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Generation and heating of toroidally confined overdense plasma in TJ-K

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Introduction

In the stellarator TJ-K, toroidally confined plasmas are created by means of microwaves. The plasma is dimensionally similar to fusion edge plasmas [1] and a main research topic is therefore turbulence studies [2]. The variable background magnetic field with a value of $B_0 \leq 0.5$ T allows for resonant heating with two microwave sources. The first source delivers at a frequency of $f_1 = 2.45$ GHz a maximum power of $P_1 = 6$ kW, and the second source delivers at $f_2 = 7.9 \ldots 8.3$ GHz a maximum power of $P_2 = 1.2$ kW. In the following, the indices 1,2 will be used to distinguish between the two microwave systems. Both systems launch the microwaves perpendicularly to the background magnetic field. With the system f_1, the antenna can be rotated around its axis to switch between linearly polarized O- or X-mode incidence. The antenna of the second system is fixed to O-mode incidence.

In this paper, two types of discharges will be presented and discussed. The first one is operated at a background magnetic field of $B_0 \approx 72$ mT and the microwave source f_1 is used to generate and heat the plasma. The breakdown is found to take place at the electron cyclotron resonance layer ω_{ce}. After breakdown an overdense plasma is developed. Hence, ω_{ce} is no longer directly accessible for the microwave. The plasma production is found to take place at the plasma boundary where the upper hybrid resonance (UHR) layer is located. Using the full-wave code IPF-FDMC [3] it is shown for the first time that, due to multiple reflections at the wall, the inclusion of the vacuum vessel wall leads to a strong increase in the absorbed microwave power, compared with the single pass absorption.

The second type of discharge is operated at $B_0 \approx 270$ mT with both microwave sources. Although $\omega_1 = 2\pi f_1$ is far below the cyclotron frequency, $\omega_1 < \omega_{ce}$, an additional heating effect of this microwave can be observed. Furthermore, it is possible to sustain (not to start) the discharge with f_1 only. The existence of the O-mode cutoff corresponding to f_1 has been found to play a crucial role for this type discharge.

Discharges at low magnetic field

Here, a brief description of the discharge operating at $B_0 \approx 72$ mT with $f_1 = 2.45$ GHz will be given. A detailed description can be found in Ref. [4].

With a multiple probe array, which consists of 32 probes distributed over the whole poloidal cross section [5], it was possible to investigate the plasma breakdown during power modulation experiments. In Fig. 1, the breakdown is shown as a time series of 4 snapshots for a hydrogen discharge. The modulation frequency was set to $f_{mod} = 100$ Hz. One can clearly see that the plasma breakdown happens at the electron cyclotron resonance layer ω_{ce}. Then, the plasma density is distributed along the flux surfaces connected with the resonance layer. After $t \approx 200$ μs, the centrally peaked density profile starts to build up until the equilibrium is achieved at $t \approx 1$ ms. Reaching values of $10^{17}\mathrm{m}^{-3} \leq n_e \leq 10^{18}\mathrm{m}^{-3}$, the plasma density n_e exceeds several times the corresponding cutoff frequency, $\omega_{pe} > \omega_1$, with ω_{pe} the electron plasma frequency.

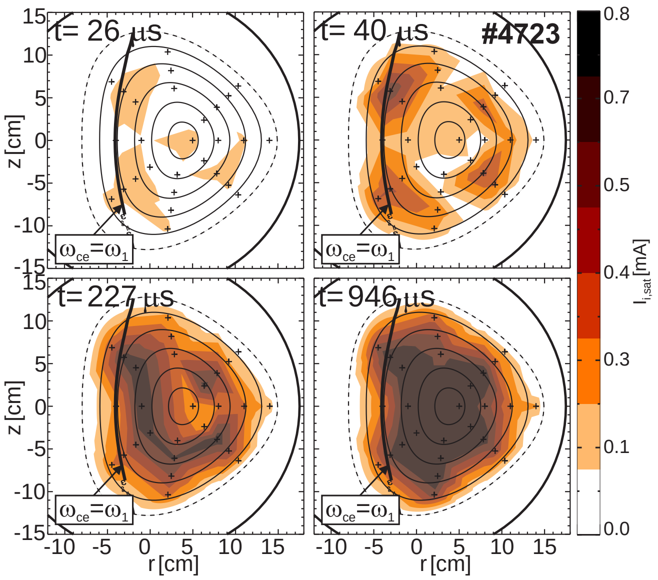

Figure 1: Plasma breakdown as time series for a hydrogen discharge.

The configuration of the microwave antenna is such that either O-mode or X-mode injection is possible. Due to the low electron temperatures of $T_e \leq 20$ eV, absorption of the O- or X-mode at ω_{ce} is not expected to play a dominant role for plasma heating. In principle, the generation of electron Bernstein waves (EBW) via the O-X-B or the X-B mode conversion process is possible (see Ref. [6] for details). The EBW would then be expected to be absorbed in the vicinity of ω_{ce}. Since neither an increase in the electron temperature profile in the vicinity of ω_{ce}, nor a non-vanishing wave electric field inside the cutoff, measured by monopole antennas, has been found in experiments, the generation of EBW is not a dominant process in these discharges. A hollow shape of the electron temperature profile indicates power deposition of the incident microwave near the plasma boundary, where the UHR is located.

With the full-wave code IPF-FDMC [3] it is possible to simulate the propagation of an incident microwave in an arbitrary geometry on a cartesian grid. Since it is basically a fluid code, the cold plasma approximation is assumed. Here, simulations in the poloidal cross section where the heating antenna is located, have been carried out. For pure O-mode injection, no absorption is expected from the cold plasma approximation. Nevertheless, a small absorption of 2% has been found in the simulation. This is due to partial conversion of the incident O-mode to an

X-mode and the subsequent absorption of this X-mode at the UHR. For X-mode injection, a single pass absorption of 12% has been found. The rms value of the wave electric field after 30 periods of oscillations is shown on the left hand side of Fig. 2. The absorption takes place at the UHR. This is visible in the plot as an enhancement in the region around the UHR.

If the geometry of the vacuum vessel is taken into account in the simulations, the absorption is strongly increased by a factor of almost 7 to 80% for X-mode injection. The corresponding plot of the rms value of the wave electric field is given on the right hand side of Fig. 2. The vacuum vessel is indicated by the thick white lines. Again, an enhancement around the UHR layer is clearly visible. The increase is due to multiple reflections at the vessel wall and the resulting multiple traverses of the microwave across the UHR.

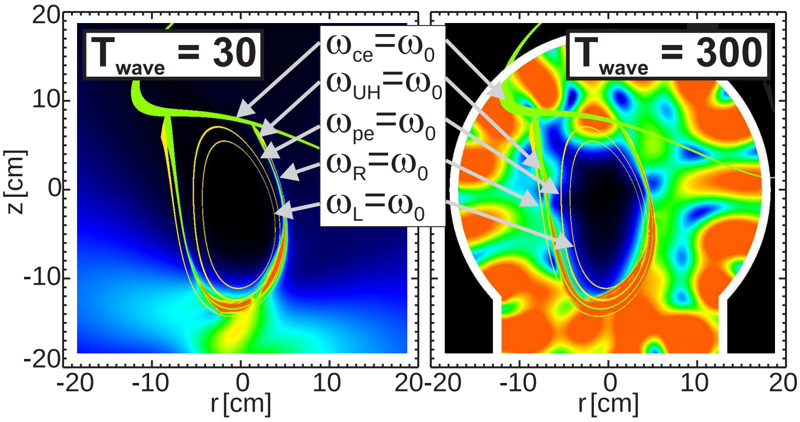

Figure 2: Full-wave simulation with IPF-FDMC for an X-mode incident from the bottom; left part without, right part with vacuum vessel included in the calculations.

Discharges at high magnetic field

Also at $B_0 \approx 270$ mT, the plasma breakdown has been found to take place at the cyclotron frequency layer $\omega_{ce} = \omega_2$ [5]. After the equilibrium state is achieved, the n_e profiles have basically the same shape as in the low B_0 case. The same applies to the T_e profiles.

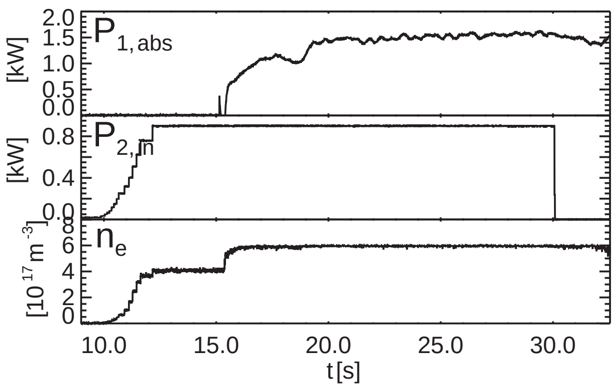

Figure 3: Time traces of discharge #5662.

An interesting effect occurs, if additional heating at $f_1 = 2.45$ GHz (the P_1 trace in Fig. 3) is applied to discharge heated with $f_2 = 8.3$ GHz (the P_2 trace in Fig. 3): The density increases, when f_1 is switched on. After f_2 is switched off, the plasma density stays at its high density level. Since $\omega_1 < \omega_{ce}$ in this regime, it is labelled as *non-resonant* heating regime. The density values achieved in these discharges clearly exceed the values in the low B_0

discharges.

It was not possible to start plasma at the high magnetic field with the microwave source f_1 alone. A minimum density is required before the non-resonant heating process starts to operate. This density is produced with the microwave system f_2. To determine the value of the minimum density, power modulation experiments have been carried out, as shown in Fig. 4. P_2 has been modulated with a triangular wave, in order to constantly increase the plasma density, whereas the P_1 has been modulated with a square wave. Also depicted is the line averaged density. The signals are averaged over 100 modulation cycles. The density threshold, where the non-resonant heating starts can be identified by the change in the slope of the density trace. It is located at $t \approx 2$ ms and corresponds to a density value of $n_e \approx 7 \cdot 10^{16}$ m^{-3} which roughly corresponds to the cutoff density of f_1. A possible explanation for this regime is as follows: For oblique propagation due to multiple reflections between the vessel wall and the plasma boundary, the resonances from cold plasma theory are shifted in their positions in the plasma. According to Ref. [7], one of the resonances is labelled as *O resonance*. Through this resonance, which occurs only if the density is above the O-mode cutoff density, it is in principle possible to couple f_1 to an R wave with a short wavelength which can then be absorbed via collisions.

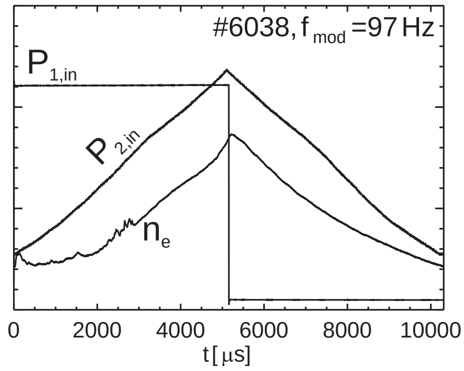

Figure 4: Density threshold for non-resonant heating at $t \approx 2$ ms.

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