Localized ECRH Power Deposition in ASDEX Upgrade

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1) Introduction

For ASDEX Upgrade an ECRH system with 140 GHz, 2 MW, 2 sec is in construction [1]. Up to now experiments with 0.4 MW, 0.5 sec, 2nd harmonic x-mode were performed, mainly for heat wave studies, where amplitude and phase of the heat wave are evaluated outside of the power deposition zone to deduce the electron heat conductivity [2]. In this paper we want to examine how and which information can be deduced from the temperature rise in the deposition region.

2) The heat diffusion equation

We assume the plasma as homogeneous within the considered volume and apply the linearized heat diffusion equation with constant coefficients to describe the temperature rise after switch-on of the ECRH

$$v_t(x,t) = \frac{2}{3}\chi\, v_{xx}(x,t) - b v(x,t) + f(x,t) \qquad (1)$$

The subscripts denote differentiation with respect to time or space. The damping term b describes changes in the local Ohmic power input and in the electron-ion collisions. For the driving term $f(x,t)$ we assume a Gaussian profile of amplitude $f_0(t)/(w\sqrt{\pi})$, width w, and a step function $f_0(t)$ in time centered at $x = x_0$. The solution to this equation is

$$v(x,t) = ac\frac{e^{ab}}{\sqrt{ab}}\left\{\Psi\left(\sqrt{ab(1+t/a)},\sqrt{abg}\right) - \Psi\left(\sqrt{ab},\sqrt{abg}\right)\right\} \qquad (2)$$

with $a = w^2/(8\chi/3)$; $c = f_0/w$; $g = (x-x_0)^2/w^2$; and the function

$$\Psi(\mu,\nu) = \frac{2}{\sqrt{\pi}}\int_0^{\mu}\exp(-\xi^2 - \nu^2/\xi^2)\,d\xi \qquad (3)$$

The quantity a is a characteristic time depending on the heat conductivity χ and the deposition width w, while c is the temperature rise per time unit at $x = x_0$ and $t = 0$, and g is a normalized space coordinate. The function $\Psi(\mu,\nu)$ can be expressed in the form of usual errorfunctions as

$$\Psi(\mu,\nu) = \frac{1}{2}\left\{e^{-2|\nu|} - e^{2|\nu|} + e^{2\nu}\Phi(\mu+\nu/\mu) + e^{-2\nu}\Phi(\mu-\nu/\mu)\right\} \qquad (4)$$

Fig.1 shows the calculated time evolution of temperature at different locations g. The time is normalized to the characteristic time a. Within the power deposition region, $g \leq 4$, the temperature rises instantaneously, outside the temperature rise is increasingly delayed. Nonzero damping, $b \neq 0$ acting as a sink of energy, leads asymptotically to a finite temperature increase. Evaluations of equ. (2) show that it takes about 10 characteristic times for the profile to expand in space by about a factor of 2.

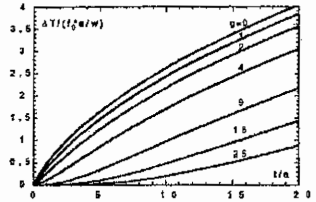

Fig. 1: Normalized temperature rise at zero damping (b = 0), at different locations g = ((x-x0)/w)^2

The temperature rise given by equ.(2) depends on the width w of the deposition profile. However, for $t/a \gg 1$ the temperature evolution becomes independent of w. Therefore the temperature evolution contains information on the initial power deposition profile only for times $t/a < 1$.

3) Application to ASDEX Upgrade shots

In ASDEX-Upgrade we apply ECRH in the 2nd harmonic x-mode to achieve a stronly localized power deposition. In addition the Gaussian microwave beam is focused such that also for off-axis heating by poloidal beam deflection the power deposition remains very localized. Ray tracing calculations, including diffraction effects to describe the Gaussian beam [3], result in power deposition profiles with widths w from 3 mm to 15 mm. Assuming a heat conductivity of $\chi = 1$ m^2/sec this corresponds to characteristic times of $a = 3.5$ to 80 μsec. With such a focused deposition at half radius in ASDEX Upgrade it takes about 50 μsec in a 1 keV plasma to distribute the energy around the flux surface. We will therefore not be able to measure deposition profiles with $w < 10$ mm. In addition, for $t/a < 1$ the temperature rise is very small and comparable to the noise level, and we need a much longer time (≈ 1 msec) to determine the rate of change of the temperature. Therefore we cannot expect to reliably determine such narrow deposition profiles from the slope of the temperature rise in a single switch-on event.

However, assuming that locally a homogeneous plasma slab model is applicable, we may use equ.(2) and fit it to the experimentally measured temperature rise (by ECE) over a time span $\Delta t/a \gg 1$. From such a fit we can determine the quantities a, b, c and x_0, but not w. For the fit we use several adjacent ECE channels at known positions x in and close to the deposition region, and assume a deposition profile w as calculated from ray tracing, but not narrower than 10 mm. The fit is done over a time span of 10 msec so that magnetic field diffusion can be neglected. Furthermore, to get unperturbed data during the switch-on of the ECRH heating, we used a time interval in ohmic discharges at the end of the plasma current ramp-up when sawtooth oscillations did not yet set in.

An example of such a fit is shown in fig.2. The fit was applied to all temperature signals simultaneously. According to the applied model, we require the quantities a and c to be constant for all channels, but let b free for each channel. The heat conductivity χ is then calculated from the fit parameter a and is multiplied by κ (κ = elongation) to take into account the variation of the temperature gradient around a poloidal circumference of a flux surface.

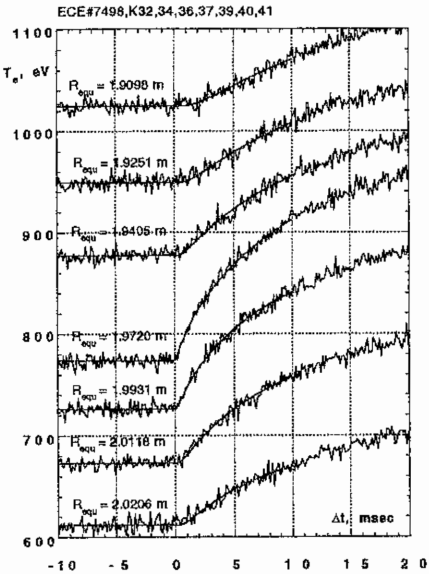

Fig. 2: Fitted ECE-temperature signals. All channels are fitted simultaneously

Values of χ thus obtained at different radial deposition centers are shown in fig.3. Most χ values are in the range of 1 m^2/sec and thus close to the values obtained from power balance analysis, but lower than those obtained from heat wave studies [2,4]. In some of the shots the power was deposited close to a resonant q-surface and did excite an mhd-mode.

From the central temperature rise c as obtained from the fit we can calculate the absorbed power

$$P_{abs} = \frac{3}{2} n_e c \, 2\pi R_0 \, 2\pi r_{dep} w \kappa \qquad (5)$$

with R_0 = major radius, r_{dep} = minor radius of deposition centre. The results are shown in fig. 4 and compared with the launched power.

The centre of deposition x_0 is also obtained from the fit. These results are compared in fig.5 with those calculated with ray tracing for different poloidal launch angles and on-axis resonant magnetic field. These results depend on the precision of the magnetic field reconstruction.

The damping term b was treated as a free fit parameter. So it was different for each ECE channel. The values were in the range 0.01 to 0.1 $msec^{-1}$, and thus of the order as expected from the local drop in ohmic heating power and the electron-ion energy exchange. The values of b tend to be higher on the low field side of the deposition centre, as expected because of the electron temperature gradient.

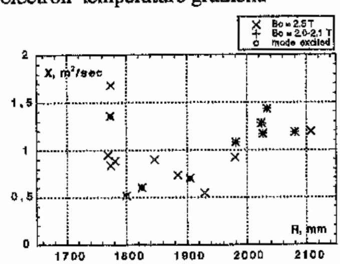

Fig. 3. Heat conductivities determined from the fit parameters as function of the major radius

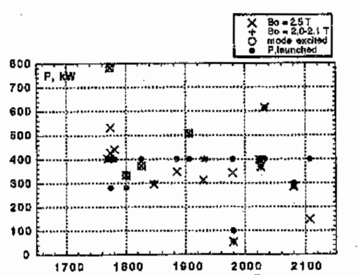

Fig. 4 Absorbed power as obtained from the fit parameter c (R_0 = 1650 mm, a = 500 mm)

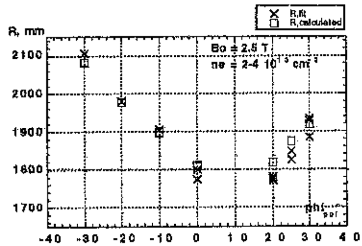

Fig. 5. Deposition centres as obtained from the fit compared to ray tracing results for different poloidal launch angles

Fits like in fig.2 are not uniquely determined. As explained above, for $t/a >> 1$ the information on the initial deposition profile is lost. Consequently we can get nearly equally good fits for different values of the profile width w. These fits differ mainly in the first millisecond, where an instantaneous rise or also a delayed rise can be fitted to the data within their fluctuations. Choosing smaller/larger w would lead to higher/lower values for the heat conductivity, but the product c^*w stays nearly constant. We consider our choice of the width obtained from ray tracing, but $w \geq 10$ mm, a reasonable one.

This fitting procedure was also applied to a test data set, which was created from a modelling of an ASDEX-Upgrade shot with the ASTRA transport code [5], specifying for χ a constant value of 0.8 m^2/sec. Two cases with deposition (width $w = 5$ mm) centered at r/a = 0.5 and r/a = 0.8 were fitted. The value of x_0 was in both cases within 1 mm of the specified deposition centre. The value of χ was within 10% of the specified one. The damping term b was as expected with a radial dependence because of the existing temperature gradient.

4) Summary

The response of the electron temperature upon the switch-on of very localized ECRH heating with Gaussian spatial profile can be well fitted to the heat diffusion equation with constant coefficients. To extract an electron heat conductivity from such a fit one needs to know the deposition profile width. This can in principle also be obtained from the fit. However, for narrow profiles, as we have them in ASDEX Upgrade, this requires better space and time resolution than available. Taking calculated values for the deposition width we arrive at heat conductivities close to those obtained from power balance.
The location of the deposition is within a few centimeters at the calculated position. The absorbed power is of the order of the launched power.

[1] Leuterer F., et al., Proc. 9th worksh. ECE and ECH, Borrego Springs, 1995, p. 529
[2] Ryter F., et al., 23rd EPS Conf. Contr. Fus. and Plasma Phys. Vol.1, 11, Kiev 1996
[3] Peeters A.G.,Phys. Plasmas 3, 4396 (1997)
[4] Ryter F., this conference
[5] Pereverzev G., et al., IPP - report IPP 5/42 (August 1991)