Transient behavior of density and temperature in experiments with modulated central electron heating on ASDEX Upgrade

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The spatial distribution of density in a fusion experiment is of significant importance as it enters in numerous analyses and contributes to the fusion performance. A profound understanding of the underlying transport phenomena is therefore mandatory in order to reliably predict the shape of the density profile in next-step fusion devices, and finally their achievable fusion power. In the recent years, it has been shown that the application of local heat sources in the plasma can influence the shape of the density profile under certain conditions [1]. In low-density L-mode discharges, for example, the application of central heating causes a reduction of the core density and thus a flattening of the density profile. This effect is often referred to as density 'pump-out'.

On ASDEX Upgrade, we recently made use of this coupling mechanism between temperature and density in order to feedback control the shape of the density profile. The density profile was calculated in real-time, and central electron cyclotron resonance heating (ECRH) was used as actuator to adjust the density peaking to the desired value [2]. We also performed feed-forward experiments with square wave ECRH power modulation with a period of 200 ms. The large number of identical heating pulses obtained that way allow us to investigate the coupling between temperature and density in much detail, especially with respect to the transient behavior. Figure 1 shows the time trace of the applied ECRH power, as well as the line-integrated electron density measured by the interferometer along 5 chords, and the electron temperature from one of the ECE channels. In that case, pump-out occurs: As ECRH is switched on, the core density starts decreasing, whereas the edge density hardly changes. When ECRH is turned off, the core density increases again. Depending on the global plasma parameters, this effect can be weaker than

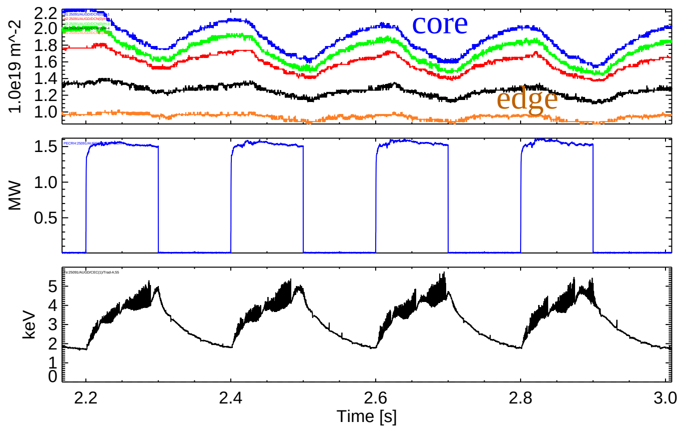

Figure 1: An example of density pump-out. From top to bottom: Time traces of the 5 interferometer channels, applied ECRH power, and T_e measured by an ECE channel at about $\rho = 0.3$.

in the above example, and even reverse sign, such that central heating makes the density profile more peaked. In the recent years, it has been found that the effective collisionality is a key parameter for characterizing the density response to central heating. Density pump-out was found to occur at low collisionality, where the dominant turbulence type is a trapped electron mode (TEM), whereas at higher collisionality, an ion temperature gradient (ITG) mode is dominant and central heating increases density peaking [3].
In the analysis of the temporal evolution of temperature and density in the transient phases, special care has to be taken in order to exclude secondary effects which might bias the result. When operating in L-mode, which we did in the majority of cases, there are basically two critical issues: On the one hand, the application of additional ECRH power might trigger an L-H-transition, which causes an increase of the edge pedestal density. On the other hand, the gas inlet rate has to be kept constant. If the gas valves are feedback controlled by an interferometer channel, which is commonly done on fusion experiments, the density pump-out in the plasma center causes an opening of the gas valves and thus increased fueling from the plasma edge. Those biasing effects can be avoided by exploring the H-mode threshold power beforehand and keeping the applied ECRH power clearly below this value, and by operating with a fixed, pre-programmed gas fueling rate, respectively.

For the analysis, we select a series of ECRH pulses which were injected into a plasma with constant global parameters. Our reconstruction of the temporal evolution of the density is based on two diagnostics, the sub-millimeter interferometer and the lithium beam diagnostic. From this data, a density profile is reconstructed via integrated data analysis (IDA) [4]. The central interferometer channel reaches a minimum ρ of about 0.2 for the plasma configurations used in the experiments, therefore, the density reconstruction for $\rho < 0.2$ has extrapolation character and is not used in the analysis. The electron temperature is obtained from the measurements of the electron cyclotron emission (ECE) radiometer. In the discharges under consideration, the innermost ECE channel probes the plasma at about $\rho = 0.25$. We select a radial location in the plasma, like $\rho = 0.5$ in the following example, extract the temporal evolution of density and temperature from the IDA density profile and the ECE measurements and finally plot the density versus the temperature. An example is shown in figure 2. When the modulation is sufficiently slow, static values of density and temperature are reached after some time, which can be found in the diagram in the top left (ECRH off) and bottom right (ECRH on) corner of the curve. When switching on and off ECRH power, the system does not evolve between those two points along a straight line, but, in contrast, is characterized by a fast response of temperature and a delayed response of density. Accordingly, a hysteresis loop in the local density-temperature diagram occurs, which is run through in the clockwise direction in the density pump-out case. In the figure, this is illustrated by plotting the data points in different color, depending on their timing relatively to the last heating pulse.

The first and second half of the pulse are shown in different color, as well as the first and second half of the time interval in between the pulses, as indicated in the legend of the figure. At higher collisionality, where ECRH increases the density peaking, the static values are located in the bottom left and top right corner, and the curve is run through in the counter-clockwise direction. Depending on the global plasma parameters and the radial location, the area enclosed by the hysteresis loop varies.

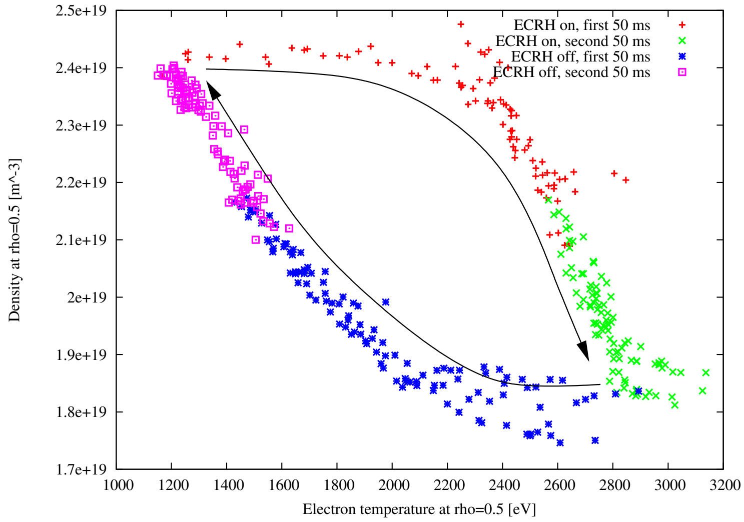

Figure 2: Density-temperature diagram at $\rho = 0.5$ during modulated central heating. The static values for ECRH off are located in the top left, and those for ECRH on in the bottom right corner. The hysteresis curve in run through in the clockwise direction.

In the existing literature on the density response to local heat sources, the focus is mostly only on the static density profiles that occur after a sufficiently long settling time after switching the heating power to a new level. The experimental data obtained here, however, opens up the opportunity to learn more about the coupling mechanism between density and temperature from the transient behavior.

In transport models, the particle flux $\vec{\Gamma}$ is commonly described by the empirical formula [5]

$$\vec{\Gamma} = -D\vec{\nabla}n_e - C_T n_e \frac{\vec{\nabla}T}{T} + \vec{v}_p n_e \, , \tag{1}$$

where D is the diffusion coefficient, v_P the pinch term and C_T the thermodiffusion coefficient. The latter provides coupling between density and temperature by introducing a contribution to the particle flux which is driven by temperature gradients.

We performed transport simulations with the ASTRA code in order to investigate whether the occurrence of a hysteresis loop in the $n_e - T_e$ diagram can be reproduced on the basis of the above transport equation. For the simulation, a static ion temperature profile was used, whereas for electron density and temperature, a measured profile only serves as initial condition and is then evolved dynamically on the basis of the transport equations. Electron cyclotron heating with central deposition and square wave power modulation in time is implemented in the model. With the 3 coefficients D, C_T and v_p in equation (1) and the heat transport coefficient (χ_e), there are all in all 4 free parameters in the simulation which have to be adjusted.

It was found that already the use of transport coefficients that are constant in time and radius yields a hysteresis loop, however, its shape is not well consistent with the experimental observation as it is unsymmetrical. By introducing a critical gradient model [6] for the heat transport coefficient χ_e, which provides more realistic temperature profiles, and a temperature-dependent inward pinch term $v_p = v_{p0} + const. \cdot \frac{T_e}{T_i}$, a more realistic description of the hysteresis curve is obtained, as figure 3 illustrates. The T_e dependence of v_p couples the density to the temperature and removes the need for the thermodiffusion term, i.e. C_T is set to zero.

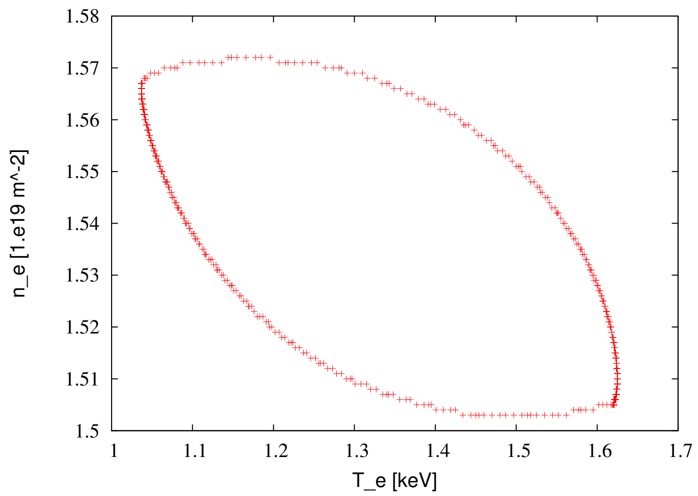

Figure 3: A hysteresis curve simulated with the ASTRA code. The thermodiffusion coefficient has been set to zero, but a temperature-dependent inward pinch was used.

To sum up, the transient behavior of density and temperature has been investigated in plasma discharges where the application of central electron heating affects the shape of the density profile. A sequence of heating pulses has been injected into plasmas with different global parameters, where secondary effects due to gas puff modulation or L-H-transition have been avoided. It has been found that the evolution of the local density and temperature at a given radial location in the plasma is characterized by a hysteresis loop. With qualitative ASTRA simulations, it has been shown that the occurrence of such a hysteresis curve is expected on the basis of the transport equations for heat and particles, and that the shape of the curve varies depending on the settings made for the transport coefficients. Therefore, more detailed information on those coefficients can be obtained by analyzing the transient behavior, which we intend to do in more detailed studies in the near future.

References

[1] C. Angioni, A.G. Peeters, X. Garbet et al., Nuclear Fusion **44**, 827-845 (2004)

[2] A. Mlynek, M. Reich, L. Giannone et al., Nuclear Fusion **51** 043002 (2011)

[3] C. Angioni, A.G. Peeters, F. Ryter et al., Physics of Plasmas **12**, 040701 (2005)

[4] R. Fischer, C. Fuchs, B. Kurzan et al., Fusion Science and Technology **58**, 675-684 (2010)

[5] C. Angioni, E. Fable, M. Greenwald et al., Plasma Phys. Control. Fusion **51**, 124017 (2009)

[6] X. Garbet, P. Mantica, C. Angioni et al., Plasma Phys. Control. Fusion **46**, B557-B574 (2004)