Electron Bernstein Wave Heating in the TCV Tokamak

A. Mueck [1], *Y. Camenen* [1], *S. Coda* [1], *L. Curchod* [1], *T.P. Goodman* [1], *H.P. Laqua* [2], *A. Pochelon* [1], *TCV Team* [1]

[1]Ecole Polytechnique Fédérale de Lausanne EPFL, Centre de Recherches en Physique des Plasmas, Association EURATOM- Confédération Suisse, 1015 Lausanne
[2]Max-Planck-Institut für Plasmaphysik, EURATOM Assoziation, D-17491 Greifswald

Electron cyclotron resonance heating of high density tokamak fusion plasmas is limited due to so-called wave cut-offs. Electron Bernstein Wave Heating (EBWH) via a double mode conversion process from ordinary (O) to extraordinary (X) and finally to Bernstein (B) mode offers the possibility to overcome this limit. The angular dependence of the O-X mode conversion process is shown in high density H-mode plasmas, with ELM and sawtooth activity. Localized heating experiments via the O-X-B mode conversion process are presented, demonstrating EBWH for the first time in an overdense standard aspect ratio tokamak plasma. The results of global and local power deposition are compared with ray tracing calculations. A temperature increase due to EBWH is measured with Thomson scattering and the soft X-ray absorber method.

INTRODUCTION

Electron cyclotron heating of high density plasmas is limited due to wave cut-offs. The double mode conversion scheme from O-mode to X-mode and finally to Bernstein mode O-X-B offers the possibility to overcome this limitation [1-3]. The power transmission function T from O- to X-mode was derived by Mjølhus [4] and defines the angular window for the O-X conversion

$$T(N_\perp, N_\parallel) = \exp(-\pi k_0 \mathbf{L_n}(Y/2)^{1/2}[2(1+Y)(\mathbf{N}_{\parallel,\mathbf{opt}} - N_\parallel)^2 + N_\perp^2])$$

with the density scale length L_n, the refraction indices $N_\perp$, $N_\parallel$ and $Y = \omega_{ce}/\omega$ with the electron cyclotron frequency ω_{ce}. Only for the optimum $N_{\parallel,opt}^2 = Y/(Y+1)$, equivalent to an optimum injection angle, the O-mode wave can be completely converted to X-mode.

In the Tokamak à Configuration Variable (TCV) Electron Cyclotron Resonance Heating (ECRH) at the second harmonic with 82.7 GHz is the main heating source, see figure 1. The power of six gyrotrons with 500 kW each can be injected at chosen angles from four upper lateral and two equatorial ports. Reflected EC power is measured in form of the EC stray radiation level via semiconductor diodes, installed in several sectors of TCV. At a standard TCV magnetic field of B=1.5 T, the plasma becomes overdense to second harmonic X-mode for electron densities of $n_e \sim 4.2 \cdot 10^{19}$ m^{-3} and to O-mode injection at $n_e \sim 8.7 \cdot 10^{19}$ m^{-3}. To achieve a large angular window, the density scale length at the plasma cut-off has to be short,

requiring a steep density gradient. This was realized in TCV H-modes with central electron densities of $n_e \sim 1.5 \cdot 10^{20}$ m^{-3} and magnetohydrodynamic activity like edge localized modes and sawteeth. At these densities, the plasma cut-off is placed at $\rho_\psi \sim$ 0.9, at the steep edge density gradient region of the H-mode.
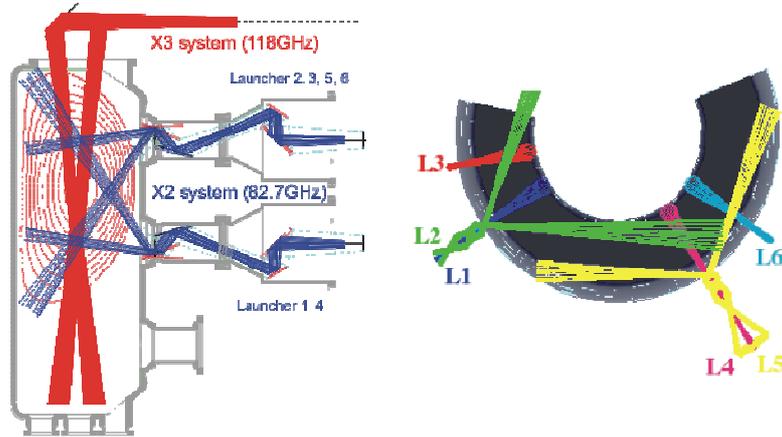

FIGURE 1. The ECRH system of TCV, heating at the second harmonic with 82.7 GHz, contains four upper lateral launchers and two equatorial launchers.

EXPERIMENTAL DETERMINATION OF OPTIMUM ANGLE

To avoid a perturbation of the H-mode, the EC power of 500 kW was injected with a low duty cycle. Poloidal and toroidal angle scans were performed to obtain experimentally the optimum injection angle. As shown in figure 2, clear minima in the stray radiation level are measured, indicating maxima of power absorption, thus determining the optimum angle. The same behaviour is found for both upper lateral and equatorial launch in all stray diode signals, taken at various positions in the torus.
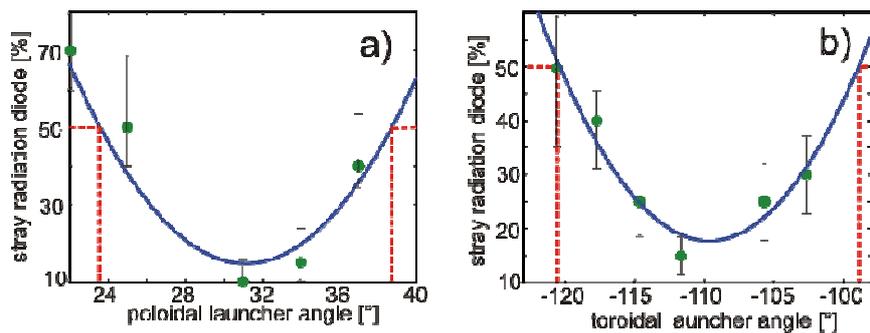

FIGURE 2. a) Poloidal and b) toroidal launcher angle scans. A clear minimum in the stray radiation level is found.

The experimentally determined optimum angles are compared with the results of a simulation with the non-relativistic ART ray tracing code [5, 6] including O-X-B

mode conversion for wave propagation and absorption. In figure 3, the simulated O-X conversion efficiency is shown. The angles of the poloidal and the toroidal scans for an equatorial launch are added as small dots and the extrapolated optimum angle as a large dot. This experimental optimum angle is in good agreement with the simulated angle within 2°. Both the angle dependence and the good agreement of experiment and simulation strongly indicate a successful O-X-B mode conversion [7, 8].
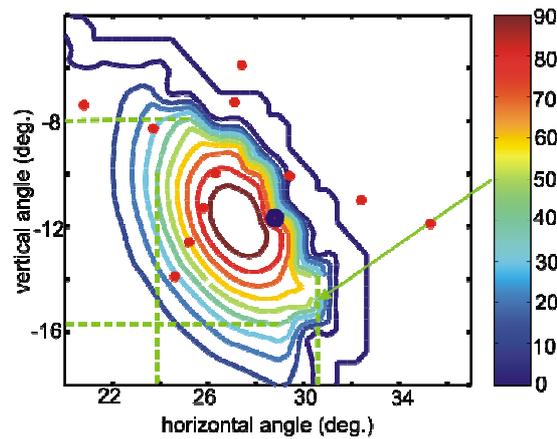

FIGURE 3. Comparison of experimental angle scans (dots) with simulated O-X conversion efficiency. The experimentally determined optimum angle (extrapolated) is within 2° of the simulated optimum angle.

GLOBAL AND LOCAL BERNSTEIN WAVE HEATING

Modulated ECRH with f = 182 Hz, P_{ECRH} = 500 kW and a high duty cycle of 60% is injected with the optimum angle, as previously experimentally determined, with the goal of measuring global and local heating.
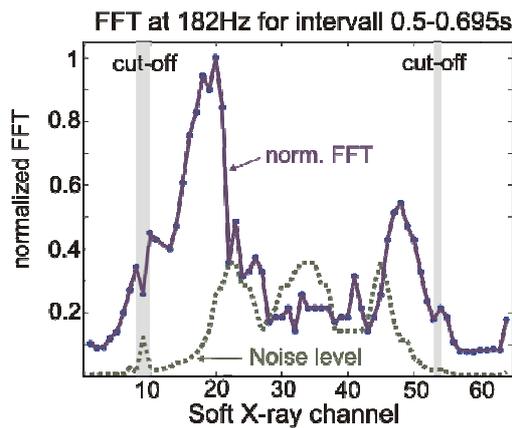

FIGURE 4. Normalized FFT amplitude of each soft X-ray channel at the modulation frequency of the injected ECRH. There are two clear radial maxima in the FFT amplitude around the channels 20 and 48.

The overall global heating can be measured with the diamagnetic loop [9]. Absorption of typically 60% is observed for O-mode injection. In X-mode, the absorption is below

10%, clearly showing that the O-mode can penetrate into the plasma while the X-mode is reflected, as expected for overdense plasmas. A small percentage seems to be absorbed by multipass absorption in O-mode and, due to a change in polarization by reflection, in X-mode. In soft X-ray time traces, a heating effect caused by the modulated ECRH is visible in several channels already to the nacked eye. A FFT analysis of each of the 64 soft X-ray chords was performed. In figure 4, the amplitude of the FFT at the ECRH modulation frequency is drawn over the soft X-ray channel. Two clear maxima can be seen, well inside the plasma cut-off, indicating the deposition location.
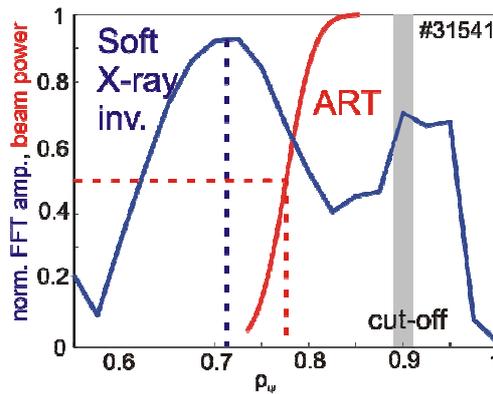

FIGURE 5. FFT amplitude of inverted soft X-ray data and simulated normalized beam power over ρ_ψ. The experimental deposition location is with $\rho_\psi \sim 0.72$ within 10% of the simulated one at $\rho_\psi \sim 0.78$.

Since the soft X-ray chords are line integrated, an inversion is necessary. In figure 5, the FFT amplitude of the inverted data over the poloidal flux coordinate ρ_ψ is shown. The maximum in the FFT amplitude is located at $\rho_\psi \sim 0.72$. The normalized beam power, simulated with the ART code, is added. 50% of the beam power is absorbed at $\rho_\psi \sim 0.78$, within only 10 % from the measured deposition location.
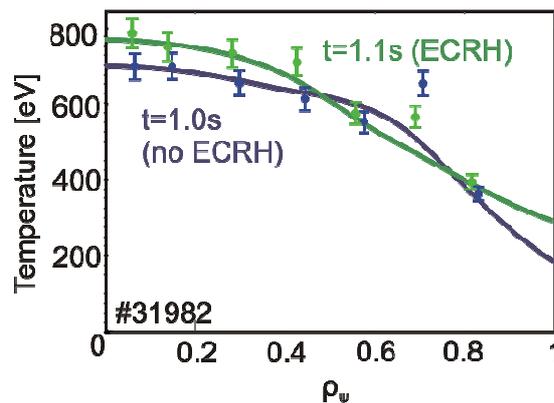

FIGURE 6. Central temperature increase of $\Delta T_e \sim 100$ eV measured with Thomson scattering, confirmed by soft X-ray temperature measurement with $P_{Ohm} = 0.6$ MW, $P_{ECRH} = 1$ MW and additional $P_{ECRH} = 1$ MW pulses of 100 ms.

The injected power is increased to 1 MW and the pulse length to 100 ms, to show an increase in the central electron temperature over several confinement times. Figure 6 shows the Thomson temperature fit before the ECRH pulse at 1.0 s and during the ECRH pulse at 1.1 s. A clear increase of $\Delta T_e \sim 100$ eV is achieved, confirmed by temperature measurements with the soft X-ray absorber method. The density was constant during the measurement, so that the temperature evolution is essentially the result of EBWH.

CONCLUSIONS AND OUTLOOK

The optimum injection angle for O-X-B conversion was determined experimentally. A clear angle dependence in the EC stray level was found. Simulations with the ART code were performed and the simulated optimum angle is within 2° in good agreement with the measurements.

Global absorption of the order of 60 % were observed with the diamagnetic loop with modulated ECRH power injection. The local deposition, well inside the plasma cut-off layer, was determined to $\rho_\psi \sim 0.72$ by FFT analysis of inverted soft X-ray data and lies within only 10 % of the simulated beam absorption at $\rho_\psi \sim 0.78$.

A temperature increase of $\Delta T_e \sim 100$ eV was measured consistently by Thomson scattering and the soft X-ray absorber method.

In summary, localized heating experiments were presented, demonstrating EBWH for the first time via the O-X-B mode conversion process in a standard aspect ratio tokamak.

ACKNOWLEDGMENTS

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