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Microwave Heating of Overdense Plasmas in the Torsatron TJ-K

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Introduction

The torsatron TJ-K is an $l = 1$ and $m = 6$ stellarator with a major radius of $R = 0.6$ m and a minor radius of $a = 0.1$ m. Since the plasma in TJ-K is dimensionally similar to fusion edge plasmas [1], a main topic for research are turbulence studies [2]. The topic of this contribution is the heating with microwaves in the low-temperature plasma in TJ-K ($T_e \leq 20$ eV, $T_i \leq 1$ eV). In contrast to high-temperature fusion plasmas, this low-temperature plasma is optically thin and absorption of the O- and X-mode at the fundamental resonance is unlikely to occur [3]. Instead, if the density of the plasma is high enough, absorption at the upper hybrid resonance (UHR) or mode conversion to the electron Bernstein wave (EBW) and subsequent absorption of the EBW can take place. A recent review of EBW related physics has been given by H. P. Laqua [4].

Two microwave heating systems are installed at TJ-K: The *first* consists of a magnetron which provides a maximum power of 6 kW at a frequency of 2.45 GHz. Together with a quartz window, an open-ended R-26 waveguide acts as the antenna. The *second* system consists of two travelling wave tubes which are fed by one oscillator. It provides a maximum power of 1.2 kW over a frequency range of 7.9 GHz to 8.4 GHz. A phased array antenna is used to couple the power into the plasma. Scanning the frequency allows to scan the angle of incidence from -45 to +45 degrees with respect to the background magnetic field $\mathbf{B}_0$. For both heating systems, the antennas can be rotated in order to choose between O- or X-mode polarization. TJ-K can be operated with a maximum magnetic field strength of 300 mT which means the fundamental resonances at ω_{ce} are accessible for both heating systems.

Here, we present investigations with a full-wave code of the heating scenarios described above. A full-wave code is necessary, since the normalized density gradient length $k_0 L_n$ (k_0: vacuum wavenumber; L_n: density gradient length) is not expected to fulfil the restriction of WKB theory, $k_0 L_n \gg 1$. Measurements of the wave electric field were performed in order to determine the region of power deposition.

The full-wave code

Maxwell's equations $\partial \mathbf{B}/\partial t = -\nabla \times \mathbf{E}$ and $\partial \mathbf{E}/\partial t = c^2 \nabla \times \mathbf{B} - 1/\varepsilon_0 \mathbf{J}$ are solved with a finite-difference time-domain (FDTD) code on a Cartesian grid. The plasma effects are included in the response of the current density $\mathbf{J}$ to the electric field $\mathbf{E}$, which is obtained by solving the equation of motion for the electrons: $\partial\mathbf{J}/\partial t = \varepsilon_0\omega_{pe}^2\mathbf{E} - e/m_e\mathbf{J}\times\mathbf{B}_0$. The FDTD scheme means that the spatial derivatives are replaced by finite differences and that **B**, **E**, **J** are calculated explicitly at each time step, which is introduced by the time derivatives. This also offers the possibility to investigate time-dependent phenomena.

In the version of the code used here, only variations in two dimensions are allowed which results in the disappearance of the derivative of the corresponding third dimension. If calculations in the poloidal cross section are carried out, the derivative in the third dimension can be replaced by the finite parallel wavenumber - parallel refers to the background magnetic field $\mathbf{B}_0$, which is taken to be perpendicular to the poloidal cross section. The inclusion of the parallel wavenumber for calculations in the poloidal cross section is mandatory if one is interested in the O-X conversion, since the efficiency of this conversion depends strongly on the angle of incidence of the microwave beam with respect to $\mathbf{B}_0$. Antenna and metal walls are realized as perfectly conducting surfaces. This means that the tangential components of the electric field vanish on these surfaces.

This code has been used previously to optimize the O-X conversion efficiency for an EBW heating scenario in the TJ-II and to investigate the fully O-X-B mode conversion process [5].

Simulation results

First, the simulation of the 2.45 GHz heating scenario will we presented.

In Fig. 1, the result of a simulation in the toroidal plane is shown. The orientation of the heating antenna is such that the electric field vector is parallel to the $x-$axis (X-mode). The geometry of the port of TJ-K where the antenna is installed and the geometry of the antenna itself are included in the simulation. The density profile used has a Gaussian shape, $n_e(y) = 5\cdot\exp\{-((y-r_0)/5)^2\}\cdot 10^{17}$ m^{-3}, with $r_0 = 17.5$ cm the vacuum vessel radius. The profile is representative of profiles measured in TJ-K. The contours in Fig. 1 correspond to the absolute value of the electric field after 80 oscillation periods, a point in time where the temporal development shows asymptotic behaviour. At the UHR an enhancement of the electric field is clearly seen. An important

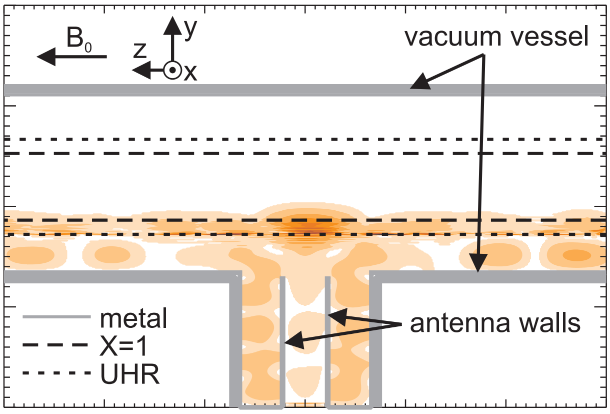

Figure 1: Simulation of 2.45 GHz heating scenario in the toroidal cross section. The contours show the absolute value of the wave electric field. Position of the UHR and the O-mode cut-off (X=1) is marked by dashed lines.

result is that this enhancement has a finite toroidal width broader than the antenna aperture. In previous simulations of the same heating scenario the enhancement at the UHR was reported to be found in the poloidal cross section as well [6].

Another important result that can be seen in Fig. 1 is that the power of the incident microwave spreads out in the torus: the gap between the conducting vacuum vessel wall and the plasma acts like a waveguide in which coaxial modes are propagating, an effect which has also been found in [7].

For the second heating system, simulations are carried out in the poloidal cross section. The orientation of the antenna is such that the electric field lies in the $xz-$plane and has the optimum parallel wavenumber for O-X mode conversion. Again, the geometry of the antenna and the outer port where it is installed are included in the simulation. In Fig. 2 is shown the absolute value of the wave electric field after 150 periods of oscillations, a point in time where the temporal development shows asymptotic behaviour. Due to the reflecting vacuum vessel wall, a complicated interference pattern has developed. Nevertheless, the enhancement at the UHR can be clearly seen. An additional effect is a pronounced up-down asymmetry with respect to the midplane, which is also found in [7].

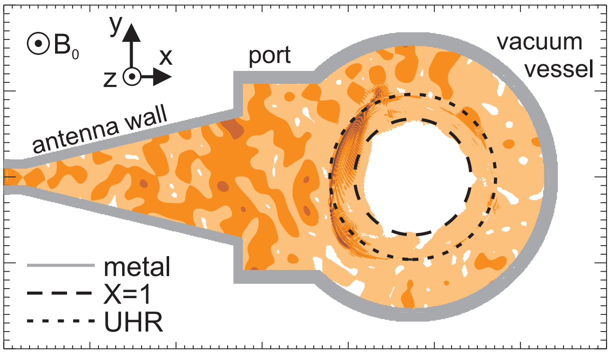

Figure 2: Simulation of 8.3 GHz heating scenario in the poloidal cross section in the same representation as in Fig. 1.

Experimental results

With an array of Langmuir probes and a fast data acquisition system (1 MHz), the start-up process of the plasma can be directly measured. The reader is referred to previous experiments in TJ-K as reported in [8]. The start-up was found to occur at the fundamental resonance. After ignition of the plasma, absorption by the O- or X-mode is not predicted to play a role [6]. Therefore, information on the propagation of the microwave in the discharge is necessary. For this purpose, monopole antennas, which measure the wave electric field can be used. They were used previously to measure the enhancement at the UHR at 2.45 GHz [6]. Now, for the 8.30 GHz, a monopole antenna is used as well.

The monopole antenna is mounted on a movable probe system, which is installed on the top port at TJ-K next to the phased array antenna. In Fig. 3 the result of the vertical scan is shown: For each vertical position the power of the incident microwave is shown and one can see that the power of the wave shows a clear decrease for at $y \leq 10$ cm. The plasma is only slightly overdense with a central density of $n_{e,peak} \approx 1.5 \cdot n_{cutoff}$. To enhance the effect of the cutoff, future experiments are planned with higher density.

One can expect that a part of the incident microwave power is converted into an EBW, which in principle can drive a net toroidal current [4]. An external Rogowski coil is used to measure net toroidal currents. A net toroidal current of the order of $I \leq 10$ A is measured during power modulation experiments. If the direction of the background magnetic field $\mathbf{B}_0$ is reversed, the direction of the current flips over as well, which points to the EBW as a driving mechanism of the current. However, more experiments are necessary to discriminate between other possible driving mechanisms.

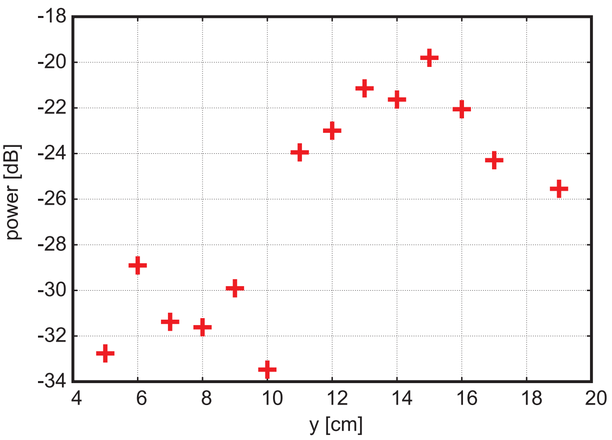

Figure 3: Power of the incident microwave at different vertical positions measured with a monopole antenna next to the phased array antenna, y is the vertical coordinate with $y = 0$ cm in the center of the vacuum vessel.

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