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ECRH Power Deposition Studies in ASDEX Upgrade

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Introduction

Electron Cyclotron Resonance Heating (ECRH) has shown its importance in tokamak studies and its present usage substantially exceeds its heating application. Perturbative transport studies, NTM stabilization, sawteeth tailoring, current profile control and formation of ITB by ctr-ECCD are best examples employing ECRH and its advantage to have narrow well localized power deposition [1]. All these scenarios in which ECRH is involved require a good knowledge of ECRH power deposition particularly in unstationary situations like sweeping of magnetic field B, steering of the launched beam or in very novel frequency tunable gyrotron applications. However ECRH power deposition is sensitive to many factors: magnetic field B and equilibrium, plasma density n and electron temperature T_e which are flux functions, and variety of geometrical factors as launching angles, launching position and initial shape of the beam.

In ASDEX Upgrade ECRH power deposition is calculated by TORBEAM [2] code. The code implements beamtracing technique [2, 3] for drawing the propagation of EC beam with Gaussian cross section in cold plasma. The code is designed to take full set of experimental conditions for a given shot including the necessary data from magnetics and essential kinetic profiles. In the case of missing data or simulation theoretical profiles can be provided as well. EC wave absorption is calculated on the central ray employing a numerical approach [4] which gives the imaginary part of the wave vector adopting a weakly relativistic approximation for the dielectric tensor. The density of the deposited ECRH power $p_{ECRH}(\rho)$ is obtained by mapping the EC absorption profile over the flux surfaces. Although the EC absorption profile may have different shapes the power density profile $p_{ECRH}(\rho)$ can be well approximated with Gaussian curve. Thus the center of the deposition ρ_0 and the width of the deposition profile w_0 are determining $p_{ECRH}(\rho)$.

The experimental recovery of $p_{ECRH}(\rho)$ requires measurement of ρ_0 and w_0 which can in principle be obtained from the response of electron temperature T_e, measured by ECE, on transient processes: switch on/off or modulation of ECRH power.

Feasibility for experimental recovery of $p_{ECRH}(\rho)$

Initially in the ECRH deposition studies slab model approximation is used for assessment of the possibility of experimental recovery of $p_{ECRH}(\rho)$ by T_e response [5]. The results from this model show that the center of ECRH power deposition ρ_0 can easily be measured by finding the position of greatest electron temperature change $dT_e(\rho) = T_e(\rho, t_{0+}) - T_e(\rho, t_{0-})$ after switch on/off ECRH at $t = t_0$ or from the maximum of the perturbed electron temperature profile $\tilde{T}_e(\rho)$, derived after FFT of $T_e(t)$, when modulated ECRH (frequency f_m) is applied.

The determination of the deposition width w_0 from T_e response is more difficult. In switch on/off (modulated) ECRH experiments the width of the temperature response $dT_e(\rho)$ ($\tilde{T}_e(\rho)$) depends [5] complexly on diffusion as described by the characteristic time $a = 3w_0^2/8\chi_e$ where χ_e is the local heat diffusivity and the damping mechanism in electron energy balance. The damping terms in electron energy balance equation account for all other power inputs and sinks and act as a saturation mechanism in T_e response to ECRH so that $dT_e(\rho)$ profile at a time $t \gg a$ long after switch on/off (the $\tilde{T}_e(\rho)$ profile for very low frequency $f_m \ll 1/(2\pi a)$) is nearly independent of $p_{ECRH}(\rho)$. So in order to recover w_0 from T_e measurements one should derive $dT_e(\rho)$ profile in time $t < a$ (or $\tilde{T}_e(\rho)$ at high modulation frequencies $f_m > 1/(2\pi a)$).

The estimation of a for $\chi \approx 1m^2/s$ and $w_0 = 1cm$ gives $a \approx 40\mu s$ and measurement of dT_e with sufficient accuracy with that time resolution is practically impossible. Another practical limitation in w_0 recovery comes from the quick broadening of the measured width by perpendicular heat transport and the finite time needed for T_e to redistribute around flux surfaces. For example, in ASDEX Upgrade $1keV$ electrons heated in the focused beam distribute their energy around a flux surface at half minor radius in about $50\mu s$ [5]. Therefore very narrow profiles as in the example above can not be recovered experimentally by T_e measurement.

The characteristic time a increases with decreasing heat diffusivity χ_e and increasing w_0. Therefore the first experimental approach in our study was to determine w_0 by decreasing χ_e after applying supplementary off-axis cw ECRH leading to lower transport in the inner region [6] and applying modulated ECRH there. For comparison experiment with supplementary on-axis cw ECRH in which χ_e is increased in the outer region where modulated ECRH is deposited was carried out. The importance of decreasing χ_e to get $\tilde{T}_e(\rho)$ profile close to $p_{ECRH}(\rho)$ is clearly seen when both experiments are compared, Figure 1. The narrowing of $\tilde{T}_e(\rho)$ profile with f_m is also observed but as the results and the calculations show even at $f_m = 1kHz$ the profile $\tilde{T}_e(\rho)$ is still broader than the calculated narrow p_{ECRH} profile.

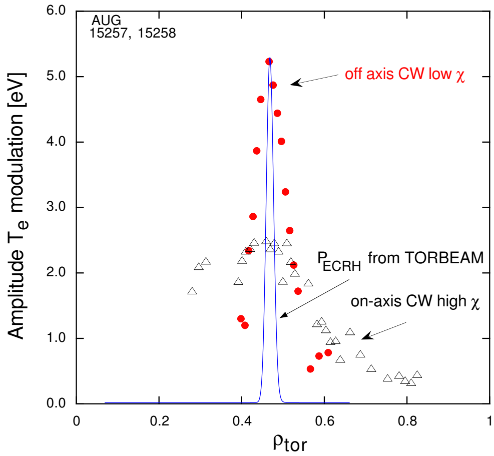

Figure 1: $\tilde{T}_e(\rho)$ profiles from experiments with $f_m = 500Hz$ and decreased (∘) and increased (△) χ_e compared with $p_{ECRH}(\rho)$ (—).

For experimental recovery of w_0 and the determination of the total absorbed power, P_{ECRH}, calculations with transport code ASTRA [7] are performed. In our study with ASTRA the equilibrium is fixed as it is in ECRH discharge and it is supposed that it changes negligible with ECRH. The Ohmic heating is determined assuming neoclassical conductivity, radiative power is taken experimentally from bolometry. In the modulated ECRH studies ASTRA is supplied with FFT and $\tilde{T}_e(\rho)$ profiles are observed. When total absorbed power P_{ECRH} is calculated ASTRA is provided with the experimental values of T_e and n and the missing power input from power balance is attributed to P_{ECRH}.

Experimental results

The position of **center of ECRH deposition** ρ_0 is obtained experimentally by (i) determination of the maximum drop(jump) of T_e in switch off(on) ECRH experiments or by (ii) maximum of perturbed T_e profile in modulated ECRH experiments.

Deposition centers at toroidal angle $\varphi = 0°$, and for different poloidal angles θ derived from the maximum change of T_e after transient process of switching on/off ECRH source are plotted in Figure 2 as a function of ρ_0 from TORBEAM for the corresponding shot. The bars cover the region between two channels with the greatest dT_e, and are bigger if adjacent ECE channels in the deposition region are for apart. Best accuracy in ECRH deposition determination can be obtained in sawteeth free discharges and for that reason not all ECRH shots were available for proper evolution.

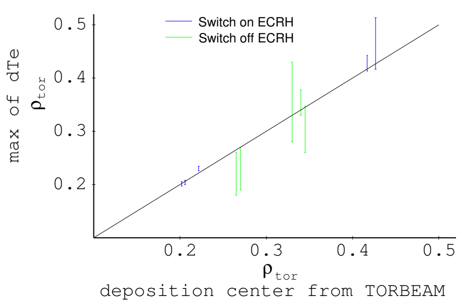

Figure 2: Deposition centers from maximum change of T_e in switch on/off ECRH experiments as a function of ρ_0 from TORBEAM.

The results in Figure 2 are taken from different discharges in ADSEX Upgrade and generally show good agreement with the beamtracing results. The problems arising from the need to avoid sawteeth in switch off/on ECRH experiments are overcome in modulated ECRH experiments. By applying FFT of the perturbed temperature the sawteeth can be filtrated and ρ_0 be more precisely derived and compared with the beamtracing results. Number of shots in ASDEX Upgrade with fixed magnetic field, equilibrium and plasma parameters and different launching angles are performed. In the case of perpendicular launching the results for three different magnetic fields and at low density are shown in Figure 3.

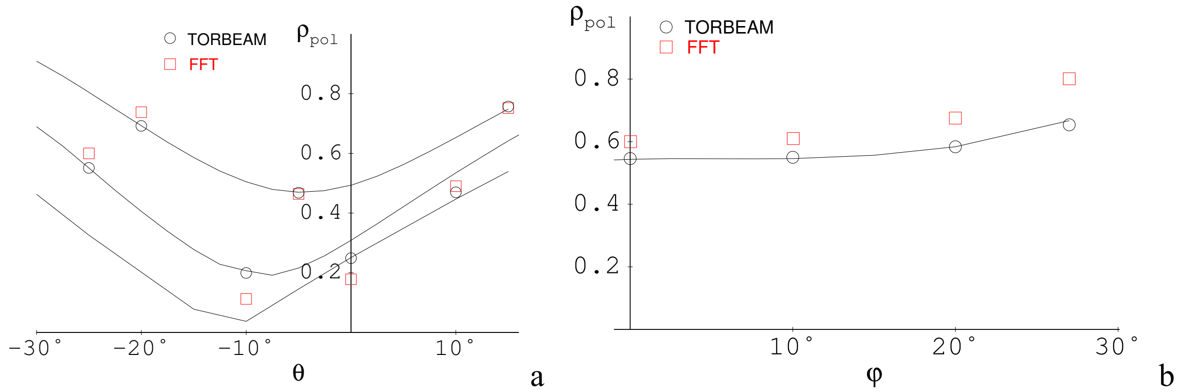

Figure 3: ECRH deposition center from FFT (□), from TORBEAM (∘) and corresponding scan (—) in the cases of perpendicularly $\varphi = 0°$ (a) and obliquely launched off-axis $\theta = -25°$ (b) EC beam at low density $n_0 \approx 2 - 4.5 \times 10^{19} m^{-3}$.

The corresponding ρ_0 from TORBEAM and the poloidal scan are shown as well. Good agreement between the experimental and calculated deposition centers is observed in the three cases in Figure 3a even when the beam is diverged much from the magnetic axis.

The deposition center is obtained and compared with the calculated one also in the case of oblique launching of off-axis ECRH beam, Figure 3b. Here larger discrepancies between the derived and calculated ρ_0 are observed. They could be due to systematic errors arising from uncertainties in magnetic field B or plasma density n. The central plasma density in this case was $n_0 \approx 4.5 \times 10^{19} m^{-3}$ i.e. diffraction of the beam becomes effective. Consequently, small discrepancies in B, n or in the direction of the launched beam, angles θ and φ, produce large uncertainties in ρ_0 determination. For instance, a 15% variation of n_0 and/or 3% variation of the magnetic field B lead to a much better match between calculation and experiment.

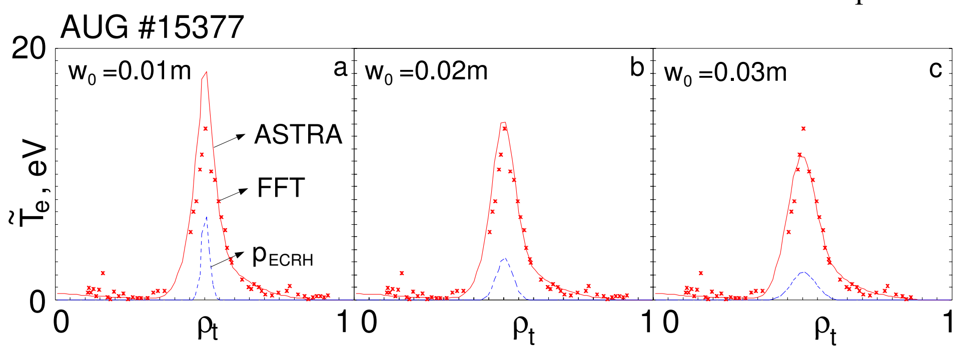

Figure 4: Experimental $\tilde{T}_e(\rho)$ profiles from FFT (dots) and from ASTRA (lines) for three different values of w_0 and $f_m = 300 Hz$. Dotted lines show the deposition profile from TORBEAM.

As it was mentioned in the previous section by applying off-axis cw ECRH the heat diffusivity χ_e in the core plasma was decreased in our experiments and the characteristic time a is increased to be larger compared to the time needed for T_e distribution around flux surfaces. Even in this case it is still difficult to measure dT_e for times $t < a \lesssim 100 \mu s$ or $\tilde{T}_e$ for high enough frequencies $f_m > 1/(2\pi a)$. Therefore we estimate the **ECRH deposition width** w_0 in an indirect way, in which $\tilde{T}_e(\rho)$ profiles determined experimentally from FFT are compared to those calculated by ASTRA, provided with experimental equilibrium, power inputs and sinks. The electron heat flux is calculated with heat diffusivity which is superposition of neoclassical and turbulent one based on a Weiland model [8]. This model describes quite good T_e evolution in ASDEX Upgrade in the case of moderately off-axis heating [9]. $\tilde{T}_e(\rho)$ profiles are calculated supposing ρ_0 as derived from FFT, slightly different from TORBEAM result, and varying w_0. In Figure 4 three $\tilde{T}_e(\rho)$ profiles for three different values of w_0 are shown and compared with the experimental results from FFT. The best match in Figure 4 is observed for $w_0 = 0.02m$. The TORBEAM result for these experimental conditions was $w_0 \approx 0.01m$ and as Figure 4a shows this is probably too narrow profile resulting in narrower and more peaked $\tilde{T}_e(\rho)$ profile. Figure 4 also shows that frequency of $f_m = 300Hz$ is too low to reproduce $p_{ECRH}(\rho)$.

The proper selfconsistent determination of the **total absorbed ECRH power** P_{ECRH} require right power balance in Ohmic and ECRH discharges to be accounted. The power balance from ASTRA provided with experimental $T_e(\rho)$ profile evolution when ECRH is switched on after the assumption of constant heat flow through the plasma boundary will give P_{ECRH} as a difference between the change of the total energy $P_w = dW/dt$ and the other power sources and sinks, Figure 5.

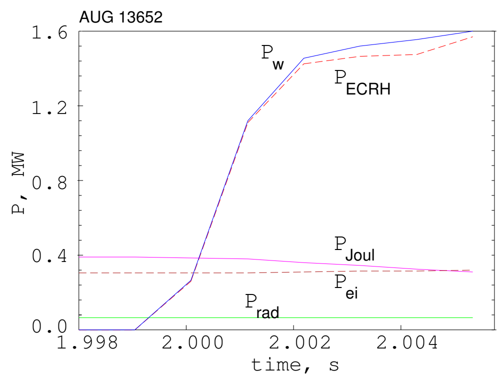

Figure 5: Power balance at switch on ECRH power.

The experimental data derived in an Ohmic discharge at low density, without external particle sources and with two main sinks of energy, Coulomb collisions and radiation, also show that $5ms$ after switching on ECRH the biggest contribution in energy balance come from the P_w term. The calculated Ohmic heating P_{Joul} drops by 10% while the energy exchange between electrons and ions P_{ei} increases by $\approx$ 4%, Figure 5. The obtained total absorbed power in this case is $P_{ECRH} \approx 1.46MW$ and it is only about 5% less than the applied power.

Conclusions

The present study is an attempt to compare experimental and calculated data related to ECRH power deposition in ASDEX Upgrade. The ECRH power deposition centers and widths are obtained experimentally from the response of the electron temperature T_e on the switched on/off or modulated ECRH. The experimentally derived deposition centers coincide reasonably well with the calculated ones for not very large deviation of the beam from the magnetic axis. A scheme with supplementary off-axis cw ECRH creating low transport region in the core plasma is applied to determine the width of the modulated ECRH deposited in this region by comparing calculated and experimentally derived FFT profiles of $\tilde{T}_e(\rho)$. The total absorbed ECRH power is obtained from power balance after switching on ECRH accounting all contributions in electron energy balance and agrees well with the experiment.

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