Overdense Plasma Operation in the WEGA Stellarator

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Introduction

The application of high power microwave systems for efficient plasma heating in magnetically confined fusion experiments is an established and very successful method. Nevertheless, electron cyclotron resonant heating (ECRH) is limited in density and high beta operation due to reflections of the heating wave at associated cut-offs that prohibit wave propagation into the central plasma region. However, overdense operation in stellarators without a density limit [1] can be achieved by an alternative heating concept based on the conversion of an incident electromagnetic wave into an electrostatic Bernstein wave (EBW) [2]. At the WEGA stellarator experiments in overdense argon and helium plasmas fully sustained by electrostatic Bernstein waves have been performed.

Experimental Setup

WEGA is a classical $l = 2$ stellarator with five field periods, a major radius of $R = 72$ cm and a maximum plasma radius $a = 11$ cm, respectively. The magnetic field coils can be sustained at 0.5 T for about 20 s. With additional vertical field coils for varying the rotational transform and the shear and an error field compensation coil the machine has a very flexible magnetic configuration. For plasma generation two microwave heating systems operating at a frequency of 2.45 GHz (26 kW, cw) and 28 GHz (10 kW, cw), respectively, and a transformer with a capacity of 440mVs for Ohmic heating are available. The 28 GHz ECRH system consists of a gyrotron and a transmission line, which is a combination of a waveguide system for mode conversion from the TE02 gyrotron mode into an elliptically polarized HE11 mode and a quasi-optical antenna system for proper beam launching into the plasma. In total, only 10 kW/0.15 m^3 of ECRH power density is available, which necessitates a highly efficient OXB-mode conversion. For the generation of EBWs the 28 GHz ECRH system was applied allowing a two-step conversion process at the plasma edge from second harmonic electromagnetic O- to X-waves and a subsequent conversion at the upper hybrid layer into EBWs which propagate into the plasma. The conversion efficiency depends sensitively on the angle between the incident wave and the magnetic field vector and should be optimum for an oblique angle of 55°. By means of a movable mirror-system this angle could be varied.

WEGA is equipped with several diagnostics. The density can be determined by a single-channel 80 GHz interferometer measuring the line averaged density and a Langmuir-probe installed on a fast reciprocating manipulator. The radiation profile is measured by a 12-channel bolometer camera. A so called “sniffer” probe, which measures the 28 GHz stray radiation level, determines the non-absorbed ECRH power. The microwave emission from the plasma can be detected by a 12-channel radiometer in a frequency range of 22.8-39.6 GHz. Furthermore, the complete spectrum can be measured with an absolutely calibrated spectrum analyzer with a sweep time of typically 300 ms during steady state plasma operation. In the discharges under consideration, the radiometer antenna viewed under an oblique angle of 55° with respect to the magnetic field vector, which is optimal for EBW emission (EBE) measurement by BXO conversion. The rectangular shaped horn could only detect linear polarization parallel to the magnetic field vector. Thus, only a part of the elliptically polarized O-wave was detected. In addition, a second horn was installed at the high field side with a viewing angle perpendicular to the magnetic field vector for comparative measurements. For the detection of possible X-ray emission a pulse height analyzer with an energy range of 0.5-15 keV was available.

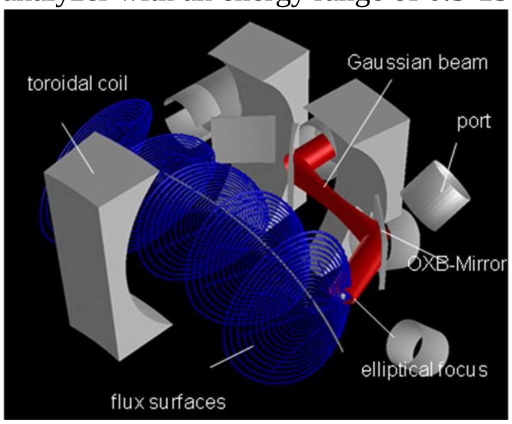

Figure 1. Arrangement of the quasi-optical mirror system used for OXB mode conversion including the incident beam (red). The magnetic flux surfaces are indicated in blue.

The heating beam was focused at the plasma edge at a toroidal position with maximum vertical plasma elongation as shown in figure 1. Here, the smallest density scale length L_n= n/grad n is expected. The broadness of the $N_{\|}$ spectrum is reciprocal to the focus diameter. On the other hand, a large poloidal focus size would prohibit central power deposition. Therefore, as a compromise, a toroidally elongated focus of FWHM 4.1 cm in toroidal direction and 2.3 cm in poloidal direction was chosen. In addition, this toroidal position of symmetry features a unique magnetic configuration, where the $N_{\|}$ component of the EBW remains small during the propagation. This behavior is similar to equatorial launch in a tokamak. Here, only slightly Doppler-shifted absorption and no current drive is expected. 3D EBW ray tracing calculations [4] predict most central power deposition for a magnetic field of 0.48 T at the axis. It should be noticed, that this calculation is not self consistent. It is assumed that the density and temperature profiles remain unchanged, even though the deposition is changed.

Results and Discussion

EBWs can only propagate inside the plasma above a density threshold (O-mode cut-off) of n_e = 1×10^{19} m^{-3}. Hence, the main challenges in achieving an EBW heated plasma is to find the optimal launch angle and to overcome the density threshold for OXB-mode conversion with the given power density. The first is straight forward in a current-less stellarator, since the magnetic configuration is mainly determined by external coil currents. The density threshold can hardly be overcome with 28 GHz only, since the cut-off density of the X2-mode is 0.5×10^{19} m^{-3}. In addition, for best OXB-conversion the microwaves should be obliquely launched with O-mode polarization (left hand side elliptically polarized). Therefore, a target plasma must be generated by an additional heating scheme with the available 2.45 GHz system. Even though no resonance

condition is fulfilled at 0.5 T, resistive absorption should generate plasma density. The 2.45 GHz waves are launched with a double slot antenna, which generates a large $N_{\|}$ number (>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. Resistive absorption generates a high density but low temperature plasma, which is appropriate to be taken over by EBW heating.
In the experiments the threshold density in helium plasmas was reached with typically 20 kW magnetron power as shown in figure 2. At t = 14.8 s the EBW-heating became effective. Now the power was absorbed at the plasma center and the density increased and became strongly peaked. After switching off the 2.45 GHz power at t = 16 s a purely EBW heated plasma was sustained up to the end of the discharge at t = 20 s. Furthermore, the sniffer probe, showed a significant drop when reaching the threshold density indicating an improved absorption of the incident waves. The radiation profile measured with the 12-channel bolometer was strongly peaked in that case. The total radiated power is above 50% of the heating power. Therefore, the achievable density is limited by the ECRH power.

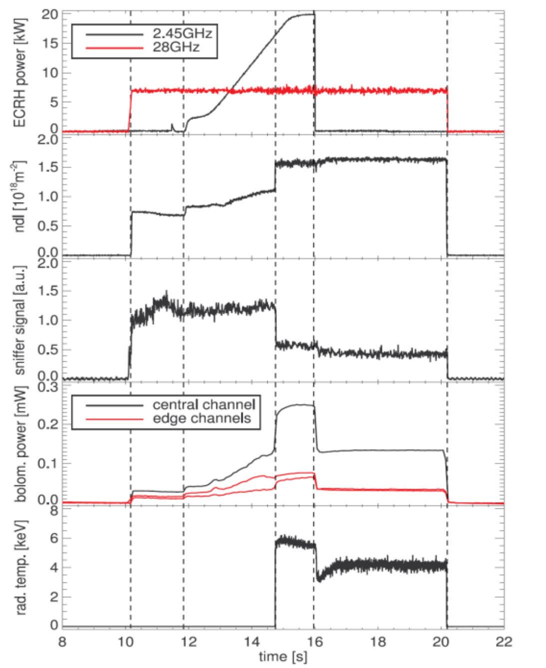

Figure 2. Left: Time traces of the ECRH forward power, the line averaged density, the non-absorbed ECRH stray radiation, the bolometer power and the radiation temperature of a central ECE channel (from above) during a helium discharge #30344. The transition into OXB-heated plasma operation takes place at 14.8 s. Right: Radiation profiles determined with the bolometer camera during OXB mode heating and pure O-mode heating phase.

While the electron temperature measured by Langmuir probes and the radiation temperature of the bulk plasma were in the order of a few 10 eV only, a radiation temperature of up to more than 10 keV could be observed in the central region of the plasma when reaching the OXB state [3].
The EBE-spectrum was strongly peaked around the 28 GHz resonance with peak levels of up to 20 keV. This result could be confirmed by soft x-ray measurements with the pulse height analyzer where Bremsstrahlung up to an energy of more than 10 keV could be detected.
The intense radiation originated from a fast electron component generated by the electron cyclotron interaction. BXO emission was detected up to a frequency of 33 GHz, thus the peak

density must have exceeded 1.4×10^{19} m^{-3}. This peak value could be confirmed by Langmuir probes within the measurement errors as shown in figure 3.

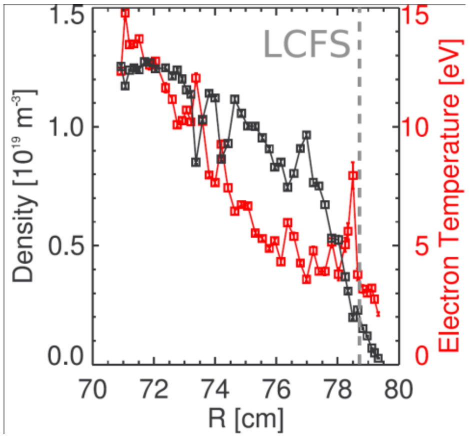

Figure 3. Electron density and temperature profile measured during OXB-phase obtained with a Langmuir probe installed on a fast reciprocating manipulator.

The resonant absorption character was confirmed by a magnetic field scan. Best central deposition was found between 0.46 T and 0.48 T, which confirmed the low Doppler-shift as predicted by the ray-tracing calculations.

By increasing the rotational transform the density threshold could be reached with less additional 2.45GHz non-resonant heating power. While in argon plasmas this threshold could be obtained by means of the 28 GHz ECRH system only it was not possible to reach the threshold density at all in hydrogen. In this case the line integrated density was by a factor of about 3 too low.

Summary and conclusions

Quasi-stationary fully 28 GHz EBW-heated plasma operation was achieved at the second harmonic resonant field of 0.5 T and densities above 1.4×10^{19} m^{-3}. While the bulk temperature of the electrons was of the order of a few ten eV, the EBE-diagnostic measured an extremely high radiation temperature in the keV range in the central region. This behavior is assumed to origin from a fast supra-thermal electron population generated by the EC-absorption of the EBWs. This is a new unexplored plasma regime, which can give access to new wave particle interaction schemes as well as to advanced current drive scenarios with EBWs.

References

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