Electron Bernstein Wave Experiments at the WEGA Stellarator

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Introduction

High density and high beta operation in fusion plasmas could not be sustained by electron cyclotron resonance heating (ECRH) yet, since the total reflection at the cut-off limit prohibits the wave propagation into the dense plasma core. However, the super-dense operation in stellarators and the high beta regime in spherical tokamaks, which are alternative reactor concepts, necessitate over-dense plasma heating. ECRH with electron Bernstein waves (EBWs) is a promising candidate. It can deposit its power into a small volume, to achieve a high power per volume ratio necessary for high beta operation and is able to drive a local toroidal current efficiently, which is needed to generate rotational transform and to stabilize MHD modes in tokamaks. EBWs are electrostatic plasma waves and have to be generated by the OXB mode conversion process at the plasma edge [1]. Their propagation is highly sensitive to the magnetic field configuration. Therefore, precise EBW ray-tracing calculation is necessary in order to control the power deposition and the EBW driven current. In this paper the recent experimental results with 28 GHz EBW heating will be reported.

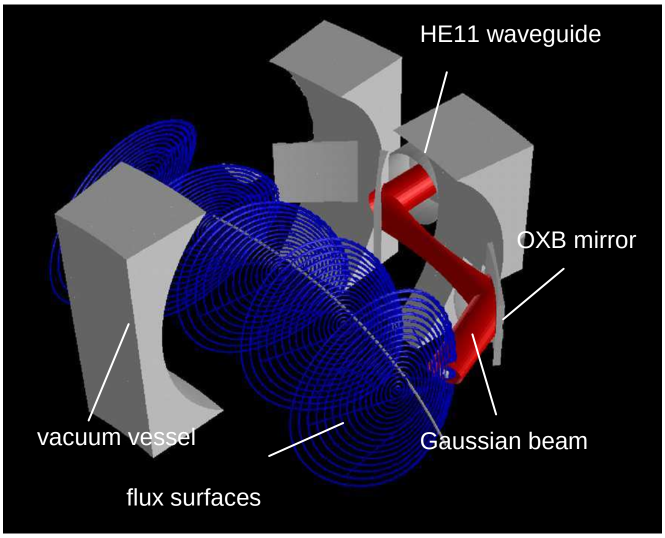

Figure 1: Quasi-optical transmission inside the WEGA vacuum vessel.

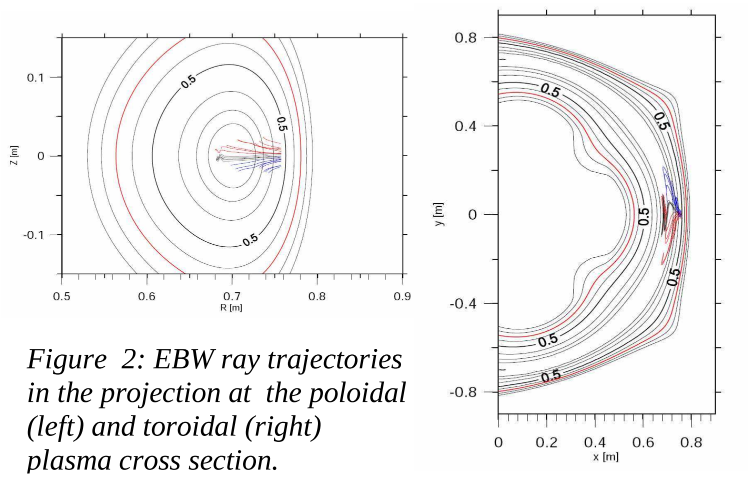

Figure 2: EBW ray trajectories in the projection at the poloidal (left) and toroidal (right) plasma cross section.

Experimental set-up

WEGA is a classical five period and $l = 2$ stellarator with a major radius of 0.72 m and an aspect ratio of 7. It is equipped with three independent coil systems. The toroidal field coils provide the toroidal magnetic field, the two oppositely charged helical field coils generate the rotational transform and thus the closed flux surfaces and the vertical field coils generate a vertical magnetic field, which can be used for radial plasma position control and shear variation. In addition WEGA is equipped with an iron OH-transformer with a capability of 440 mVs. The discharge length at 0.5 T is typically up to 20 s, which allows operating the plasma in a stationary state. The heating system of WEGA consists of a 10 kW 28 GHz cw gyrotron with a transmission line, which is a combination of a waveguide system for mode conversion from the TE02 gyrotron mode into an elliptically polarised HE11 mode and a quasi-optical antenna system for proper beam launch 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. Therefore, the 28 GHz power was launched with a pure O2-mode elliptical polarisation with the optimal angle (55°) for OXB-conversion. The beam was focussed at the plasma edge at a toroidal position with the maximum vertical plasma elongation. Here the smallest density scale length L_n was expected. The quasi-optical mirror system is shown in Fig. 1. The broadness of the $N_{||}$ spectrum is reciprocal to the focus diameter. On the other hand large poloidal focus size would prohibit central power deposition. Therefore, as a compromise, we chose a toroidally elongated focus of FWHM 4.1 cm in toroidal direction and 2.3 cm in poloidal direction. In addition, this toroidal position of symmetry features an unique magnetic configuration, where the $N_{||}$component of the EBW remains small during the propagation. This behaviour 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 predict most central power deposition for a magnetic field of 0.48 T at the axis. The ray trajectories are shown in Fig. 2. It should be noticed, that these calculation is not self consistent. It is assumed that the density and temperature profiles remain unchanged, even though the deposition is changed. The operation at 0.5 T is also supported by a 26 kW 2.45 GHz cw magnetron system with a double-slot antenna, which provides a large $N_{||}$ to excite resistively absorbed R-waves in the plasma.

WEGA is equipped with several diagnostics. The line averaged density is measured by a single line 80 GHz interferometer. The radiation profile is measured by a 12 channel bolometer camera. Very useful is the so called “sniffer” probe, which measures the 28 GHz ECRH-stray radiation level in order to estimate the absorbed ECRH power. The probe is located at a toroidal position nearly opposite to the ECRH launch antenna. Unfortunately the in-vessel diamagnetic loop was damaged by rf and was not available for the experiments. The X-ray emission can be detected by a pulse height analyser in an energy range of 0.5-15 keV. Recently a 12 channel radiometer (22.8- 39.6GHz) has been installed. The antenna was viewing obliquely with an angle of 55° with respect to the magnetic field vector, which optimal for EBW emission (EBE) measurement by BXO conversion. The rectangular shaped horn could only detect linear polarisation, which was 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. Furthermore, the complete spectrum can be detected with a spectrum analyser with a sweep time of typically 300 ms during steady state plasma operation. The system was absolutely calibrated by the "hot cold" method at room and liquid nitrogen temperature.

Experimental results

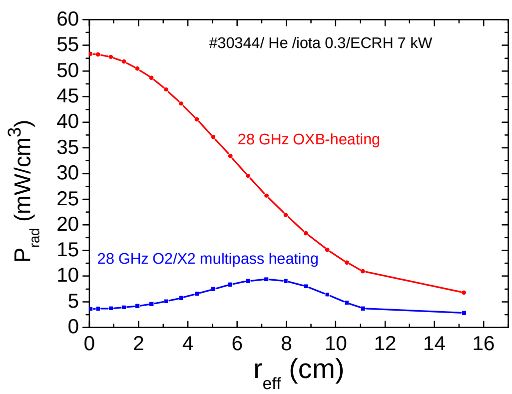

Figure 3: Radiation profile of over-dense EBW-heated plasma with central total single pass absorption in comparison with the profile of a low density plasma with multi-pass O2 heating. The profiles are reconstructed from the signals of a 12-channel bolometer camera.

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, which is $1{\cdot}10^{19}$ m^{-3}. 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 not be overcome with 28 GHz only, since the cut-off density of the best absorbed X2-mode is $0.5{\cdot}10^{19}$ m^{-3}. In addition for best OXB-conversion the microwaves should be obliquely launched with O-mode polarisation (left hand side elliptically polarized). Therefore, a target plasma must be generated by an additional heating scheme with the available 2.45 GHz. 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) or the 2.45 GHz waves. With multiple reflection 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 low temperature plasma, which is appropriate to be taken over by EBW heating. The threshold density was reached with typically 20 kW magnetron power as shown in Fig 4. At that point the EBW-heating became effective. The power was absorbed at the plasma center and the density is increased and strongly peaked. The 2.45 GHz power is switched-off and a purely EBW heated plasma was sustained. The sniffer diagnostic showed a drop down to 20 % of the power level with no ECRH absorption. The radiation profile is strongly peaked in that case as shown in Fig. 3. The total radiated power is above 50% of the heating power. Therefore the achievable density is limited by the ECRH power. The plasma temperature should be detected by the EBE-diagnostics, but when the transition into the OXB-heated plasma took place, a radiation temperature of more than 5 keV is measured in the central channels. The EBE-spectrum was strongly peaked around the 28 GHz resonance at peak levels of 20 keV. The radiation temperature is decreasing with the collision cross section and pressure of the operating gas (helium and argon). This intensive radiation originated from fast electrons, which are generated by the EC-interaction. This could be confirmed by the X-spectrum which also shows electron energies above 10 keV in the OXB-phase exclusively. The highest BXO emission frequency is detected for 33 GHz, thus the peak density must have been above $1.4 \cdot 10^{19}$ m^{-3}. The resonant absorption was confirmed by a magnetic field scan. Best central deposition was found between 0.46 and 0.48 T, which confirmed the low Doppler shift as predicted by ray-tracing calculations.

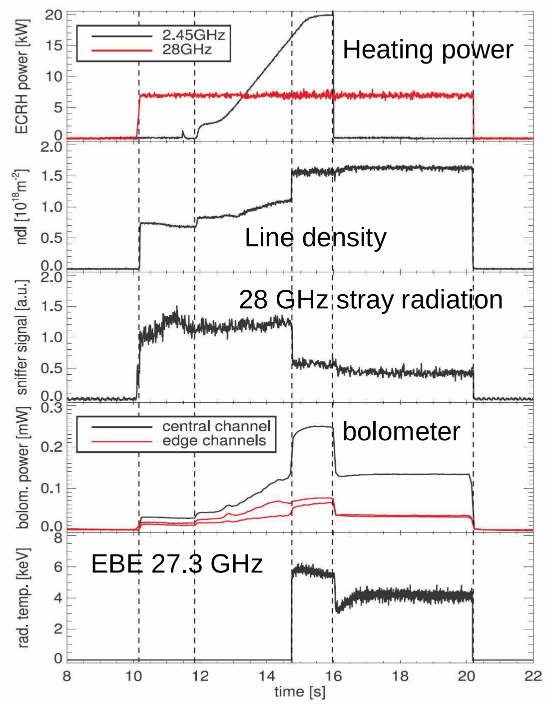

Figure 4: Time traces of a OXB-heated plasma operation. The transition takes place at 14.8 s.

Summary and conclusion

Steady state full 28 GHz EBW-heated plasma operation was achieved at WEGA. The EBE-diagnostics measures an extremely high radiation temperature, which origin from a fast supra-thermal electron population generated by the EC-absorption of EBWs. Note, that in contrast to the electromagnetic waves the EC-interaction of EBWs is not limited in energy. This is new unexplored plasma regime, which can give access to new wave particle interaction schemes as well to advanced current drive scenarios with EBWs.

References:

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