2 = \frac{1-X \mp Y}{1 \mp Y}\, for\, X > 1.$$

The upper sign corresponds to O-mode the lower to X-mode. Since $N_z^2 \le 1$ must be fulfilled in the vacuum below X=1 only O-mode propagation is possible. Above X=1 only X-mode can propagate. At X=1 both modes coincide. Therefore the optimal launch angle is given by

$$\sin^2\theta_{opt} = N_{||,opt}^2 = \frac{Y}{1+Y}.$$

For non-optimal launch there is always an evanescent region ($N_x^2 < 0$) below or above the critical density as shown in Figure 9. If this region is small compared with the wave length, a large fraction of the wave power is transmitted though that region. This means, that the O-X-conversion process not only takes place for a certain angle of incidence θ_{opt}, but is possible for an angular window, which depends on the vacuum wave length and the density gradient.

The key parameter here is the normalized density scale length $k_0 L_n$ at the critical density, where $\omega = \omega_p$. Analytic formulas for the angular window were given by Preinhaelter [22], Weitzner and Batchelor [23], Zharov [24] Mjølhus [25]. The four formulas were compared with full wave calculation by Hansen [26]. Best agreement was found for the formula of Zharov and Mjølhus. The latter is the mostly used and shown below.

$$T(N_{\|}, N_y) = \exp\left\{ -\pi k_0 L_n \sqrt{\frac{Y}{2}} \left[2(1+Y)(N_{\|,opt} - N_{\|})^2 + N_y^2 \right] \right\} . \qquad (2.2.4)$$

The full wave calculation also showed, that the analytic formula is a reasonable estimation of T for the condition $k_0 L_n \geq 10$. The O-X conversion shows in some sense a similarity to the Brewster angle in optics, where a beam passes through an interface without reflection, with the appropriate choice of its angle of incidence and its polarisation

Once the X-waves are generated, they propagate up to the high density X-mode cut-off, the so-called L-cutoff. There they are reflected back towards the upper hybrid resonance (UHR).

Up to this point it was sufficient to describe the wave propagation in the “cold” plasma approximation, which means to neglect temperature effects. At the UHR the wave number increases or the wave length decreases respectively, such that it reaches the size of the electron gyro radius and the “hot” plasma approximation have to be taken into account. Here the X-mode coincides with the electron Bernstein mode. In the linear description the X-waves are completely converted into the EBWs. This process is called X-B-conversion. It should be noted, that the OXB-process can only take place if the plasma density is above the O-wave cut-off density.

2.4 Bernstein wave absorption

When EBWs are generated they propagate into the dense plasma until they were absorbed by strong cyclotron interaction near the harmonic resonance. At fusion plasma parameters the absorption is very high and therefore the plasma can be assumed to be optically thick for EBWs. On can consider two absorption mechanism. In the case of quasi perpendicular propagation $N_{\|} < v_{th} / c = \beta$ the absorption is dominated by the relativistic EC-interaction and the deposition is broadened by the relativistic mass increase. In most launch scenarios the condition $N_{\|} > v_{th} / c = \beta$ is fulfilled and the non-relativistic Doppler broadened absorption can be assumed. As an example the absorption coefficient α_{ω}^{B1} for the first harmonic EBW is shown in comparison with the absorption coefficient α_{ω}^{X2} for the second harmonic X-wave.

$$\alpha_{\omega,r}^{B1} = 2\sqrt{\pi} \frac{s}{s_{\perp}} \frac{N}{N_{\|}} k_0 \frac{\tilde{I} X}{\beta^3} e^{-\zeta_{-1}^2}$$

$$\alpha_{\omega}^{X2} = \frac{\sqrt{2\pi}}{8} \frac{G}{N} k_0 \frac{X\beta}{Y} e^{-\zeta_{-2}^2} \text{ with}$$

$$G = \frac{\sin^2\theta}{|\cos\theta|} \left(1 + \cos^2\theta + \frac{\sin^4\theta + 8\cos^2\theta}{\sqrt{\sin^4\theta + 16\cos^2\theta}} \right)$$

The multiplicative factor $s/s_{\perp}$ has been introduced to redefine in radial units (in x direction, corresponding to the radial direction in a toroidal device) the absorption coefficient previously defined as decay rate per unit length in the propagation direction s. In comparison with the absorption of an electromagnetic wave the Bernstein wave features the proportionality with N and with $1/\beta^3$. The refractive index N is usually large, because of the small wavelength of the EBW, while $N_{\|}$ is of the order of unity. For the X2 mode the absorption is mainly proportional with β. Therefore the EBW power is absorbed within a much smaller region then for the electromagnetic wave as shown in Figure 10 and

Figure 11. Interestingly, the absorption of EBWs with a finite $N_{\|}$ increases with decreasing temperature.

Detailed calculation on this topic can be found in [27] and [28]. The arguments above also counts for EBW-emission (EBE), which is strongly localized for EBWs. EBE can be used to measure the plasma temperature since all mode conversion processes are reversible, at least as long as $\nabla B \,\|\, \nabla n_e$. According to Kirchhoffs law, the radiation, which leaves the plasma by BXO-conversion is a measure for the central plasma temperature [29].

2.5 Experiments on O-X-conversion

There are three characteristic footprints for the OX-conversion.

- First there is the angular dependence as shown in chapter 2.3.
- Second there is the mode dependence, which implies that the OX-conversion can only take place for the O-wave. For oblique propagation the O-wave is defined as a left-handed elliptically polarised wave, where the large axis of the ellipse is orientated parallel to the magnetic field.
- Finally there is the density threshold at the O-mode cut-off as already discussed.

At the Wendelstein7-AS Stellarator (W7-AS) all these footprints could be evidenced experimentally.

The angular dependence had been detected for the case of plasma heating by the increase of plasma energy as a function of launch angle [30]. In the analysis the scaling of the energy confinement time with heating power ($\tau_E \sim P^{-0.5}$) has to be considered, this makes this kind of measurement rather uncertain. More precise is the measurement of the electron Bernstein wave emission. The OXB mode conversion process is reversible [31], at least if density gradient and magnetic field gradient are parallel to each other, which is the case for the equatorial launch, therefore the measurement of the XO-conversion is equivalent with the measurement of the OX-conversion. As already discussed in chapter 2.4, in fusion plasmas the optical thickness of the EBWs is much larger than unity even for the higher harmonic resonances. Therefore the plasma is a blackbody emitter for EBWs as it is the case for the well known standard thermal EC emission (ECE) below the cut-off density. The emission intensity is proportional the electron temperature following Kirchhoff´s law. The BX conversion can be assumed to be total for our experimental parameters (see chapter 2.7). The emission intensity is then only a function of central electron temperature and the XO-conversion efficiency. With the knowledge of the electron temperature from other independent temperature measurement, one gets information about the total. In Figure 12 XO-conversion efficiency is plotted as a function of the viewing angle of the EBE antenna. Here the angular window could be measured for the first and second harmonic EBE. The theoretical angular dependence could be reproduced in within the error bars. A similar experiment has been performed at the MAST spherical tokamak for 60.5 GHz EBE [32]. The emitted radiation expresses a narrow angular window of 2° FWHM (full width at half maximum) as shown in Figure 13. The angular dependence could also be demonstrated for the OX-conversion at the TCV Tokamak [33]. In a heating experiment the launch angle was varied in poloidal and toroidal direction. The signal of the non-absorbed ECRH stray radiation [23], [34] shows a minimum at the angular window in both toroidal and poloidal direction as shown in Figure 14.

The arguments, which were mentioned for the use of EBE to detect the angular window, also count for the measurement of the polarisation. In Figure 15 the EBE is shown as a function of both, the direction and ellipticity of the polarization measured at W7-AS [18]. The larger diameter of the polarisation ellipse is orientated parallel to the magnetic field lines. The RF-detector is only sensitive to linear polarised waves, therefore for pure mode detection the radiation the polarisation has to be transformed into a linear one, which is orientated parallel to the maximum detector sensitivity direction. In the experiment first the orientation of the elliptical polarisation was rotated until the maximum sensitivity at the detector is reached. For this a polarisation rotator was rotated from -100° to 100°. In Figure 15a) the sinusoidal variation of the EBE intensity as a function of the rotation angle is shown. At the maximum intensity the circular part of the polarisation was transformed into linear by a quarter wave shifter (elliptical wave-guide) as shown in Figure 15b). Here the maxima and minima represent the O-mode and X-mode radiation part. The latter was interpreted as isotropically polarised EBE stray radiation, which is multiply reflected between the plasma and the metallic vacuum chamber wall.

The third evidence for OX-conversion is its density threshold. Again it could be demonstrated for both heating and EBE at W7-AS [29, 30]. In the case of OXB-heating the plasma was built up by one 70 GHz gyrotron in X-polarisation in a resonant central magnetic field of 1.25T. Then the density was slowly ramped up to a density above the O-cut-off by neutral beam injection (NBI). In parallel as shown in Figure 16 a second 70 GHz beam with O-mode polarisation and with the optimal angle was launched into the plasma. In addition the beam power was modulated with 20% amplitude. During the plasma build-up thermal EC emission (ECE) was detected. As soon as the cut-off density is reached ECE vanished and OXB heating started, which caused an increase of the plasma energy and central soft-x emission shown in Figure 16.

For the EBE measurement the receiving mirror was turned to the optimum viewing angle of 47° with respect to the magnetic field and the plasma density was ramped up to above the cut-off density as shown in Figure 17. The plasma was sustained by two neutral beam injectors (NBI) with 360 kW power each. The central magnetic field was lowered to 2.1 T to compensate the Doppler shift of the EBE-spectrum. This shift origins in the non-vanishing $N_{\|}$ component of the EBW, which were observed by the BXO-process. For comparison the plasma temperature measured with the soft-X filter method for the central line of sight is plotted at the top of Figure 17. This line-integrated temperature measurement is independent on any mode conversion process and was used in combination with the Thomson scattering measurement as a temperature reference. Below, the low field side EBE radiation, the central EBE and the high field side EBE are shown. When the central line density as measured with a microwave interferometer and by Thomson scattering reaches the cut-off density of the emitting frequency, the B-X-O window opens and EBE appears. It is clearly seen that the BXO-window opens at higher densities for higher frequencies.

2.6 The impact of density fluctuation on the mode conversion processes

In our consideration up to now, the conversion layer was assumed to be smooth. In reality it is rough and wavy due to density fluctuations. These fluctuations have mainly poloidally directed wavevectors [35], which introduces an effective poloidal beam divergence much higher than the intrinsic one and can reduce the O-X-conversion efficiency considerably (see Figure 18).
If the fluctuation scale length is large compared to the wave length of the cyclotron waves, a treatment using geometrical optics is adequate. With a statistic description of the cut-off surface roughness (only fluctuations with a wave vector in the poloidal direction were considered), the probability density function of the poloidal component N_y (similar to a poloidal beam divergence)

$$p(N_y)=\frac{\lambda_y}{\sqrt{2\pi}\sigma_x}\exp\left(-\frac{N_y^2\lambda_y^2}{\left(1-N_y^2\right)2\sigma_x^2}\right)\left(1-N_y^2\right)^{-\frac{3}{2}}$$

could be calculated as a function of the fluctuation amplitude standard deviation $\sigma_x = L_n\,\tilde{n}_e/n_e$, where $\tilde{n}_e/n_e$ is the relative fluctuation amplitude and λ_y is the poloidal correlation length [20]. The modified power transmission function T_{mod} (O-X conversion efficiency) is then

$$T_{mod}(N_z)=\int_{-1}^{1}T\left(N_z,N_y\right)p\left(N_y\right)dN_y \ .$$

In Figure 19 the modified transmission is calculated as a function of the parameter $k_0\,L$ for five different relative density fluctuation amplitudes. In all calculations the poloidal correlation length was assumed to be 2 cm, which is in consistency with microwave and laser scattering measurements. It can be clearly seen that a significant heating efficiency is obtained only at a very small density scale length or a very low fluctuation amplitude. This could be verified in the experiments. The edge turbulence level could be changed at W7-AS by the boundary conditions, which means a change of the edge rotational transform $\iota\!\!\!-$ [36]. This has an influence on the density profile shape and the density fluctuation activity. In order to investigate the influence of both on the O-X-conversion efficiency and to proof our statistical model a scan of $\iota\!\!\!-$ was done. The flexibility of W7-AS allows to investigate both extreme cases, i.e. target plasmas with $k_0\,L \leq 10$ and with a relative density fluctuation amplitude of more than 25 % or peaked density profiles ($k_0\,L = 60$) with a relative fluctuation amplitude of less than 2%, which was measured by microwave reflectometer. For both cases, high conversion efficiencies (>70%) were experimentally measured, while for target plasmas with $k_0\,L > 30$ and high fluctuation amplitudes (>20%) only low or no O-X-B heating could be detected [30]. The observation supports our statistical model (see Figure 19).
Similar results had been achieved at the spherical Tokamak MAST [37]. The experiments have first concentrated on the EBE measurement to investigate the mode conversion efficiency. Typically the plasma is well over-dense in spherical Tokamaks. On MAST the EBW emission is studied with a frequency scanning heterodyne radiometer, which covers three frequency bands 16-26 GHz, 26-40 GHz and 40-60 GHz. The experiments have been conducted with the antenna with optimised viewing angle for the B-X-O mode conversion for the frequencies within the radiometer range. An experimentally measured spectrogram (see Figure 20) illustrates the main features of the B-X-O mode converted emission in MAST. As soon as the

plasma density reached the value required for B-X conversion, the EBW signals from several ω_{ce} harmonics appear in the spectrum. The emission from the first two harmonics (and partly from the third) was clearly seen during the initial stage of the discharge. The dark gaps in the spectrum always separate neighbouring harmonics. These gaps correspond to the plasma layers, where cyclotron harmonics are coincident with the UHR and therefore no EBW-emission is expected. The spectral maxima of harmonics moved up in frequency during the phase of the discharge where the plasma current was ramped up, while the toroidal field remained constant. At about 100 ms the emission from the second harmonic had a well-pronounced jump down in frequency from 35 GHz to 30 GHz and simultaneous increase in intensity. At this time the plasma entered the ELMy H-mode. The associated increase in edge density gradient and the usually reduced density fluctuation level enhanced the mode conversion efficiency resulting in the increase of the emission intensity at all harmonics. The L-H transition also shifted the mode conversion layer from the bulk plasma outwards into the lower magnetic field resulting in the frequency jump down. At about 200 ms the plasma had a back-transition to the L-mode resulting in the decrease of the EBW emission intensity. During the second L-phase no significant changes in emission intensity occurred because the electron temperature remains almost constant. The steady drift of the spectrum to higher frequencies was related to the plasma current ramp up from 0 to 180 ms and plasma compression started at 100ms. At the end of the toroidal field flattop at 350 ms the EBW emission spectrum quickly drifted down over the frequency range. Such behaviour was consistent with modelling of thermal EBW emission from the ST plasma. In comparison with the temperature profile measured by Thomson scattering it was concluded that the BXO conversion efficiency can reach up to 100% even for higher harmonics. Unfortunately the reconstruction of a temperature profile from the EBE in a spherical Tokamaks is rather difficult since it requires the knowledge of the actual magnetic configuration, which was strongly varied by the large internal currents. On the other hand the high conversion efficiency had encouraged the development of OXB-heating schemes at MAST. In an initial heating experiments in MAST (60 GHz, 250 kW) first indications of OXB-heating were found by the increase of plasma energy during EBW-heating [37]. The small heating efficiency was attributed to an antenna misalignment.

The XB mode conversion scheme is more sensitive on density fluctuations than the OXB-scheme. For the total XB mode conversion fine adjustment of the phase factor or the distance between the R- and L-cutoff is needed. Here the density fluctuation changes the thickness of the evanescent layer, while for OX-conversion only the angle of incidence is varied, which can be compensated by increasing the angular acceptance angle.

The influence of the density fluctuations on the conversion efficiency was investigated at CDU-X [18]. Large fluctuations in the emission signal were observed. The T_{rad} profiles shown in Figure 5 represent single radiometer sweeps selected at the peak of fluctuating emission within the analysis time window. Vertical arrows show the peak-to-peak fluctuation at 6 GHz and 10 GHz. Evidence that fluctuating L_n is playing a role in modifying C, leading to fluctuating emission, was seen by comparing the T_{rad} and probe I_{sat} time evolution. For several probe tip positions, the cross correlation between these signals was calculated in a time window ~1 ms wide. 70% anti-correlation was observed for the probe located 0.6 cm behind the local limiter and emission at 5.5 GHz, which mode converts near the probe location. The emission peaked when the density behind the limiter dropped, consistent with L_n shortening. Correlation was not seen for probes 2 cm on either side of this location, suggesting that the T_{rad} fluctuation was caused by density fluctuation local to the UHR layer. Variation in L_n was not the only factor leading to T_{rad} fluctuation. One additional effect was changing refraction of the emitted EBW. Ray-tracing calculations indicated that the EBW-emission location viewed was sensitive to the vertical position of the plasma. Correlation between fluctuations in T_{rad} and strong MHD activity may indicate the emission location was oscillating across a region of varying T_e as the changing plasma profile modulates the EBW ray paths. These results indicated that efficient direct XB-conversion is rather difficult to achieve for fusion plasma experimental condition.

2.7 Losses at the XB-conversion

In addition to losses at the OX conversion, we have to consider effects at the UHR, which can reduce the XB conversion efficiency. In the limit of WKB the conversion is total, but taking into account non-linear and wave effects the conversion can be reduced. In addition collisional damping should not be neglected for any conditions.

In case of EBH at high power density non-linear effects can arise. Especially at the UHR the group velocity is strongly reduced, which creates a high energy density und thus a high amplitude the electric field. Here a part of the input wave can decay into daughter waves by the parametric instability (PI). The PI is characteristic for the X-B conversion at high heating power and was already measured in the high field side launch experiments as reported in [9], [10] and [38]. For over-dense plasma heating the PI was measured at Wendelstein7-AS [20] first. This result is important, because the PI is also a footprint of high power XB-mode conversion. For the appearance of the PI several necessary conditions have to be fulfilled. A power threshold has to be overcome. This can be seen in Figure 16: Temporal development of some plasma parameter during an O-X-B heated discharge [30]. From the top: plasma energy estimated from the diamagnetic signal, average density from the interferometric measurement, heating power, intensity of ECE and of the parametric instability (PI), central soft X signal. The markers show the O-X-B heating interval., where with increasing density the OX-conversion efficiency is rising and thus the power density at the UHR. In addition the ECRH power was modulated by 20 % amplitude reduction, while the PI amplitude showed a modulation of up to 80% of the maximum signal amplitude, which clearly shows the non-linear character of the PI. A further condition for the PI is, that beside the resonance condition for the pump wave, in our case the UHR, there must be a resonance for the decay wave. It can be an Ion cyclotron resonance as reported in [9] and [10] or a lower hybrid resonance like in the W7-AS experiments. Figure 21 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 (~900MHz). The reason for the asymmetry in the spectrum is the reduced XO-back-conversion efficiency for the high frequency part. Here the conversion had to take place at a higher density outside the step density gradient region. The spectrum of the 900 MHz LHR oscillation itself, which is shown in Figure 22, could be detected by a loop antenna. The LHR oscillation shows a high degree of correlation with the high frequency decay waves. The power level of the PI is only an order of magnitude above that of the thermal electron cyclotron emission (ECE). Therefore the conversion losses by PI were negligible in the experiments at W7-AS.

At MAST the PI could be detected for OXB-heating, too [39]. During the 60 GHz EC-wave injection a strong increase of lower hybrid frequency wave emission was detected as shown in Figure 23. The PI was rising with density, which implied an improved coupling with increasing density gradient. The theoretical analysis of the non-linear PI-process gave a power threshold of 80 kW for the MAST parameter.

Another loss mechanism can arise in the case where the wavelength is equal or larger than the density gradient length. Here the WKB-approximation fails and wave effects have to be considered. A part of the slow X-wave, which propagates towards the UHR is not converted to an EBW but excites a fast X-wave beyond the evanescent region [40], which leaves the plasma and reduces the XB-conversion efficiency.

Further losses can arise by collisional damping at the UHR, if the UHR is at the cold plasma edge. Due to their small group velocity the waves propagate for a rather long time in the region with non-negligible collisional damping. In case of a flat gradient at the UHR, this effect is of particular importance. More details can be seen in [27].

3 The Propagation of EBW

3.1 Ray-tracing calculation

Following Preinhealters work [20], Meakawa [41] performed ray-tracing calculation with the hot dielectric tensor in the so called “slab” geometry for fusion plasma parameters. He showed that EBWs propagate into an over-dense plasma and deposit the power at the plasma center if the magnetic field is chosen properly. Hansen and Lynov [21] calculated the ray trajectories in three dimensions for the magnetic configuration of the Princeton Large Tokamak (PLT) as shown in Figure 24. In addition they calculated the EBW driven toroidal current. Their simulation for the characteristic density and temperature profiles of PLT showed, that the angular window for an efficient (>50%) OX-conversion was about 2° FWHM. Since the beam divergence of the 28 GHz ECRH beams was nearly 1.5°, a realisation of the OXB-heating seemed to require a rather precise launching system. In addition the effects on conversion by density fluctuations remained unexplored. Many ray-tracing calculations for several experimental devices followed that pioneering works. It is beyond the scope of that review to refer to all of them. EBW propagation is strongly sensitive on the magnetic configuration, therefore for all codes the main difficulty in comparing the ray-tracing results with the experiments is the uncertainty in the magnetic configuration. This problem is more severe for tokamaks than for stellarators, since tokamak confinement is strongly determined by the internal currents, while in stellarators the external coil field is dominating.

3.2 Heat waves and cold pulse experiments

Heat wave and cold pulses are experimental methods to reproduce the ray-tracing calculation and to show the propagation, the resonant absorption and emission of EBWs in overdense plasmas. With the knowledge of the deposition profile these techniques can be used to determine the plasma heat conductivity. The cold pulse experiments at W7-AS were conducted to establish the relation between the frequency of the thermal EBE and the radial position of the emission zone. Temperature perturbations at the plasma edge were induced by carbon laser blow off [29]. The amount of ablated carbon was matched to a value where we could find a sufficiently large temperature decrease in all EBE channels, but with a minimum disturbance of the plasma discharge, especially with no significant density increase. An example is shown in Figure 17 where at 0.34 s the cold pulse occurred. One could identify a steep temperature dip in the edge EBE channels (64.84 GHz, 72.26 GHz), a small dip in the central channel (69.14 GHz) and nearly no change in the average plasma density. In Figure 25 the amplitude and the delay time in which the signal reaches 1/e of the amplitude of the cold pulse are plotted as a function of the emission frequency. Assuming that the cold pulse propagates from the outer radii towards the center, both the amplitude and the delay time indicate that for the thermal part of the spectrum there is a clear relation between the emitted frequency and the radial position of the emission. This means a decaying amplitude and an increasing delay time for frequencies, which are emitted more in the plasma center. In our case the central emission was 70 GHz. For the spectrum above 73 GHz no amplitude variation and no clear phase attachment could be found, which indicates the non-local character of the high frequency part of the EBE. Here is assumed that the radiation originate from different regions inside the plasma. The over-dense plasma is filled with EBW-radiation. The radiation cannot leave the high density plasma region since it is completely surrounded by the UHR. Most of it is reabsorbed. Only those EBW which have achieved an $\mathbf{N}_{\|}$-component which is optimal for BXO-mode conversion is emitted out of the plasma.

The cold pulse technique was also used to show EBW propagation at CDU-X [42]. Here the cold pulse was generated by edge gas puffing. In Figure 26 the radial cold pulse propagation measured by EBE is shown. With modulated local EBW heating heat waves can be generated, which can be used to find the radial power deposition or as a measure for the perturbative temperature transport. At W7-AS the heat wave method has been extended to over-dense plasmas by combining EBWs for heating and as a diagnostic [28]. The plasma cannot be diagnosed and heated at the same harmonic, because the heating beam drives a parametric instability at the UHR layer, where the XB conversion occurs (see chapter 2.7). Such an instability results in high non-thermal peaks overlapping the thermal spectrum. The problem has been overcome by combining EBE measurements at the first harmonic ~66–78 GHz with EBW heating at the second harmonic ~140 GHz, modulated in this case with a frequency of 184 Hz. It should be emphasized that for this purpose the plasma had to be over-dense up to the second harmonic O-mode, i.e., $n_e > 2.4\ 10^{20}\ \mathrm{m}^{-3}$. In particular, the measurements of Figure 27 were carried out for a central density $n_e = 3\ 10^{20}\ \mathrm{m}^{-3}$. A cross-correlation analysis of the response of the EBE channels to the periodic temperature perturbation yielded the heat wave amplitudes and phases. The two amplitude peaks and delay zeros correspond to off-axis power deposition at effective radii $r_{\mathrm{eff}} \sim -3{,}5$ cm and 6.5cm. This asymmetry is probably due to high β effects such as the Shafranov shift, which was not included in the analysis and is expected to remove the systematic 1.5 cm offset. Heat waves can be recognized, in Figure 27, propagating from the deposition regions inward and outward.

Another method to detect heat wave is to measure the soft X-ray emission (SX). This method is not really a local measurement since the line of sight of the individual SX-channels cross the flux surfaces tangentially and one has to reconstruct the profile by Abel inversion. Nevertheless at W7-AS the deposition profile could be found by that method as shown in Figure 28 [43]. Here the magnetic field was varied and the deposition changed from off-axis (high field side) to on-axis and then to off-axis (low field side) with increasing magnetic field.

4 The absorption and emission of Bernstein waves

4.1 Phase space interaction

An effective momentum and energy transfer between the electrons and the waves is only possible if the resonance condition is fulfilled.

$$1 - n\omega_c/(\omega\gamma) - N_{\|}\frac{V_{\|}}{c} = 0\ , \quad \gamma = \left(1 - V^2/c^2\right)^{-1/2}$$

For a given magnetic field or ω_c respectively, the resonance condition defines geometric curves in the velocity space of the electrons, where the perpendicular velocity points in the y-direction and the parallel velocity points in the x-direction. In case of $|N_{\|}|<1$ the resonance curve is an ellipse. For $|N_{\|}|=1$ it is a parabola, while for $|N_{\|}|>1$ it becomes a hyperbola. In addition, a non-vanishing $N_{\|}$-component leads to a shift of the curves along the $V_{\|}$-axis. Usually only changes of the electron distribution function at the collisional time scale are of interest. Therefore one can average over the cyclotron and bounce motion of the electrons. The interaction can then be described by a so-called quasi-linear diffusion operator. For EBWs the situation is quite different compared with the electromagnetic EC-waves like O- and X-waves. The perpendicular refractive index $N_\perp$ is about 40 ore even more, which means that the wave length is of the order of the electron gyro radius or even smaller. In that case the quasi-linear diffusion operator splits into many maxima and the interaction takes place even with the high energy supra-thermal electrons at their resonance condition as shown in Figure 29. The physical reason for the large number of maxima is that not only electrons with gyro radius ρ_e of 1/4 of the EBW wavelength interact with the wave, but also supra-thermal electrons, which satisfy the condition $4(2n-1)\rho_e = \lambda_{EBW}$ as shown in Figure 30. This is a unique property of Bernstein waves.

An asymmetric interaction with the electron distribution function leads to an asymmetric distribution function. Although mainly the perpendicular momentum of the electrons is changed by the EC-interaction, pitch angle collisions cause momentum transfer into the parallel direction. As a result a net motion of the electrons in the parallel direction is obtained, which generates a toroidal current.

4.2 EBCD with high field side launch

Efficient non-inductive current drive (CD) may allow steady state operation of Tokamaks as a fusion reactor. Moreover, for high-density operation and in spherical Tokamaks like NSTX the plasma density can exceed the accessible plasma density for electron cyclotron current drive (ECCD) with electromagnetic waves. For the electrostatic EBW no upper limit exists. Even more, due to their electrostatic character EBWs can achieve parallel refractive indices ($N_\|$) larger than 1. This makes the EBWs an attractive candidate for efficient current drive as postulated in [44].

At the COMPASS D Tokamak EBCD experiments have been performed with 600 kW ECRH at 60 GHz [12]. The EBWs were generated by X-waves launched from the high field side in a low-density plasma of 1.8 10^{19} m^{-3} at a temperature of 3.5 keV. Up to 100 kA EBCD current was estimated from the loop voltage change as shown in Figure 31. Remarkably, the direction of the current was mainly determined by the change of $N_\|$ during EBW propagation and not as usual for ECCD by the launch angle.This could be confirmend by raytracing calculations.

4.3 EBW current drive (EBCD) in over-dense plasmas

Two kinds of EBCD experiments were performed at W7-AS [45]. First, in “current-free” discharges the plasma current was compensated by an inductive current of a feedback controlled transformer. In the second type of experiments, the plasma current could freely develop.

Since the CD efficiency scales like T_e / n_e the experiment were performed with 70 GHz first harmonic EBW-heating at a density of 1.05 10^{20} m^{-3} and at a temperature of 800 eV. An ECRH beam with 0.4 MW power was launched in a current free NBI (0.5 -1MW) sustained target plasma. The magnetic field was adjusted to 2.15 T in order to get central power deposition. Here the large $N_\|$ component of the EBW’s requires a stronger reduction of the resonant magnetic field than for standard ECCD with electromagnetic waves. Since OXB mode conversion needs an optimal launch angle no angular scan is possible to investigate and optimise the driven current. However the $N_\|$ component of the EBW’s could be varied by both, the reversal of the magnetic field and the change of the magnetic configuration, which experimentally implies to place either a local minimum or maximum of the magnetic field at the EBW launch position. In the first case the ray-trajectories remain unchanged but the relation between the magnetic field is changed for co- to counter current or vice versa. In the second case the magnetic configuration changes the direction of the ray-trajectories. Figure 32 illustrates the variation of the beam trajectories and the accompanied $N_{||}$ component. The microwaves were launched always at the same position with the with the optimal launch angle for OX-conversion. For a local maximum the EBW propagate to the left side and the $N_{||}$-component remains negative, while for the minimum B configuration the EBW propagation is to the right and $N_{||}$ becomes positive. Finally, it is the sign oft $N_{||}$, which defines the direction of the driven current.

In the current free discharges all plasma currents are compensated by the inductive current. The loop voltage is then a measure of the plasma currents.

$$R_{Plasma} I_{ind} = -U_{loop} = R_{Plasma}\left(I_{BSC} + I_{NBCD} \pm I_{EBCD}\right)$$

For co- and counter-EBCD the contribution to the loop voltage changes its sign, while the other currents remain unchanged at constant plasma parameters. Beside the EBCD drive current there are also the pressure driven Boostrap current I_{BSC} and the neutral beam driven current I_{NBCD}. The later arises mainly due to the non-balanced neutral beam injection in these experiments.

In Figure 33 the loop voltage signals for discharges with co- and counter-EBCD are shown.

According to the sign of the final $N_{||}$ the loop voltage change is positive for co-EBCD and negative for counter-EBCD. The reason of the positive sign of U_{loop} is that these experiments had been performed at a negative magnetic field in our sign convention. The estimation of the total EBW current in the background of I_{BSC} and I_{NBCD} is rather uncertain since the change of U_{loop} due to EBCD is of the same order as the error bars for the calculated U_{loop} of all other current contributions. Even in absence of EBCD the temperature increase due to EBW-heating changes I_{BSC}, I_{NBCD} and also the plasma resistivity R_{Plasma}. For that reason the analysis was not based on the total U_{loop} value, but on its variation at EBCD switch-on and –off. Therefore the calculated U_{loop} associated with the other currents was adjusted within its error bars to U_{loop} measured before EBCD switch-on. An additional complexity of these studies at the high-density was that the plasma parameters could not be held completely stationary. To get nevertheless a sufficiently precise estimation of the different contribution to the loop voltage, the plasma currents were calculated for a large parameter ranges in the electron temperature T_e, density n_e and the effective charge Z_{eff}. The functional dependencies on these parameters were found by a three -dimensional least square fit. With this, the time slope of the loop voltage could be calculated as a function of the plasma parameters. The T_e and n_e profiles were measured with the YAG-Thomson scattering every 50 ms. For the time in between, the temporal evolution of T_e and n_e was inferred using the softX filter method and the microwave interferometer respectively. Additionally, to improve the calibration of the Thomson scattering the n_e profile was calibrated according to the cut-off for the second harmonic extraordinary mode (X-mode), as detected by the ECE-system. The Z_{eff}–slope was calculated from the Bremsstrahlung intensity. Its value varied around 1.5. As shown in Figure 34 the experimental time slope of the loop voltage could be reproduced by the calculations. Finally, a dimensionless EBCD-efficiency [46] of

$$\zeta = \frac{e^2 I_{CD} n_e R_0}{\varepsilon_0^2 P_{HF} T_e} = 0.43 \pm 0.1\left(\frac{I_{CD}}{P_{HF}}\left[\frac{kA}{kW}\right], \frac{n_e R_o}{T_e}\left[\frac{1}{m^2 eV}\right]\right)$$

could be estimated for both, the co- and counter EBCD case. Here I_{CD}, P_{HF} and R_0 represent driven current, the HF power and the major plasma radius. In numbers this efficiency gives a current of 2±0.5 kA for 400 kW HF power at a density of 1.05 10^{20} m^{-3} and a temperature of 800 eV. Without EBCD the change of plasma temperature would lead to an increase of U_{loop} which is in contradiction with the measurement. In the other type of experiments the plasma parameters were set such, that the bootstrap current was approximately compensated by the NBI driven current. To achieve this the magnetic field had been reversed. The current feedback control was switched off and after EBW heating start the plasma current rose up to 1.2 kA on the L/R_{plasma}-time scale of the plasma as shown in Figure 35. The plasma parameters were n_e = 1.2 10^{20} m^{-3} and T_e = 500 eV. Due to the limited pulse length the stationary condition could not be reached, but the extrapolation to stationary conditions confirmed the measured CD-efficiency of the “current-free” type experiments. The CD-efficiency is also in consistency with the COMPASS-D results taking into account that CD efficiency scales like T_e / n_e and that in a Stellarator the trapped particle fraction is larger than in Tokamaks.

4.4 Theoretical calculation for EBCD

Due to a large $N_{\|}$ value and to the associated strong Doppler shift, the EC-interaction takes place at more than two times the thermal velocity. Thus the quasi-linear diffusion is situated far away from the trapped electron loss cone, as illustrated in Figure 29. The perpendicular refractive index $N_{\perp}$ is about 40**.** With the experimental plasma parameters and with the N-vector from the ray-tracing calculation Fokker-Planck calculations were performed to estimate the distortion of the electron distribution function. For the experimental parameters a driven current of 2.3 kA for co-EBCD and 3.7 kA for counter EBCD were predicted, which overestimates the experimental results by a factor of up to 1.8. Since these calculations are based on the assumption of one ideal single ray, ignoring the broader power deposition of a real beam, this result must be considered as a theoretical upper limit. Nevertheless the favourable properties of the EBWs for current drive are evident from Fokker-Planck calculation.

In this calculation also a supra-thermal population for electrons with 5 times the thermal energy is predicted. Experimental hints for this supra-thermal population could be found in T_e measurements from the soft-X emission with the filter method. Three central lines of sight were equipped with pairs of Be filters of different thicknesses. Therefore the temperature was determined at different electron energies. Before the EBCD the SX-temperatures were approximately equal at 740 eV. As EBCD was switched on the X-ray filter method yielded a rise of T_e, which increases with the thickness of the filter pairs corresponding to the shift of the spectral range to higher electron energies. In numbers, the temperature increases by 55 eV, 95 eV and 145 eV for an electron energy of 2.7, 3.9, and 5.7 times T_e. This is attributed to a non-Maxwellian tail, which is unaccounted for in the T_e analysis. Supra-thermal electrons had also been found in the Heliotron-DR device as reported in the next chapter.

4.5 Further EBW heating experiments

A first evidence of resonant EBW-heating in a fusion plasma was found by Morimoto and Yanagi [46] at the toroidal plasma experiment Heliotron-DR. Here over-dense plasma generation was demonstrated with 28 GHz ECRH with up to 200 kW power. In fact, microwaves were neither launched with O-mode polarisation, nor with the optimal OXB-launch angle, but the power density was up to 2.4 MW/m^2, which was much more than the other ECRH-experiments at that time. In addition a rather high density gradient could be achieved at Heliotron–DR, such that the angular window for OX-conversion was above 20° FWHM. The antenna was a rigid open wave-guide perpendicularly targeting at the plasma surface. The waves were launched with a polarisation perpendicular to the magnetic field (X-mode). As shown in Figure 36: Experimental traces for EBW-heating at the Heliotron-DR device. From the top: Electron density, plasma energy, hard- and soft-X-ray emission. the plasma energy strongly increased when the plasma density passed the O-wave cut-off, which is a characteristic threshold for OX-conversion. Therefore it was assumed that by multiple reflections of the microwaves at the vacuum chamber some part of the power was scattered into the optimal angle and polarisation for OX-conversion. Although the magnetic field dependence of the heating efficiency remained unexplained, over-dense plasmas could be created up to the fifth harmonic resonance. This was an additional evidence for EBW-heating, since only EBWs experience remarkable cyclotron absorption at those plasma parameters. In addition, power switching experiments showed a central power deposition. A further interesting observation was, that even at high density supra-thermal electrons appear, which is due to the special kind of phase space interaction of the EBWs.

All the W7-AS experiments which were reported hitherto have been done with 70 GHz ECRH at the first and second harmonic resonance. The so-called high-density H-mode (HDH) [47], which was found with divertor operation at W7-AS, has opened promising properties for OXB heating with 140 GHz [48]. The central density in Figure 37 exceeded 3.5 10^{20} m^{-3} and the density scale length at the ECRH launch position was 0.5 cm. The density profile was measured by Thomson scattering. OXB-heating with 70 GHz was not efficient because in th HDH regime the separatrix density was above the UHR-density. Thus the X-B-conversion took place outside the LCFS, at the magnetic island structure and the main part of the EBW were lost at the edge by collisional damping and probably diffraction effects. Often the separatrix density exceeded even the O-wave cut-off of 0.6 10^{20} m^{-3} and thus the mode conversion was out of the steep density gradient region, which is required for efficient OX-conversion.

Three 140 GHz beams with a total power of 1.5 MW were launched into a NBI sustained (up to 4 MW) HDH-plasma. Due to technical limitation only 1.1 MW ECRH power had reached the criteria for OXB-conversion. The ECRH launch was optimised with respect to the angular window necessary for efficient EBW generation. Here the optimisation criterion was the increase of plasma energy shown in Figure 38 and the reduction of the non-absorbed ECRH stray radiation [24]. Further on, a magnetic field scan was performed to achieve central power deposition. The deposition profile was estimated by power modulation and coherent heat wave detection with the EBW emission diagnostic (EBE) [6], [7]. Even though the first harmonic EBE (60-80GHz) was damped at the UHR the phase shift and the amplitude decay clearly showed the local power deposition profile of the 2nd harmonic EBW heating. Here we have got a power deposition at an effective radius of about 4 cm as shown in Figure 27, more details on the heat wave experiments had been already shown in the chapter 3.2. The EBW-heating increased the power flow across the separatrix, which initiated a transition from detachment to attachment. Therefore the increase of plasma energy is not an adequate measure of the heating efficiency. It is more realistic to compare EBW- with NBI-heating efficiency. For this two NBI beams with 0.5 MW power each were replaced by about 1.1 MW ECRH. This did not degrade the plasma performance, thus demonstrating that, the EBW heating efficiency was comparable with that of NBI-heating as shown in Figure 39. Even more, EBW heating becomes more effective with increasing density. In contrast to NBI, which gets more off-axis deposited with increasing density, the EBW power absorption remains unaffected and the OX-coupling efficiency is improving with increasing density gradient.

One key issue for commercial fusion reactors is the stability at high beta values at limited heating power. High beta experiments at W7-AS were performed at low magnetic field [48]. For a fixed ECRH-frequency (140 GHz) this requires heating at a higher harmonic resonance. The plasma is usually optically thick for even higher harmonic EBWs. Nevertheless the plasma density has to surpass the threshold for OXB-conversion. The accessibility of the plasma core can further be restricted by the appearance of the next resonance at the plasma edge. Therefore the experiments have mainly been concentrated on the third and fourth harmonic heating at a magnetic field of 1.5-1.6T and 1.0-1.2T respectively. At least 3 MW of NBI heating was necessary to sustain the OXB-threshold density at that low magnetic field. Due to the confinement time degradation with heating power ($\sim P^{-0.5}$) only small effects on the plasma parameters could be expected by additional EBW-heating 1.1 MW power. Nevertheless in a magnetic field scan clear resonance effects could be found. The largest increase of the average plasma beta was found at 1.1 T. The power was mainly deposited at half the plasma radius. Central power deposition was not possible due to the appearance the next harmonic resonance at the plasma edge. The off-axis deposition was confirmed by the tomographic reconstruction of the change of the SX-emission at the ECRH switch-off shown in Figure 40, which indicates a maximum at half the plasma radius. With the ECRH stray radiation diagnostic the total efficiency of OX- coupling could be estimated. An example is shown for the third harmonic EBW-heating in Figure 41 The maximum stray radiation was found near the cut-off density. Assuming that no power is coupled to the plasma in that case, a reduction of the stray radiation down to 20% with increasing density indicates that 80% of the ECRH radiation has been absorbed in the plasma. Of course some part of the ECRH power may have been absorbed at the plasma edge without a large contribution to the increase of plasma energy.

A similar experiment was performed at the large helical device LHD [49]. Here in a scan of the OXB-injection angle the maximal increase of the central temperature was achieved when the stray radiation was minimized.

4.6 Further EBW emission experiments

On NSTX efficient OXB-mode conversion of up to 80%±20% was found in EBE experiments [50]. A quad ridged antenna with a lens in front was used to measure the emitted microwave radiation of 16.5 GHz (first harmonic resonance frequency in the plasma centre) with a viewing angle optimal for OX-conversion as shown in Figure 42 . The temporal behaviour of the EBE signal could be reproduced by 3D ray-tracing calculations taking into account the magnetic equilibrium as well a the density and temperature profiles from Thomson scattering measurements. The assumed Gaussian beam profile was simulated by a bundle of 41 rays. The OX-mode conversion was modelled by a full-wave calculation, which predicts a coupling efficiency of 65%. With the quad ridged antenna both orthogonal linear polarisations could be measured. The linear O-mode to linear X-mode ratio was 1.2±0.4 shown in Figure 42, which was lower than the predicted ratio of 1.6 for pure oblique O-mode emission. Here oblique O-mode radiadion is mainly circularly polarised. The higher X-mode content could probably origin from EBE stray-radiation as already mentioned in chapter 2.5. The measurement also shows a strong fluctuation of 30% in the EBE-signal. This was attributed to the density fluctuations at the plasma edge, which are typical spherical Tokamak operation in L-mode.

5 Summary

EBWs are used in many fusion experiments, now. Their theoretical description is well established and verified by many experimental results. Both mode conversion schemes had been investigated. Efficient direct XB-conversion requires a normalized density scale length of $k_0 L_n \approx 0.3$ and is very sensitive to density fluctuations. Therefore direct XB conversion is only applicable for low frequency (<20 GHz) EBW-heating. For higher frequencies the OXB-mode conversion seems to be advantageous compared with the direct XB-conversion. The required density scale length of $10 < k_0 L_n < 40$ is easier to achieve. Even more the sensitivity on density fluctuations can be reduced by decreasing $k_0 L_n$. The best results in mode conversion had been achieved with H-mode like plasmas, which combine a steep density gradient with a low fluctuation level at the plasma edge. Furthermore the EBW-heating could be demonstrated not only for the first harmonic resonance, but for higher harmonics, too. The experimental frequency ranges was from 10 GHz up to 140 GHz. The reverse mode conversion process can be used to measure thermal EBW emission (EBE). The EBE measurement had become a routine diagnostic for temperature profiles and heat wave analysis in over-dense plasmas at W7-AS. The OXB- EBWs can achieve $N_{||}$ components >1, which makes them a good candidate for efficient current drive. Current drive with EBW could be demonstrated at the Compass-D Tokamak and the W7-AS Stellarator. In both experiments the predicted high current drive efficiency was found. Presently, new low frequency (28 GHz) ECRH systems for EBW-heating and current drive are being build up at the WEGA and TJ-II Stellarators.

6 Figure Caption

Figure 1 : Schematic description of EBW propagation. The electrons gyrating around their guiding centre in phase with the electrostatic wave, which creates periodic charge accumulation with a wave length four times the gyro radius.

Figure 2: Dispersion relation of EBW adapted from [3]. Here the frequency is normalized by the cyclotron frequency ω_c and the wave vector is normalized by the thermal electron gyro radius ρ_e.

Figure 3: Density dependence of EBW dispersion relation for the electrostatic approximation between the first and second harmonic resonance. EBWs show no upper density limit, but can be excited at densities above the upper hybrid resonance only. No BX-coupling is incorporated in the electrostatic approximation. In reality the EBWs are converted into X-waves before reaching the UHR as sketched by the green line.

Figure 4: Maximal conversion C_{max} as a function of frequency for typical NSTX plasma parameter [13].

Figure 5: The radiation temperature without the local limiter (red triangles). With the local limiter, the peak fundamental emission (black diamonds, solid line) and second harmonic emission (black diamonds, dashed line) together map out the T_e profile and are consistent with T_e measured by Thomson scattering (blue squares) and Langmuir probe (circle). Error bars are shown for selected points. The emission fluctuation levels at 6 and 10 GHz are indicated by vertical arrowed lines.

Figure 6: Plot of the theoretical maximum B–X mode conversion efficiency, C_{max} and the theoretical B–X mode conversion efficiency (C) vs. L_n at the B–X mode conversion layer, for 11.6 GHz EBW and the edge conditions at NSTX. Also plotted is the measured T_{rad} /T_e from the experiment (closed circles). Error bars indicate the fluctuation amplitude of T_{rad} and L_n within the 0.28–0.32 s analysis time window.

Figure 7: Spectrum for O- and X-mode EBE radiation temperature mapped to minor radius at the MST reversed pinch [19]. Also shown is the electron temperature measurements from Thomson scattering. The vertical dashed line separates two cyclotron harmonics.

Figure 8: Refractive index (perpendicular component) of a wave launched with $N_{z,opt}$ from the vacuum in a plasma with a density gradient in x-direction. The O-mode coincides with the X-mode at $\omega = \omega_p$.

Figure 9: $N_\perp^2$ of a wave, which was launched with different launch angles into a plasma with a perpendicular density gradient.

Figure 10: Absorption coefficient α, optical thickness τ and reabsorption-corrected emissivity $\hat{j}$ for oblique 2nd harmonic X-mode. Doppler-broadening prevails over the relativistic one (compare with Figure 11).

Figure 11: like Figure 10 but for 1st harmonic B-mode in double density, half temperature plasma. Here the absorption is completely dominated by Doppler-broadening. Notice different units on vertical axis.

Figure 12: Angular dependence of EBE for different central magnetic fields, for central density of 1 $10^{20}\mathrm{m}^{-3}$ and temperature of 600 eV. The signal is normalised to the central soft-X temperature. The solid line represents the expected shape and position of the angular window. The maximum transmission was fitted to the experimental values.

Figure 13: Measurements of EBW emission at a frequency of 60.5 GHz undergoing B-X-O mode conversion, for various viewing angles. The conversion efficiency degrades with different rates as the line of sight deviates toroidally (left) or poloidally (right) from the optimal direction [28]. The solid lines (spline fit) should illustrate the angular window.

Figure 14: Variation of the stray radiation level as the function of the poloidal (a) and toroidal (b) angle of the ECRH antenna launcher. The 100 % level was determined by the maximum of the stray radiation power. The solid curves represent polynomial regression fits to the data.

Figure 15: Experimental dependence of the EBE polarization on angular settings of

a) the polarisation rotator ϕ_{rot} and b) the quarter wave shifter (elliptical waveguide) ϕ_{ell}. During the rotation of ϕ_{ell} the value ϕ_{ell}-2ϕ_{rot} was held constant to compensate the rotation of the main axes of the polarisation ellipse by the quarter wave shifter.

Figure 16: Temporal development of some plasma parameter during an O-X-B heated discharge [30]. From the top: plasma energy estimated from the diamagnetic signal, average density from the interferometric measurement, heating power, intensity of ECE and of the parametric instability (PI), central soft X signal. The markers show the O-X-B heating interval.

Figure 17: Signals of an NBI sustained discharge with a density ramp. From the top: soft-X temperature, radiation temperature of the low field side edge EBE, central EBE and high field side edge EBE and central density. The temperature dip at 0.34 s is due to a perturbation induced by carbon laser blow off.

Figure 18: Non-optimal slopes at the turbulent cut-off layer. The transmitted power is the sum over the beamlets and is degraded vs. the laminar case, since the local angle of incidence differs from the average angle.

Figure 19: Modified O-X-conversion in the presence of density fluctuations at the plasma cut-off layer versus normalised density scale length k_0L_n for different relative fluctuation amplitudes.

Figure 20: EBW emission spectrogram measured during high density plasma shot #7798 in MAST [37]. Red areas correspond to higher emission intensity. ECRF power was injected at 0.21-0.24 s. Below there are the plasma current, the position of the last closed field surface (LCFS) and the current of the toroidal field coils.

Figure 21: High frequency decay spectrum for 70 GHz OXB-heating. The 70 GHz pump wave is excluded by a Notch-filter.

Figure 22: Low frequency decay spectrum near the LH-resonance frequency. The decay waves were measured by a loop antenna.

Figure 23 a) RF power injected into the plasma, b) line integrated density c) lower hybrid emission for EBW heating experiments at MAST [39].

Figure 24: Ray trajectories in the toroidal (top) and poloidal (center) cross-section of the PLT Tokamak . At the bottom the beam power is plotted over the large plasma radius. When the beam was launched into the plasma with the proper launch angle it crosses the cut-off density ($\omega = \omega_p$), where it is converted into a X-wave. It is reflected towards the UHR, where it is converted into an EBW. This wave propagates into the over-dense plasma center, where it is absorbed by cyclotron damping as illustrated in the bottom figure.

Figure 25: Amplitude decay (left) and delay time (right) of the 1/e amplitude as a function of EBE frequency. Indicating the inward propagation of the temperature perturbation induced by carbon laser blow off at the plasma edge, thus demonstrating the localisation of the radiation origin.

Figure 26: Plot of heat pulse versus major radius at CDU-X [42] comparing χ_e model to data from fast-scanning EBW radiometer. The shaded region corresponds to model parameters covering χ_e = 3.2±2.2 m^2/s and $r_{perturbation}$ =7.6±3.3 cm, i.e., a perturbation localized around $r_{perturbation}$ =7.6±3.3 cm , i.e., a perturbation around $r_{perturbation}/a \sim 1/3$.

Figure 27: Heat wave amplitude and phase generated by off-axis 140 GHz 2nd harmonic EBW heating and reconstructed from 1st harmonic electron Bernstein wave emission (EBE). The reason for the apparent asymmetry of the power deposition is due the strong Shafranov shift of the plasma, which could no be taken into account completely in the EBE temperature profile reconstruction.

Figure 28: Changes of temperature 3 ms after O-X-B heating switch-off and the related ECRH absorption profiles different central magnetic fields [43]. The profiles were reconstructed from the line integrated soft-X signals. By changing the magnetic field it could be verified, that the EBW power deposition is moving from the high field side (top figure) through the center toward the low field side (bottom picture).

Figure 29: Contours of the electron distribution function in a logarithmic scale as a function of the parallel velocity V_{par} and of the perpendicular velocity V_{perp}. Both are normalised to the thermal velocity. The grey structure is the quasi-linear diffusion operator for EBWs with $N_{\|}$ =1.0. The calculation was limited to $|V|<8V_{thermal}$ [45].

Figure 30: Schematic description of EBW interaction with electrons with different gyro radii. The periodic charge accumulation is performed by the electrons with a gyro radius 1/4 of the EBW wave length and electrons with gyro radii of 3/4 the EBW wave length. With a half gyro cycle the maxima and minima of the charge density are exchanged by the electron gyro motion.

Figure 31: Non-inductive current driven in the plasma estimated from experimental data of the COMPASS D tokamak and the net current from ray-tracing simulations [12].

Figure 32 Top: Ray trajectories in the equatorial plane for different magnetic configurations at the Wendelstein7-AS stellarator. The parameter I_s/I_m is the ratio of two coil set currents which defines wheather there is a local maximum (I_s/I_m=1.2) or minimum (I_s/I_m=1.0) of the magnetic field at the ECRH-launch position. Bottom: Variation of $N_{||}$ for the according ray traces.

Figure 33: Change of loop voltage during co- and counter EBCD (0.4-0.65s) at Wendelstein7-AS. Since the magnetic configuration was different for the two cases, the signals refer to different scales.

Figure 34: Calculated loop voltages (grey) for EBW heating only (top trace) and with additional counter current drive (lower trace) in comparison with the measured loop voltage (black curve) at Wendelstein7-AS. The consistency with the measured loop voltage yields a dimensionless CD efficiency ζ=0.43. The resulting EBCD current (bottom trace) is then a function of T_e, n_e and P_{HF} . The later was modulated with 20% amplitude.

Figure 35: EBW current drive without inductive current compensation at Wendelstein7-AS. Top: Power signals for NBI and modulated ECRH (EBCD). Bottom: Plasma current during EBCD.

Figure 36: Experimental traces for EBW-heating at the Heliotron-DR device. From the top: Electron density, plasma energy, hard- and soft-X-ray emission.

Figure 37: Density profile for the normal confinement mode (NC) and the high density H-mode (HDH) at the Wendelstein-7 AS stellarator. For the first harmonic cyclotron frequency heating with 70GHz the UHR is outside the LCFS for the HDH-mode plasma.

Figure 38: Increase of plasma energy at W7-AS due to second harmonic Bernstein wave heating (B2) with 140 GHz.

Figure 39: Comparison of second harmonic OXB-heating with NBI-heating. A constant density of 3.5 10^{20} m^{-3} was reached at 350 ms.

Figure 40: Change of the SX-emission (tomografic reconstruction) after ECH switches off. The grey scale is linear and in arbitrary units.

Figure 41: Total coupling efficiency for the 140 GHz waves, deduced from the stray radiation level in the torus, versus the central density.

Figure 42: Top) Time evolution of the sum of the absolutely calibrated radiation temperature measured by EBW emission at NSTX. Bottom) The ratio of the radiation temperature measured by radiometer1 divided by the radiation temperature of radiometer 2. The thicker black line in the two figures shows the same radiometers tuned to receive 16.5 GHz data time averaged with a time constant of 3.3 ms. The shaded area indicates the time period when the magnetic field pitch at the last closed flux surface on the plasma outboard midplane, as calculated by EFIT magnetic equilibrium code, lies between 35° and 40° and therefore optimal for the antenna to receive mode-converted EBW emission.

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