Mode conversion and parametric decay instabilities in electron cyclotron resonance heated helium, deuterium and hydrogen plasmas in TOMAS

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The International Thermonuclear Experimental Reactor (ITER) will rely on three sources of external heating to produce and sustain a plasma; Neutral Beam Injection (NBI), Ion Cyclotron Resonance Heating (ICRH) and Electron Cyclotron Resonance Heating (ECRH). ECRH is a way to heat the electrons in a plasma by resonant absorption of electromagnetic waves. The energy of the electrons is transferred indirectly to the ions by collisions. The electron cyclotron heating system can be directed to deposit heat in very specific regions in the plasma and can be used to perform Electron Cyclotron Wall Conditioning (ECWC) between shots to enhance the plasma performance.

ECRH at the fundamental resonance in X-mode is however limited by a low cut-off density. Electromagnetic waves cannot propagate in the region between this cut-off and the Upper Hybrid Resonance (UHR) and cannot reach the Electron Cyclotron Resonance (ECR) position. Higher harmonic heating is hence preferred in nowadays heating scenarios to overcome this problem.

Additional power deposition mechanisms can occur above this threshold to increase the plasma density. This includes collisional losses in the evanescent region, resonant power coupling at the UHR, tunneling of the X-wave with resonant coupling at the ECR, conversion to the Electron Bernstein Wave (EBW) with resonant coupling near the ECR and parametric decay of the injected waves to other frequencies.

Several ECRH experiments are performed on the TOroidally MAgnetized System (TOMAS) to identify the conditions for Electron Bernstein Wave (EBW) heating and Parametric Decay Instabilities (PDI). Density and temperature profiles are measured with movable Triple Langmuir Probes. Measurements of the forwarded and reflected power allow to evaluate the coupling efficiency. A spectrum analyzer is subsequently connected to a movable pin probe and to a single strap ICRF antenna, to verify the different waves present in the machine.

The TOMAS device The TOMAS device is a TOroidally MAgnetized System (TOMAS) [1], which is operated by LPP-ERM/KMS at the FZ-Jülich. It is a facility designed to study plasma production, wall conditioning and plasma – surface interactions. A magnetron with a frequency $f_{EC} = 2.46\ GHz$ is used as microwave source for ECRH of the plasma and can inject 0.7-6.0 kW of power. The device is equipped with various plasma diagnostics [2]. The Langmuir probe system consists of two quadruple movable probes. The optical diagnostics include video diagnostics, a photo-detector, optical emission spectroscopy and a microwave interferometer. Particle diagnostics include a time-of-flight neutral particle analyzer, a retarding field energy analyzer, a residual gas analyzer (quadrupole mass spectrometer) and vacuum gauges. A sample holder allows us to study plasma-material interactions, e.g on boronized tungsten samples.

Langmuir probe calibration An absolute calibration of the horizontal density measurements of the triple Langmuir probe in TOMAS - based on the presence of the O-cutoff - has already been performed (Figure 1) [3]. The results were confirmed by spectrometer measurements [4]. This allows to identify the presence of the R- and L-cutoff and the UHR and evaluate the different power deposition mechanisms.

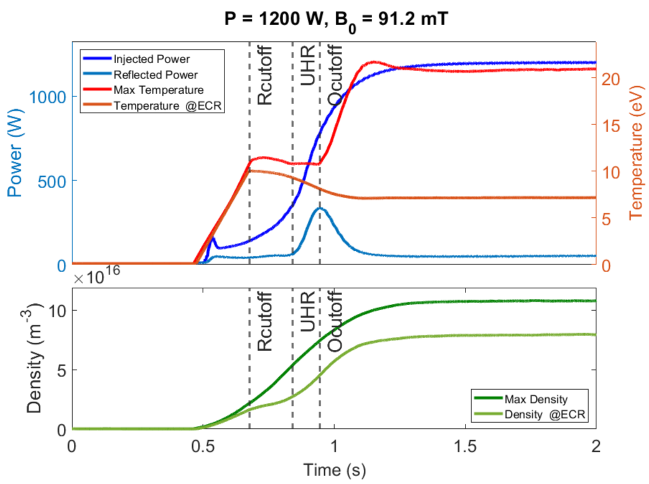

Figure 1: Evolution of the injected and reflected power, temperature, and density over time for a helium plasma with a pressure of 6.0×10^{-4} mbar, a magnetic field on-axis of 92.1 mT and 1200 W of injected power.

Power deposition in a helium plasma The initial power deposition is located near the ECR [5]. Mode conversion to the EBW appears beyond the R-cutoff when the UHR is reached (FX-B and FX-SX-B conversion), with additional mode conversion to the EBW beyond the O-cutoff (O-X-B conversion). This is visible in the density profile around $\approx +10\ cm$ (Figure 2). The location of the UHR is characterized by a non-monotonic density profile ($\approx +19\ cm$) where an absolute instability can occur: Two Plasmon Decay (TPD) [6].

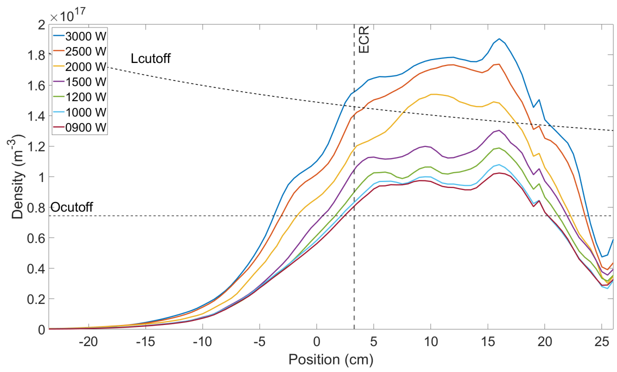

Figure 2: Density profile for different values of the injected power up to 3000 W for a helium plasma with a pressure of $6.0 \cdot 10^{-4}$ mbar and a magnetic field of 92.1 mT.

Additional mode conversion to the EBW appears beyond the L cutoff (FX-SX-B conversion) which increases the density at $\approx +10\ cm$. Additional power deposition locations appear when the power exceeds $3000\ W$ (Figure 3). This could be due to a convective instability at the UHR.

It is clear that additional power deposition mechanisms are present and a more in-depth investigation is needed.

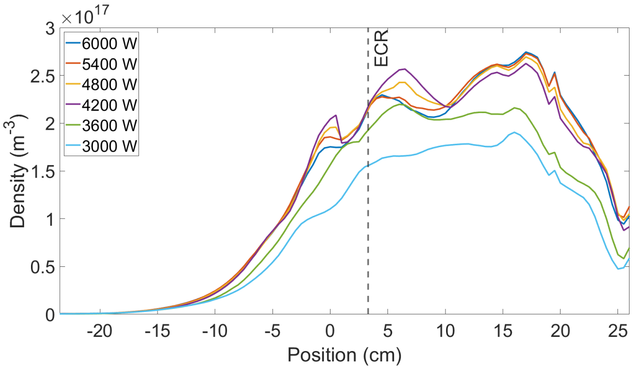

Figure 3: Density profile for different values of the injected power up to 6000 W for a helium plasma with a pressure of 6.0×10^{-4} mbar and a magnetic field on-axis of 92.1 mT.

Spectral Analysis of a deuterium plasma A spectrum analyzer is subsequently connected to a movable pin probe and to a single strap ICRF antenna, to verify the different waves present in the machine in a deuterium plasma. Both measurements give similar results (Figures 4-5). The injected frequency is clearly visible near 2.46 GHz. An additional frequency is observed near 321 MHz and 696 MHz, following the shape of the injected frequency. Additional signals are observed at lower frequencies (e.g. 21, 35, 63, 106 MHz), even at low powers. This could indicate the presence of an absolute instability. At higher power ($> 3000\ W$), the number and intensity of the signals below 200 MHz grows, suggesting a convective instability at the UHR. A hydrogen plasma shows a similar behavior as a deuterium plasma.

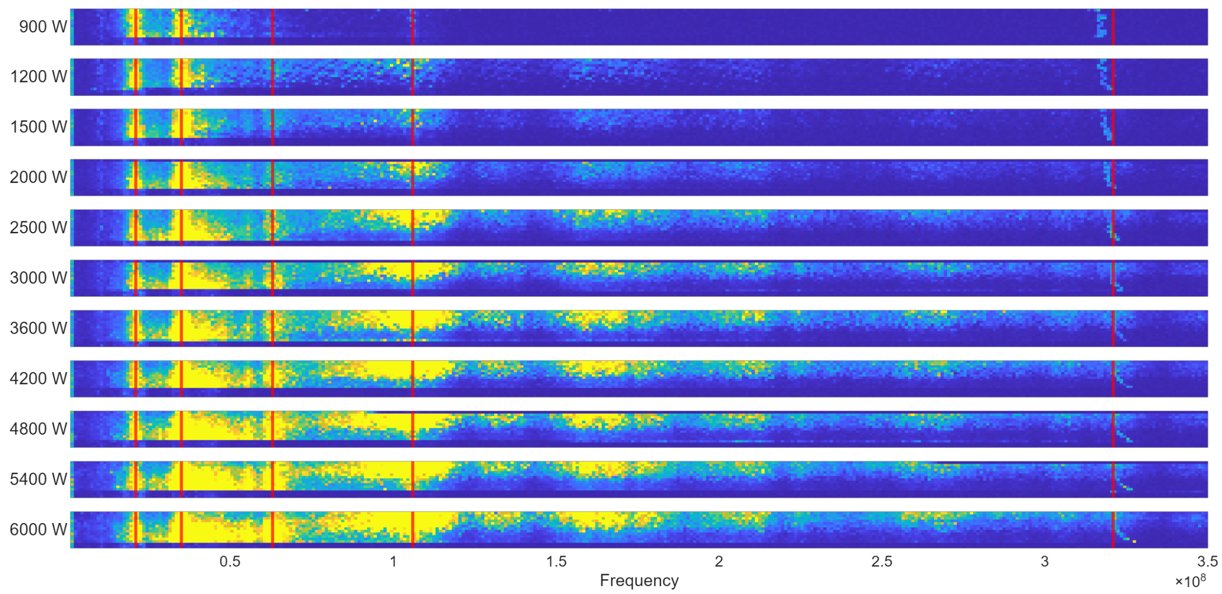

Figure 4: Spectral analysis up to 350 MHz for different values of the injected power for a deuterium plasma

Spectral Analysis of a helium plasma For a helium plasma, we can observe a similar behavior. Increasing the power, increases the signals up to 300 MHz, but this effect is less visible compared to a deuterium plasma. However the signal near 321 MHz is clearly more pronounced, especially at higher powers. This could indicate the presence of a convective instability near at the UHR, as observed in the density profiles.

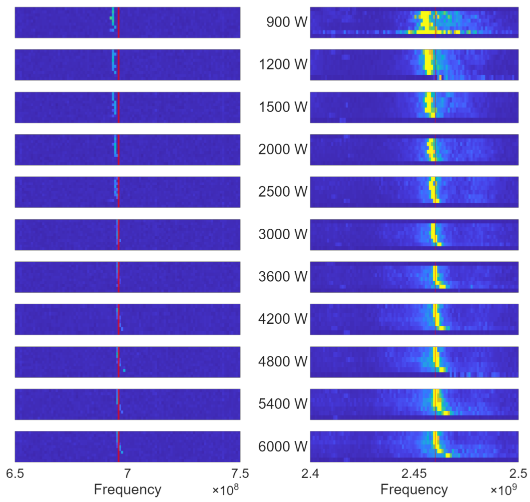

Figure 5: Spectral analysis near 700 MHz and 2.46 GHz for different values of the injected power (deuterium)

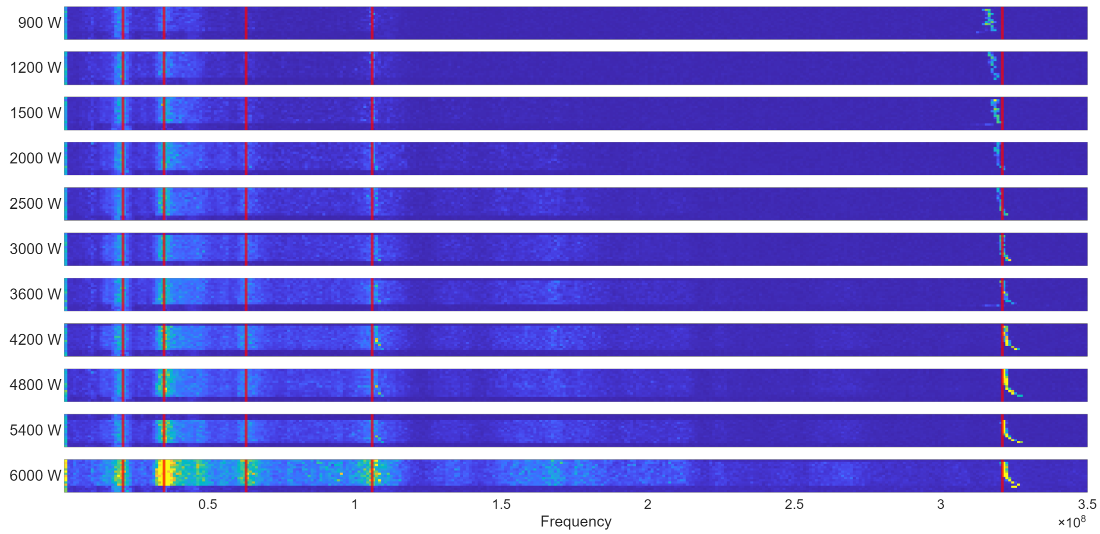

Figure 6: Spectral analysis up to 350 MHz for different values of the injected power for a helium plasma

Conclusion In the TOMAS device we observe that Electron Cyclotron Resonance Heating of over-dense plasmas causes conversions to the Electron Bernstein Wave and possibly parametric decay instabilities. This introduces additional power deposition mechanisms which can be useful to heat the plasma, but could also damage diagnostics. Additional research is needed to identify the conversion and parametric decay mechanisms and get a better understanding of these power deposition mechanisms.

References

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