Microwave heating by electron Bernstein waves at the stellarator TJ-K

A. Köhn, E. Holzhauer, R.B. Morales, S. Wolf, M. Ramisch

Institute of Interfacial Process Engineering and Plasma Technology, University of Stuttgart, Stuttgart, Germany

Electron Bernstein waves (EBWs) [1] constitute a tool to heat over-dense plasmas which are otherwise inaccessible to electromagnetic waves. The EBWs have no high-density cut-off and are very well absorbed near the electron cyclotron resonance (ECR) layer and its harmonics for both, high- and low-temperature plasmas. Due to their electrostatic nature, however, they need to be coupled to externally injected electromagnetic waves. A potential coupling mechanism is the O-X-B mode conversion process: An injected O-mode, propagating at an optimum angle with respect to the background magnetic field, is converted into an X-mode around the plasma frequency layer. The X-mode is then reflected and propagates radially outwards. In the vicinity of the upper-hybrid resonance layer, the X-mode is converted into a backwards propagating EBW.

The overall conversion efficiency depends strongly on the O-X conversion efficiency, which itself depends on the injection angle of the O-mode. The optimum angle is given by the normalized density gradient length $k_0 L_n$ (with the vacuum wavenumber k_0 and the density gradient length $L_n = n_e/|\nabla n_e|$) and by the magnetic field strength at the conversion layer. The sensitivity on angular mismatch decreases with decreasing values of $k_0 L_n$, i.e. with increasing steepness of the density profiles (see e.g. Ref. [2]). For too steep profiles, however, the X-B conversion efficiency starts to drop and the O-X-B mode conversion scenario can no longer be applied.

The stellarator TJ-K is a low-temperature device with major and minor radii of 0.6 and 0.1 m, respectively [3]. Heating by EBWs has been successfully established as a standard and efficient way of producing the plasma in TJ-K [4]. The microwave heating system consists of a klystron operating at 7.9–8.4 GHz with a maximum output power of 2.5 kW. A phased array antenna allows to sweep the angle of incidence of the microwave beam by sweeping the microwave frequency. Such an antenna has the advantage that no mechanical movable parts are required for varying the injection angle. The vacuum transition is realized by an HDPE window. The window is designed as a lens based on numerical optimization to achieve maximum conversion efficiency: As was shown previously, it is important to match the wave front curvature of the injected beam to the curvature of the conversion layer [5].

With this optimized antenna coupling, the dependency of the plasma energy on the injection angle was clearly show and, hence, the major role that EBW-heating plays in this scenario.

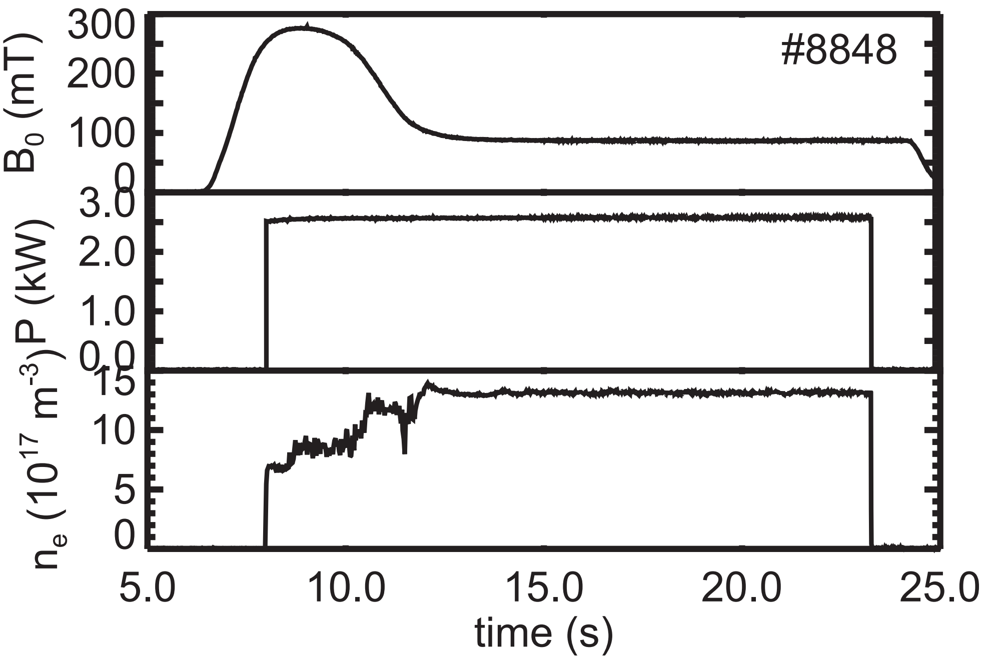

Figure 1: Time traces of an EBW-heated discharge, shown is the background magnetic field strength (top), the injected microwave power (middle) and the line-averaged density as obtained from an interferometer (bottom). The microwave heating frequency was 8.256 GHz.

A toroidal net current, driven by the EBW using the Fisch-Boozer mechanism could also be identified [4]. It is possible to achieve heating at harmonics of the ECR by simply reducing the magnetic field strength during the discharge. As can be seen from Fig. 1, the plasma must be started at the fundamental resonance. Then, the magnetic field strength can be continuously ramped down by almost a factor of three. The achieved high-harmonic heating scenario turns out to be very efficient, demonstrated by the increase in the line-averaged density when decreasing the magnetic field strength.

To make use of this scenario, the plasma density must be large enough before the ramping-down of the magnetic field starts: it must be slightly over-dense to allow the O-X conversion and the subsequent X-B conversion to happen. A sudden and strong increase in the density is actually observed during the discharge as soon as the cut-off density is reached, further supporting the high efficiency of the harmonic EBW-heating.

If, on the other hand, the injected microwave power is slowly reduced in the high-harmonic scenario, the plasma extinguishes as soon as the plasma density falls below the cut-off density. Obviously, no other heating mechanism except EBW-heating is possible in this configuration.

An interesting feature, occurring at the low magnetic field values, can be seen in the interferometer time trace from Fig. 1: The noise level is reduced, indicating a reduction in the density

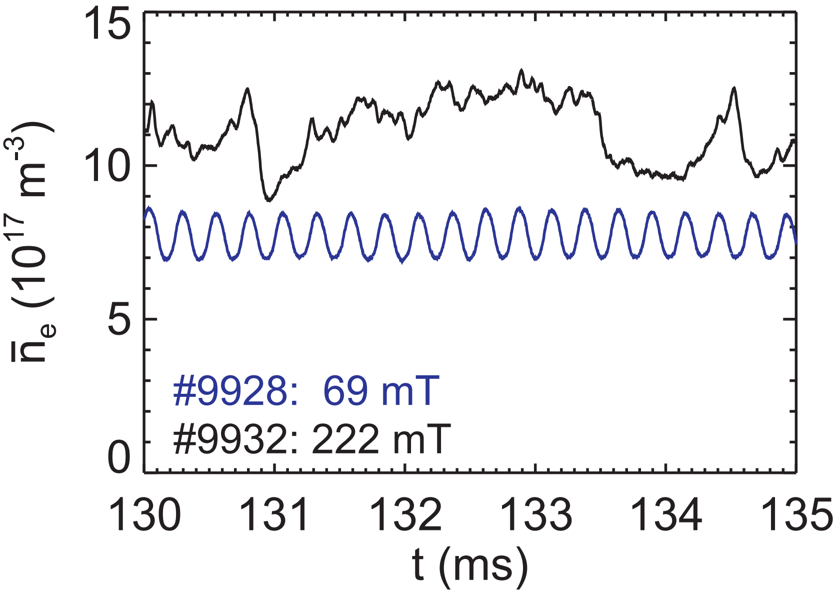

Figure 2: Time traces of the microwave interferometer installed at TJ-K, corresponding to the line-averaged plasma density. Both shots are EBW-heated discharges, not the difference in the magnetic field strength.

turbulence. To further investigate this phenomenon, dedicated measurements have been carried out: Figure 2 shows two time traces of the microwave interferometer, i.e. of the line-averaged plasma density. The two time traces correspond to two different shots, one shot with fundamental EBW-heating and one shot with high-harmonic EBW-heating.

The difference between the two cases is obvious: in the high-field case, the plasma density shows an irregular, fluctuating behavior, whereas in the low-field case a periodic behavior is observed corresponding to a dominant mode being present in the plasma (keep in mind that these are line-averaged measurements of the plasma density).

A reciprocating Langmuir probe biased to acquire the ion saturation current allowed to get radially resolved density measurements. Their power spectra are shown in Fig. 3. Again, a high-field case and a low-field case are compared. The dominant mode in the low-field case can be clearly identified at a frequency of approximately 4 kHz along with a large number of higher harmonics. The fundamental mode extends across the whole plasma cross section. As compared to the high-field case, the broadband turbulence is strongly reduced. A similar behavior is observed in the floating potential. This transition from a turbulence-dominated regime to a mode-dominant regime is not abrupt but continuous, similar to the observations from linear devices reported in Refs. [6, 7].

To summarize, it is possible to routinely operate TJ-K in EBW-heated scenarios. A toroidal net current driven by the EBW has been found with the underlying Fisch-Boozer mechanism.

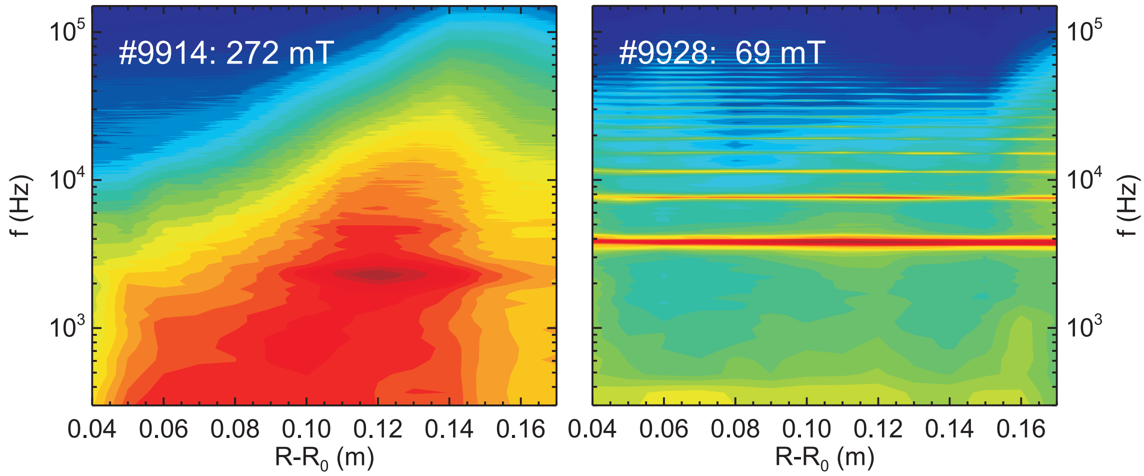

Figure 3: Power spectra of the ion saturation current as a function of the radial coordinate obtained in the mid-plane. The plasma center is located at $R-R_0 = 4$ cm, the separatrix at $R-R_0 \approx 13$ cm and the vessel wall at $R-R_0 = 17.5$ cm.

EBW-heating at high harmonics of the ECR was shown to be more efficient than heating at the fundamental ECR in TJ-K. It was also found that the degree of turbulence gradually changes when decreasing the magnetic field strength until a regime is reached with a dominant quasi-coherent mode.

References

[1] H. Laqua, Plasma Phys. Control. Fusion **49**, R1 (2007)

[2] A. Köhn *et al.*, Phys. Plasmas **18**, 082501 (2011)

[3] U. Stroth *et al.*, Phys. Plasmas **11**, 2558 (2004)

[4] A. Köhn *et al.*, Plasma Phys. Control. Fusion **55**, 014010 (2013)

[5] A. Köhn *et al.*, Plasma Phys. Control. Fusion **50**, 085018 (2008)

[6] M.J. Burin *et al.*, Phys. Plasmas **12**, 052320 (2005)

[7] T. Klinger *et al.*, Plasma Phys. Control. Fusion **39**, B145 (1997)