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Cold Pulses and Heat Pulses at ASDEX Upgrade

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Introduction

Understanding energy transport in plasmas devoted to fusion research is the subject of intensive studies. A particular observation of electron transport is the so-called "non-local" transport phenomenon, discovered first in the TEXT tokamak [1] in ohmic discharges at low densities. It is characterized by a fast increase of the electron temperature in the plasma centre in response to edge cooling pulses produced by injection of impurities by means of Laser-Blow-Off (LBO).

An extensive study of cold pulses in TFTR [2] indicates that the phenomenon occurs if the empirical condition $n_e(0)/\sqrt{T_e(0)} \leq 0.035\ 10^{19}$ [m^{-3}/eV$^{1/2}$] is fulfilled. Although this condition implies, that the discharges are not of direct relevance for a reactor, the pronounced effect may help to distinguish between different transport models. Recent simulations by Kinsey et al. [3] using different transport models revealed that the coupling between the electron and the ion transport is an essential feature needed in the models for describing the observed perturbative behaviour. It could also be shown [3], that a critical gradient model, like the IFS/PPPL model, can qualitatively reproduce the experimental observations, while depending only on local variables. In this contribution the characteristics of the cold pulses performed in ASDEX Upgrade will be examined in detail. We used repetitive pulses and varied the source of cooling, the electron density and the safety factor. The behaviour of a typical cold pulse is compared to simulations with the IFS/PPPL model. Heat pulses from ECR-heating were applied to the edge of the plasma to study the symmetry of the phenomenon.

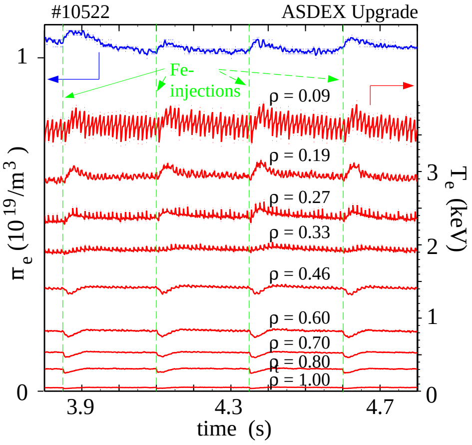

Figure 1: *Time traces of the electron temperature at different radii showing cold-pulses from the injection of Fe. The time trace of the line averaged density is shown on the top.*

Experimental Setup

The cold pulses were produced by impurity injection via a repetitive laser ablation system. It consists of a 0.6J/pulse Nd-YAG laser (λ=1.064μm) with pulse-rates of up to 20 Hz. The laser beam is focussed on the target by a combination of movable lenses and fixed mirrors to allow the deflection and focusing of the laser beam. As targets 2.0 μm films of Fe or layers of about 1.5 mg/cm^2 of C or Si deposited on a glass substrate were used. The amount of injected material was varied with the size of the laser focus. Typical values for the number of injected particles are a few 10^{18} in the case of C and about 10^{17} in the case of Fe. The heat pulses were launched by heating with a gyrotron emitting at 140 GHz. The deposition zone can be adjusted by choosing the adequate magnetic field and by directing a movable mirror onto selected flux surfaces out of the horizontal plane.

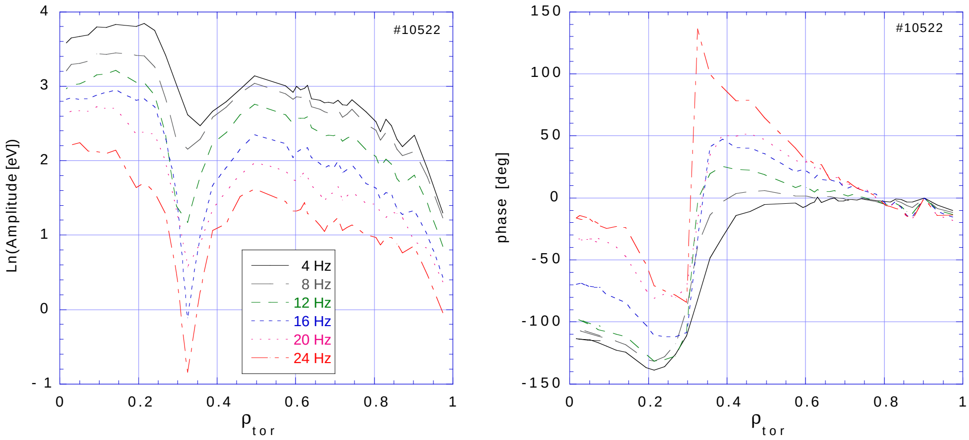

Figure 2: *Logarithm of the amplitude (*$\ln|\Delta T_e|$*, left) and phase (right) of Fe-LBO cold pulses versus radius at for the first six harmonics.*

The electron temperature is measured with an 60 channel ECE radiometer system with a maximum sampling rate of 31.25 kHz. The electron density is gained from a combined DCN interferometer and a lithium beam diagnostic for the edge. The radiation from the plasma is detected by a bolometer system and by spectroscopic measurements in the VUV and the soft X-ray spectral range.

Cold Pulses

Cold pulses were performed mostly in ohmic plasmas by injection of C, Si and Fe by means of LBO and by fast gas-puffs with pure deuterium (5 ms duration). Fig. 1 shows time traces of the electron temperature from an ohmic discharge with $I_P = 600$ kA and $B_t = 2.46$ T and $\bar{n}_e \approx 10^{19}$ m^{-3} with a series of cold pulses produced by Fe-LBO. The density is enhanced at each injection by about 3%. A rather strong enhancement of the central T_e is observed as a reaction to the edge cooling. The central heating does not appear immediately, but is delayed by at least 5 ms, as can be judged already from Fig. 1. Similar results are obtained by injecting C or Si, whereas stronger edge cooling yields a larger enhancement in the centre. Even cold pulses initiated by fast deuterium puffs lead to the same behaviour in respect of propagation and inversion of the perturbation, indicating that the contribution of the radiation of C, Si and Fe from further inside the plasma is not relevant. This observation is supported by impurity transport calculations using transport coefficients deduced from earlier dedicated experiments using Ne and He [4]. Their results are consistent with the measured temporal behaviour of the line radiation and yield a much slower inward propagation of the radiation front, as that observed for the cold pulses.

Repetitive pulses allow the use of the Fourier transform of the ECE-temperature data to extract the radial propagation of the perturbation. An example of such an evaluation is shown in Fig.2 for the ohmic discharge #10522 with 4 Hz Fe injection. For harmonics 1 - 6 a strong decrease in the amplitude occurs at $\rho_{tor} = 0.30 - 0.35$ correlated with a clear phase jump at the same radial position. Since the Fourier transform yields for the amplitude only a positive value, the phase jump reflects the inversion of the pulse. The negative phase is therefore not in contradiction with causality. Comparing the slope of the phase before and after the phase jump one can conclude, that the propagation is almost the same. Except for the region of the inversion of the pulse, the amplitude of the perturbation shows a clear increase towards the centre. At least for radii larger than $\rho_t > 0.8$ an error of the ECE measurement due to a too small optical thickness can be excluded. The increase cannot be explained by a simple diffusive Ansatz even apart from the inversion of the sign. Whether it could described by a heat pinch has still to be verified. Calculations with the transport code ASTRA show, that the effect cannot be produced on this fast time scale by a rearrangement of the ohmic heating power.

To interpret the underlying processes, simulations using the IFS-PPPL model [5] – the only model yielding the inversion [3] – were performed. As input for the model the experimental electron density profile and edge T_e and T_i at $\rho_t = 0.9$ were used. The density profile is kept constant throughout the calculations. The calculated equilibrium temperature profiles were in good agreement with the experimental ones. As in the case of the earlier analyses of TEXT cold pulse data [3], a qualitative agreement of the calculations with the experiment is obtained and the inversion radius is described rather well as can be judged from Fig.3. However the amplitude of the perturbation at the edge has to be assumed much stronger in the model and the response to the perturbation in the centre is faster. The sawteeth present in the experiment, may also be a reason for some of the differences. An essential prediction of the model is the enhancement of the ion temperature over the whole radius [3]. The ion temperature measurement is not possible on this short timescale, however a statistically significant transient increase of the neutron-rate is observed for most of the cold pulses.

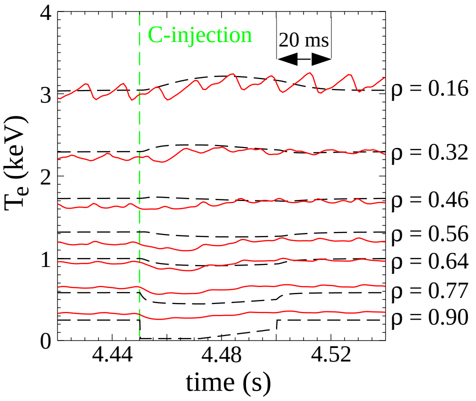

Figure 3: *Time evolution of T_e from the measurement (solid line) and the simulation with the IFS-PPPL-model (dashed line). The oscillations seen on the central temperature are sawteeth.*

For further testing of the predictive power of the model a series of cold pulses were performed in discharges with different B_t and I_P values. It turned out, that the inversion radius of the cold pulse was always found outside the sawtooth inversion radius. Its position is independent of the strength of the perturbation, of the element injected and also of the electron density. Fig. 4 shows the sawtooth as well as the cold pulse inversion radii versus the edge safety factor (q_{95}). As can be seen in the figure, q_{95} seems to be a good ordering parameter for both inversion radii which behave quite similarly. An attempt to relate this behaviour to the local electron temperature or its gradient did not yield such a correlation. The circles mark a discharge with additional central ECRH (300 KW cw). In this case an even stronger effect is found for the amplitude of the cold pulse inversion and the inversion radius moves outward whereas the sawtooth inversion radius is only slightly influenced. Density ramps show that the inversion of the cold pulses disappear at line averaged densities of about $(1.5 - 1.8) \cdot 10^{19}\mathrm{m}^{-3}$. The higher values were found for higher I_P and in the case of additional central heating by ECRH. These observations comply with the condition given in [2].

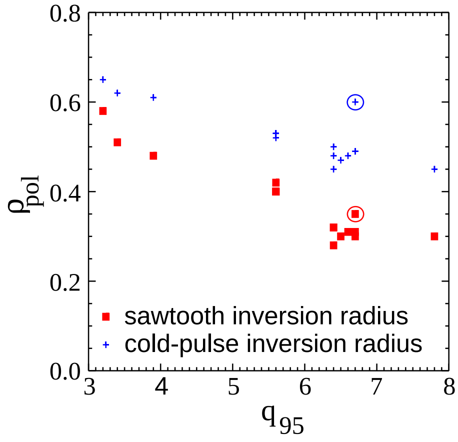

Figure 4: *q-dependence of the sawtooth (squares) and the cold pulse inversion (crosses) radii.*

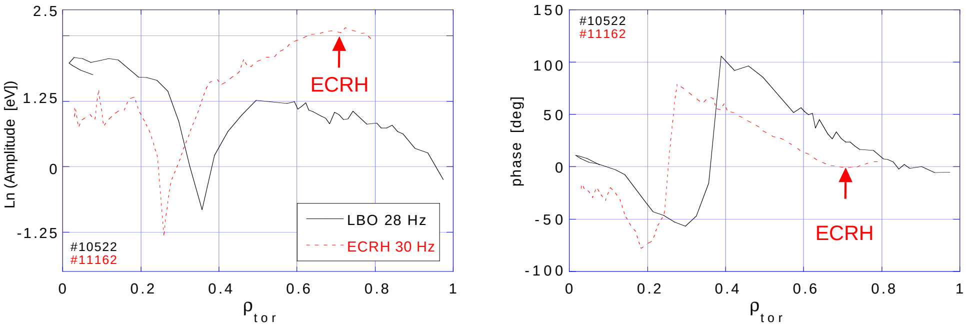

Figure 5: *Amplitude (left) and phase (right) of LBO cold and ECRH heat pulses versus radius at similar frequencies. The arrows indicate the ECRH deposition*

Heat Pulses

To study the symmetry of the phenomenon we heated the plasma edge ($\rho_{tor} \approx 0.9$) with ECRH pulses of 5 ms duration at a frequency of 10 Hz. They provide a perturbation of T_e at the plasma edge quite comparable in amplitude and time evolution to the T_e decrease of cold pulses. The ECRH scheme used here is 2nd harmonic in the X-mode which provides a single-pass absorption of about 90% under these conditions. Inspecting the T_e time traces by eye reveals, that the expected cooling of the central temperature is much weaker than the corresponding increase for cold pulses.

However, the Fourier transformation reveals some features of the pulse quite comparable to those from cold pulses, as shown by the comparison of Fig 5. The inversion radius is clearly seen on both amplitude and phase at $\rho_{tor} = 0.27$. The deposition of the ECRH is clearly visible on both, phase and amplitude at $\rho_{tor} \approx 0.75$. One advantage of the ECRH heat pulses is that no particle source is coupled to the energy pulse and thus the propagation between the ECRH deposition and the inversion radius can be analyzed using both amplitude and phase. As expected, the amplitude of the ECRH pulses decreases while propagating inwards until the inversion radius and the phase increases. The propagation, calculated under the assumption of a diffusive process corresponds to $\chi_e^{HP} \approx 4$ m^2/s. This is quite similar to the value for cold pulses, deduced from the phase only. Note therefore in Fig. 5 the similarity of the phase for ECRH and cold pulses. On the other hand, the figure underlines also the different behaviour of the amplitude of the LBO cold pulse compared to that of the ECRH pulse. The reason why the amplitude increases as the cold pulse propagates towards the inversion radius is not yet clear. It might be due to the simultaneous propagation of the energy and particle pulses.

Although heat pulses by ECRH at the plasma edge also show hints for a conversion to cold pulses in the centre, there are also important differences in both kinds of experiments. Together with results from the parameter scans for the cold pulses these facts lead to new constraints for the theoretical description.

Acknowledgment

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