Electron Bernstein Waves at the WEGA Stellarator – Heating and Emission

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This paper gives an overview of recent results on the application of electron Bernstein waves for plasma heating and diagnostic purposes at the WEGA stellarator. By applying a two-step mode conversion process it was possible to reach over-dense argon and helium plasmas with central densities of above $0.97 \times 10^{19}\,\mathrm{m}^{-3}$ at a magnetic field strength of 0.5 T fully sustained by electrostatic Bernstein waves. An unexpected feature observed during the experiments was the detection of a strong increase of the radiation temperature associated with the existence of a super-thermal electron component in the keV-range during this heating period.

Keywords: stellarator, Bernstein wave, over-dense plasma, supra-thermal electron

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1. Introduction

The application of electron cyclotron resonance heating (ECRH) for high density and high beta operation in magnetically confined plasmas is limited due to reflections of the heating wave at the associated density cut-off that prohibits a propagation into the central plasma region. However, over-dense operation in stellarators can be achieved by an alternative heating concept utilizing electron Bernstein waves (EBW) [1–3]. These electrostatic waves, once excited, are not limited by an upper density so they can propagate inside the over-dense plasma until they are absorbed when the resonance condition is fulfilled. The propagation is linked to coherently gyrating electrons as medium, hence Bernstein waves can not directly coupled from the vacuum to the plasma. The generation of these waves bases on the conversion of an electromagnetic wave into an electrostatic Bernstein wave. At WEGA a two-step conversion process was chosen, starting with an electromagnetic wave (second harmonic) in ordinary (O)-mode polarization. This wave propagates up to the O-mode cut-off where a part is converted into an extraordinary (X)-mode wave. In the second step the X-mode wave can propagate to the upper hybrid resonance (UHR) layer where it is finally converted into the electrostatic Bernstein wave. This process is called OXB-mode conversion in the following. Moreover, by reversing the mentioned mode conversion process Bernstein waves can also be used as a diagnostic tool to determine the radiation temperature of the plasma. However, a more direct indication of the existence of EBWs e.g. by means of probe measurements was not possible because of their small wave length which is of the order of the Larmor radius.

2. Experimental Setup

WEGA is a classical five period and $l = 2$ stellarator with a major radius of $R = 72$ cm, a minor radius of the vessel of $r = 19$ cm and a maximum plasma radius of $a \approx 11$ cm [4]. WEGA is generally used for educational purposes, basic plasma research as well as for diagnostic development and the test of the prototype installation of the Wendelstein 7-X control system. The magnetic field coil system allows quasi-steady state operation at 0.5 T for about 20 s. At this field strength a maximum rotational transform of $\iota/2\pi = 0.4$ can be reached, which is a limiter configuration. The limiting components are either the plasma wall or the microwave antenna system of the 2.45 GHz ECRH. Furthermore, WEGA is equipped with a set of vertical field coils used for shear variation and radial plasma shifting. In combination with an additionally installed error field compensation coil WEGA has a very flexible magnetic configuration.

2.1 Diagnostics

In the following an overview of the diagnostics used to obtain the experimental results is given. The central line-integrated density was determined by a single-channel 80 GHz interferometer. Because the electron density and temperature in typical WEGA plasmas are sufficiently small, typically in the order of a few 10 eV, Langmuir probes can be used inside the whole confinement region without restrictions. For the experiments discussed in the following a single Langmuir probe installed on a fast reciprocating manipulator allowed the determination

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of the radial profiles of the density and electron temperature from the plasma edge up to the center within 1 s. With the help of a 12-channel radiometer microwave radiation emitted in the range between 22-40 GHz from the plasma could be detected. Furthermore, a spectrum analyzer allowed to measure the whole spectrum continuously with an integration time of 300 ms. The radiometer was absolutely calibrated with the hot-cold technique at room- and LN_2- temperature. With the help of this radiometer and associated antennas inside the plasma vessel the detection of electron cyclotron emission (ECE) and electron Bernstein emission (EBE) due to the reversed conversion process from Bernstein waves to X- and O-mode waves was possible. The radiation temperatures discussed in the following have been obtained with an antenna system looking under an oblique angle of 55° with respect to $\vec{B}$ which is optimal for EBE. Furthermore, the non-absorbed 28 GHz stray radiation was determined by a sniffer probe. Additionally the plasma radiation can be determined utilizing a 12-channel bolometer and a fast 16-channel AXUV-diode array which have been developed as prototype diagnostics for Wendelstein 7-X and which are covering nearly the whole confinement region of WEGA. For the detection of possible highly-energetic electrons a soft X-ray detector was installed, which is sensitive in a range of about 1-15 keV.

2.2 Plasma heating systems

At WEGA three different heating systems are available. When operating at a low magnetic field strength of about 87.5 mT two 2.45 GHz electron cyclotron heating (ECRH) systems with a total power of 26 kW, cw are available. With this system OXB-mode heating has been already successfully demonstrated. It was possible to reach plasma densities of $n_e \geq 10 \times n_{c,o}$ with an O-mode cut-off density of $n_{c,o} = 2\pi f \epsilon_0 m_e/e^2 = 7.45 \times 10^{16}\,\mathrm{m}^{-3}$ at a low magnetic field of about 57 mT [5]. However, at 0.5 T operation this system can also be used as a non-resonant heating method. Additionally, a 5-arm transformer with a capacity of 440 mVs is available for pre-ionization and current drive. The EBWs have been generated with a 10 kW, cw gyrotron operating at a frequency of 28 GHz (second harmonic) ECRH system dedicated for 0.5 T operation. In order to achieve the critical density threshold for the O-mode cut-off of $n_e = 0.97 \times 10^{19}\,\mathrm{m}^{-3}$ a highly efficient conversion system had to be established because of the low emission power density of $10\,\mathrm{kW}/0.15\,\mathrm{m}^3$ only available at WEGA. The gyrotron emitting in the TE_{02}-mode is connected to the plasma vessel via a waveguide transmission line necessary for the stepwise transformation into a TE_{01}, then a TE_{11} and finally into an elliptically polarized HE_{11}-mode. The HE_{11} mode is nearly a free space Gauss'ian beam which is needed for quasi-optical transmission.

The transmission line, aligned radially with respect to the plasma vessel and in the horizontal plane, includes a polarizer and ends up into a quasi-optical antenna system, which consists of two elliptical mirrors providing optimal launching conditions for the OXB-mode conversion. The beam with a width of about 4 × 2 cm in horizontal and vertical direction, respectively, is focused in the gradient zone on the low-field side of the plasma in the vertically elongated symmetry plane. The mode conversion takes place inside the gradient region of the plasma where the smallest value of the normalized gradient length $L_n = n/\,\mathrm{grad}\,n$ is expected. The total O-X-conversion efficiency is $\int_{-1}^{1}\int_{-1}^{1} f(N_\parallel, N_\perp)\, T(N_\parallel, N_\perp)\, G(N_\perp)\, \mathrm{d}N_\parallel\, \mathrm{d}N_\perp$. Here, f represents the N-spectrum originated by the quasi-optical imaging, T is the O-X-conversion efficiency, which depends on L_n, and G is the distribution of the local $N_\perp$, which is generated by the poloidal density fluctuation (wavy surface). Thus even for optimal $N_\parallel$ the total O-X-conversion is less than one and a reduction of L_n improves the efficiency.

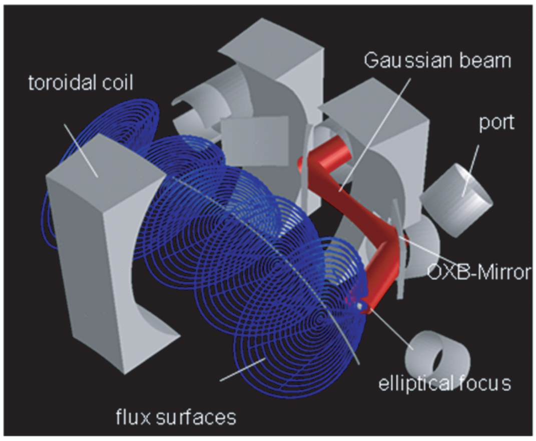

Fig. 1 Setup of the focussing mirror system inside the plasma vessel. The beam trajectory is indicated in red, the magnetic flux surfaces in blue.

The setup of the mirror arrangement as well as the beam trajectory and the magnetic flux surfaces inside the plasma vessel are shown in Fig. 1.

3. Results

The propagation of possibly excited Bernstein waves was calculated using a 3D ray-tracing code including the measured density profiles [6,7]. The prediction of the code showed a propagation of the EBWs starting at the UHR layer into the direction of the density gradient. However, a propagation in less dense plasma outside the UHR layer is prohibited. In the calculations no ray-tracing is performed from the antenna to the UHR. Instead, straight rays are used and when they hit the plasma (LCFS or O-mode cut-off) the code starts with (electrostatic) ray-tracing with one of the two electrostatic solutions which is generally the lower value that belongs to the almost electrostatic slow X-mode. The absorption takes place at the layer where the resonance condition is fulfilled (0.5 T). Due to the fact that the emission started in the symmetry plane the waves are propagating in parallel and anti-parallel direction as well, so no large net-current drive was expected. Furthermore, best power absorption was predicted due to only a small Doppler shift at a magnetic field strength of 0.48 T.

Experiments based on EBW heating at a magnetic field strength between 0.45-0.5 T have been successfully performed in helium and argon plasmas at WEGA. On the example of a helium discharge as shown in Fig. 2, the temporal evolution to reach a fully electron Bernstein wave sustained plasma will be discussed in the following. In order to excite EBWs by means of the OXB mode conversion process starting on the low field side a density threshold of $n_\mathrm{e} = 0.97 \times 10^{19}\,\mathrm{m}^{-3}$ has to be reached. On the other hand the X-mode cut-off is already reached at a density of $n_{\mathrm{c,x}} = 5 \times 10^{18}\,\mathrm{m}^{-3}$ which prohibits a further density increase by X-mode absorption. Therefore, it is necessary to overcome this density gap by alternative heating methods. For this purpose a target plasma was generated by non-resonant power absorption of the 2.45 GHz emission system. The 2.45 GHz waves were launched with a double-slot antenna, generating a large $N_\parallel$ number of > 0.7. Due to multiple reflections at the metallic vacuum vessel, the waves can couple with R-waves (whistler waves), which have no density limit for propagation. This resistive absorption generates a high density but low temperature plasma, which is appropriate to be exclusively sustained by EBW heating.

Furthermore, optimum condition for the creation of EBWs is an oblique angle between the incident electromagnetic wave and the field vector $\vec{B}$. The proper alignment of the mirrors including a part of the transmission line were checked by a laser. In a later step the spatial position of the wave front was additionally detected by an infrared camera looking onto an absorber target installed at the high field side of the plasma vessel.

The plasma start-up takes place at the time $t = 10\,\mathrm{s}$ when the 28 GHz gyrotron starts to emit with a forward power of about 7 kW. The line-integrated density reaches a value of about $ndl = 0.7 \times 10^{18}\,\mathrm{m}^{-2}$. With a given integration length of about $l = 0.14\,\mathrm{m}$, representing the interaction zone of the microwave interferometer crossing the confinement region, a mean density of $\overline{n}_\mathrm{e} = 5 \times 10^{18}\,\mathrm{m}^{-3}$ can be expected for a flat density profile. The sniffer probe detects a value well above the noise level indicating the existence of a significant level of non-absorbed 28 GHz stray radiation. The central bolometer channel shows in contrast to both edge channels a by a factor of two higher intensity, so most power deposition is expected in the center of the plasma. The radiated power deduced from the bolometer signal is above 25% of the heating power. The radiation temperature of the central EBE channel is in the low eV range. At about $t = 12\,\mathrm{s}$ the ramp-up of the 20 kW and 2.45 GHz ECRH system starts. Although no resonance condition is fulfilled at 0.5 T the wave is resistively absorbed and creates additional density as shown in the line-integrated density signal. The sniffer probe shows no

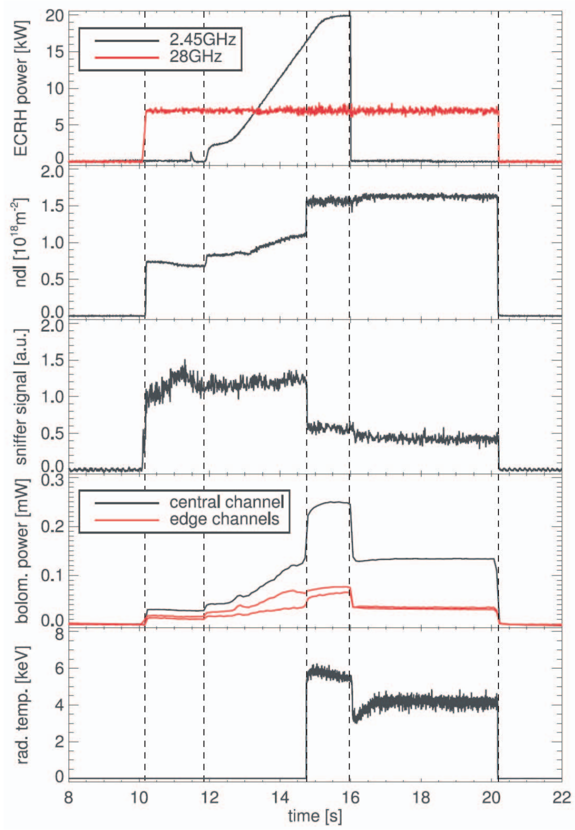

Fig. 2 From above: Time traces of the forward power of the 2.45 GHz and the 28 GHz microwave system, the line-integrated density, the signal of the non-absorbed 28 GHz stray radiation, a central (black) and two edge channels (red) of the bolometer camera and a central channel of EBE diagnostic measuring the radiation temperature for the helium discharge #30344.

change, because it is insensitive to changes in the 2.45 GHz stray radiation. The central channel as well as the edge channels of the bolometer show a linear increase in intensity although the central one shows a steeper increase and the radiation temperature of the EBE channel has again a very small signal in the eV-range. At $t = 14.8\,\mathrm{s}$ the situation drastically changes: While the forward power of the 2.45 GHz system still increases monotonically a sudden jump in the line-integrated density is visible. At this moment the threshold density for the O-mode cut-off of $n_\mathrm{e} = 0.97 \times 10^{19}\,\mathrm{m}^{-3}$ has been reached and the OXB mode conversion process became effective. As a result the EBWs were efficiently absorbed at the resonance position in the central region of the plasma.

This could be independently confirmed by Langmuir probe measurements that showed during repeated discharges a locally measured density of about $n_\mathrm{e} = 1.3 \times 10^{19}\,\mathrm{m}^{-3}$ in the plasma center. The sniffer signal dropped by a factor of about two indicating a much better absorption of the 28 GHz heating wave inside the plasma as expected. While the edge channels of the bolometer are staying on the level beforehand the central channel jumps by

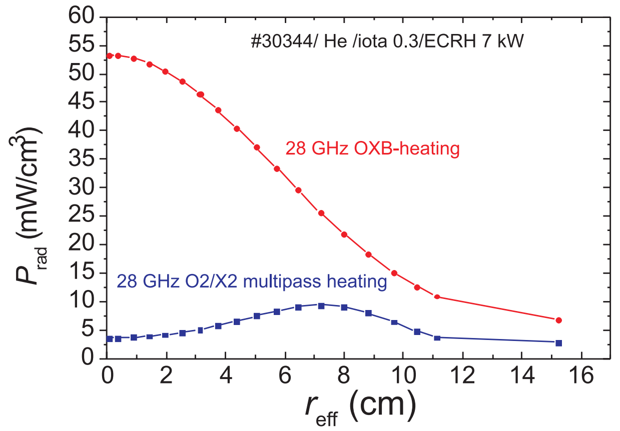

Fig. 3 Reconstructed radiation profiles measured with the bolometer camera before (blue) and during (red) OXB mode heating phase.

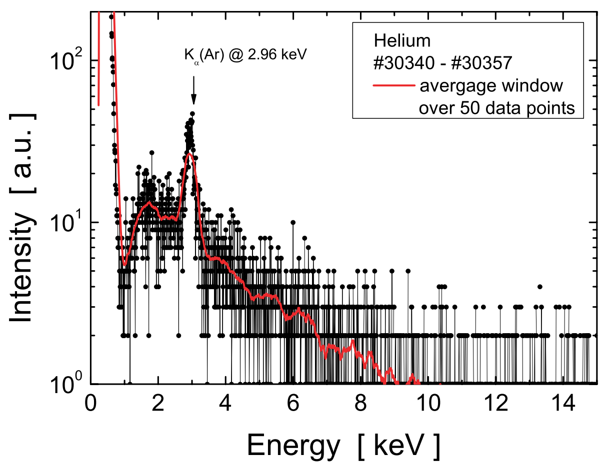

Fig. 4 Soft X-ray signals during the OXB heated plasma phase averaged over 15 identical discharges and for comparision a 10 keV curve representing the supra-thermal electrons.

a factor of two. But most surprisingly the radiation temperature of the central EBE channel exhibits an immense jump from the low eV into the keV range. Moreover, after the shut down of the additional non-resonant 2.45 GHz heating system at $t = 16$ s the density stays on the level necessary for the propagation of the Bernstein waves i.e. above $n_e = 0.97 \times 10^{19}\,\mathrm{m}^{-3}$. Hence during this period of the discharge a fully Bernstein wave sustained heating regime has been established. The sniffer signal keeps basically constant but due to the lack of additional heating power, the bolometer signal of all channels drops but remains peaked.

The reconstructed radial profile of the bolometer channels showed a strong change. While the profile was broad during the non-OXB regime due to multi-pass absorption of the O-mode waves a peaked emission was obtained during the OXB phase as shown in Fig. 3. A further indicator that the OXB mode conversion was still active was the radiation temperature of the central EBE channel with an amplitude still in the keV-range.

But what could be the origin of the detected radiation temperature in the keV range during the OXB phase? It is assumed, that this behavior can be explained by a small fraction of super-thermal electrons getting their high energy due to the effective coupling of the resonant absorption of the EBWs in the central region of the plasma. However, the bulk electrons remain at a temperature of a few 10 eV which could be confirmed by Langmuir-probe measurements. While from Langmuir probe characteristics a small fraction of highly energetic electrons can not be deduced other diagnostic methods had to be applied. For this purpose soft X-ray (SXR) measurements have been performed. Exclusively during the OXB phase a soft X-ray signal could be detected. As can be seen in Fig. 4, the SXR-signal is mainly characterized by Bremsstrahlung with a maximum energy of above 10 keV. The peak around 3 keV has been identified as the Ar K_α line and resulted from background gas of previous argon discharges. However, the K_α lines from typical materials of the plasma vessel like Fe or Cr could not be detected. Hence we assume that the SXR-signal is generated in the center of the plasma. This behavior is a further indicator that a superthermal electron component is generated during the OXB heated phase in the center of the plasma due to local absorption of the Bernstein waves. Although the absolute value of the density of the super-thermal electron component could not be determined by this method at present a qualitative description of the underlying mechanism could be given.

Furthermore, angular scans of the launching antenna were additionally performed to optimize the mode conversion. As expected the additional power of the non-resonant 2.45 GHz necessary for reaching the OXB phase was smallest for an oblique angle of about 55°.

Analogue experiments have been performed in argon discharges as well. Again it was possible to generate a plasma fully sustained on EBW heating. In this particular case it was possible to reach a fully sustained OXB heating even without any additional heating. On the other hand experiments performed in hydrogen discharges were not successful. Even with maximum additional non-resonant power of the 2.45 GHz system the density gap could not be overcome. It was also possible in argon and helium discharges to reach the OXB phase with more sophisticated heating methods applying the transformer.

4. Summary and Outlook

In WEGA stellarator quasi-stationary fully 28 GHz EBW-heated plasma operation was achieved in helium and argon plasmas at a field strength of 0.5 T. The generation of the EBWs was possible with the help of a highly efficient emission system. For the generation of the electrostatic Bernstein waves a two-step mode conversion process from an O- to X-mode wave and in a second step from a X-mode to a Bernstein wave was successfully applied. Best conversion efficiency was achieved when the wave was emitted under an oblique angle of about 55° with respect to the magnetic field vector $\vec{B}$. The density threshold necessary for the propagation of Bernstein waves of $0.97 \times 10^{19}\,\mathrm{m}^{-3}$ could be achieved by additional non-resonant 2.45 GHz heating. At maximum a density of $n_\mathrm{e} \approx 1.3 \times 10^{19}\,\mathrm{m}^{-3}$ could be observed. Once the critical density was reached the additional heating system could be switched off and the plasma was fully sustained by OXB heating only. During the OXB heating phase an electron bulk temperature of the order of a few ten eV could be observed. However, a superthermal electron component in the keV range in the center of the plasma could be detected by means of EBE and soft X-ray measurements. It is assumed that this supra-thermal electron population is generated by the EBWs due to electron cyclotron absorption. The fraction of super-thermal electrons seems to be very small although absolute values could not been determined so far. However, this should be possible in the future with an absolutely calibrated SXR-system. Furthermore, it is planned to explore the OXB heating scenarios at fundamental frequency of 1.0 T operation. This should be possible by minor modifications of the power supply of the toroidal field coils.

To sum it up a new and very promising operation regime has been opened with respect to plasma wave interactions and wave propagation.

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