

## Evolution of $T_e$ and $n_e$ Profiles during ECH and ECCD in TCV

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### INTRODUCTION

The use of electron cyclotron waves for plasma heating (ECH) and non-inductive current drive (ECCD) has the advantage of local power deposition determined by the location of a resonance layer in the plasma and the orientation of the microwave beams. Localized deposition of heating power can be used as a means to modify the shape of temperature and pressure profiles and their gradients with substantial consequences on the current distribution as well as on heat and particle transport. Local non-inductive generation of current provides a tool to optimize the shape of the q-profile with the aim of reaching regimes of improved confinement.

Depending on the exact location of the power deposition with respect to the rational q-surfaces of the plasma (in particular q=1), different types of sawtooth oscillations have been observed on the signals from soft X-ray emission. These lead to transient perturbations in the millisecond time scale of the electron temperature ( $T_e$ ) and density ( $n_e$ ) profiles. In the following, measurements by Thomson scattering are used to investigate these characteristic changes in the spatial and temporal variation of  $T_e$  and  $n_e$  during different scenarios of EC-heating and EC-current drive.

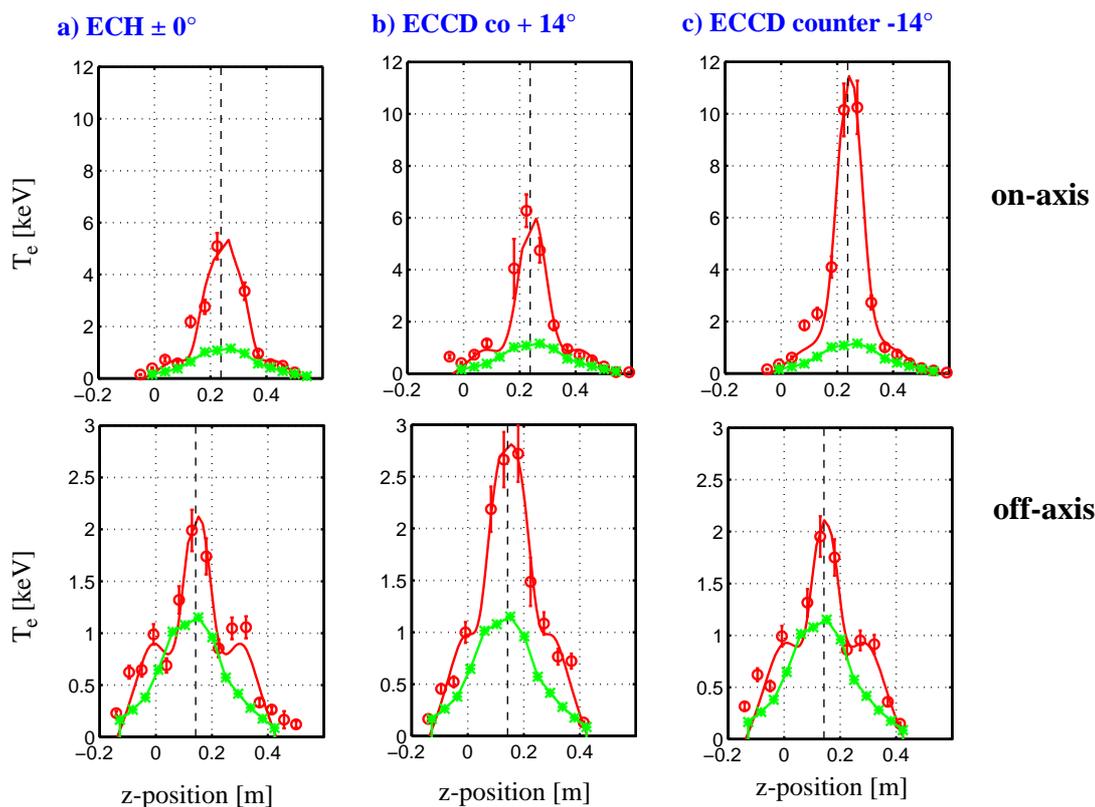
### THE THOMSON SCATTERING SYSTEM ON TCV

Using a laser beam, which passes the TCV vessel in vertical direction at the position of its major radius, and 35 viewing chords distributed on 3 horizontal ports, the system provides measurements of  $T_e$  and  $n_e$  profiles with a spatial resolution of about 40mm along the laser beam and 3mm in toroidal and radial directions. Recently the system has been upgraded and now comprises 3 high-power Nd:YAG lasers. By combining the beams of these lasers in a fan and focusing them to a common spot inside the plasma, the system permits us to measure profiles at sampling intervals which can be varied via delayed triggering of the individual lasers. The minimum time interval between laser pulses is 0.4ms, limited by the data acquisition system.

### $T_e$ AND $n_e$ PROFILES DURING ECH AND ECCD

Apart from sweeps in the direction of the microwave beams or variations of the toroidal magnetic field strength, the location of power deposition in TCV can also be changed by moving the plasma in the vertical direction during a shot. This method has been used in the cases presented here, in order to investigate the effects of central or off-axis power deposition. The parameters of the plasma and the heating system were the following :

$I_p=170\text{kA}$ , line-integrated  $n_e \geq 1.10^{19}\text{m}^{-2}$ ,  $q_{\text{edge}}=4.4$ ,  $\kappa=1.25$ ,  $P_{\text{EC}}=1.5\text{MW}$  (3 beams),  
82.7GHz (second harmonic), X-mode.



**Fig. 1**  $T_e$ -profiles measured by Thomson scattering for different conditions of EC-heating and -current drive total injected power using 3 beams :  $P_{inj} = 1.5\text{MW}$   
 a) **ECH** (inject. at  $0^\circ$ ); b) **co-ECCD** (inject. at  $+14^\circ$ ); c) **cntr-ECCD** (inject. at  $-14^\circ$ )  
 top row : power deposition on-axis; bottom row : off-axis (near  $q=1$  surface).  
 The fitted curves (in red) assume constant  $T_e$  on flux surfaces.  
 The  $T_e$ -profiles of an ohmically heated plasma with the same parameters are given for reference (curves in green, labeled by \*). The dashed vertical line marks the  $z$ -position of the magnetic axis.

The power deposition in the centre and near the  $q=1$  surface (off-axis), respectively, is confirmed by calculations using the TORAY code, which predicts full absorption in both cases.

In the case of perpendicular injection (**EC**, fig. 1a), the  $T_e$  and  $n_e$  profiles measured by Thomson scattering at different time steps during the two phases show a clear trend : high central temperatures and peaked profiles for central power deposition and a significant broadening of the profiles in the off-axis phase. This can be quantified by a variation of the profile peaking factor (defined as  $T_e(0) / T_e(\text{avg})$ ), which drops from about 6 to values below 4. The region of central heating is delimited by sharp gradients in the vicinity of the location of the  $q=1$  surface. During the phase with off-axis deposition local minima and side lobes appear on the profiles. These structures vary with time and seem to be located close to the  $q=1$  surface, which suggests the presence of islands. Compared to the very pronounced changes of the  $T_e$  profiles, there is only little change in the  $n_e$  profiles, which remain fairly flat (peaking factor around 1.7).

In a similar scenario and starting from the same target plasma, two cases of non-inductive current drive (**ECCD**) have been investigated (figs 1b,c). In the first case, the toroidal angle ( $14^\circ$ ) was adjusted to produce current drive in the co-direction, whereas the second case refers to a counter-orientation.

For co-injection aiming at the plasma centre, there still is significant heating and peaked  $T_e$ -profiles are observed with the central value reaching that of the pure heating case ( $T_e(0) > 5\text{keV}$ , see fig. 1b). The phase with off-axis deposition is again characterized by lower central temper-

atures and smaller peaking factors. The density profiles do not show any significant change (peaking factors varying around 1.5).

It is regularly observed on TCV that launching conditions with counter injection lead to the highest central electron temperatures. For the case shown in fig.1c, the central  $T_e$  reaches 10 to 12keV during the phase with on-axis power deposition. This results in extremely peaked  $T_e$ -profiles and an electron energy content close to 6kJ . Again, during the phase with off-axis deposition the central temperature is lower and hardly exceeds the ohmic reference value by more than a factor of 2. During this phase slightly hollow  $T_e$ -profiles have also been observed. The behaviour of the electron density is similar to the case with co-ECCD.

Table 1 summarizes the results of these measurements.

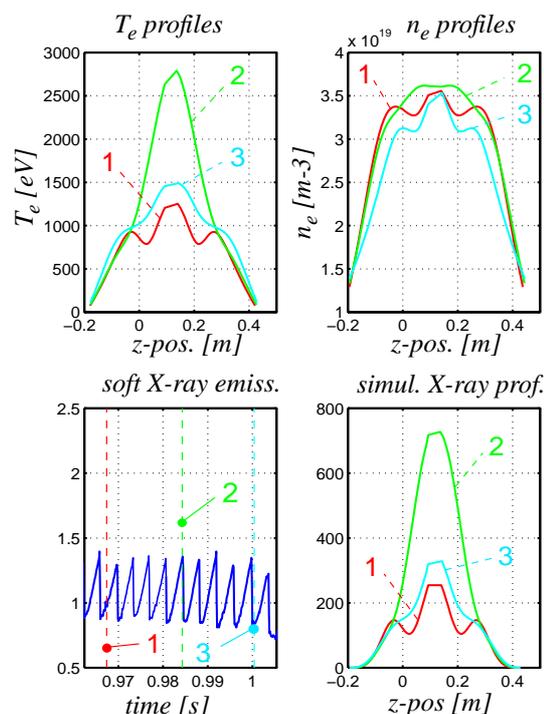
**Table 1:**

TCV-shot	type	on axis			off axis		
#		$T_e(0)$ [keV]	$T_e$ -prof. peaking	$W_e$ [kJ]	$T_e(0)$ [keV]	$T_e$ -prof. peaking	$W_e$ [kJ]
15'853	ECH, $\pm 0^\circ$	5 - 6	6 - 7	4.5 - 5	2.2 - 2.7	3 - 4	3.0 - 3.2
15'854	ECCD-co, $+14^\circ$	5 - 6	7 - 8	4 - 5	2 - 3	3 - 4	3 - 4
15'855	ECCD-cntr, $-14^\circ$	8 - 12	9 - 11	5 - 6.4	2 - 3	3 - 3.5	3.5 - 4.5

### INFLUENCE OF SAWTOOTHING ACTIVITIES ON $T_e$ AND $n_e$ PROFILES

Under conditions of local deposition of auxiliary heating power, which is typical for EC-heating and EC-current drive experiments, the appearance of the sawtooth oscillations changes significantly [1]. Apart from the ordinary triangular shaped sawteeth the oscillations can take the form of saturated or inverted sawteeth or features with a more sinusoidal variation interrupted by a short crash (so-called ‘‘humpbacks’’).

Although observation of the soft X-ray emissivity provides essential information for investigations of these phenomena, measurements based on other diagnostic methods are required for interpretation. Thomson scattering offers the advantage of local measurements and a clear separation of the contributions from different plasma parameters ( $T_e$ ,  $n_e$ , etc). Until recently, the limitations in sampling rate usually did not permit us to follow the evolution on the time scale of a sawtooth period. Valuable information could still be obtained in quasi-stationary cases where repetitive measurements at a lower frequency produced samples at different phases in the sawtooth cycle.



**Fig. 2**

Top: measured profiles of  $T_e$  and  $n_e$  at different times during a sawtooth cycle.

Bottom : recorded soft X-ray emission and simulated emissivity profile (using  $T_e$  and  $n_e$  data as input).

The data of fig.2 refer to an EC-heated plasma with power deposition inside the  $q=1$  surface and a prolonged phase of large regular sawteeth. The crash in the soft X-ray emissivity is clearly identified as a collapse of the central part of the  $T_e$  profile, which in this case reaches an amplitude of more than 1keV. Variations on the  $n_e$  profile are small and within the uncertainty of the measurement. For comparison with the soft X-ray emissivity, measured approximately along the same chord, expected emissivity profiles have been calculated using  $T_e$  and  $n_e$  data as input (fig.2 bottom right). Integration of these profiles along  $z$  produces a data set, which has been superposed on the signal of the measured soft X-ray emission (labeled 1,2,3) to compare the tendency of the temporal variation.

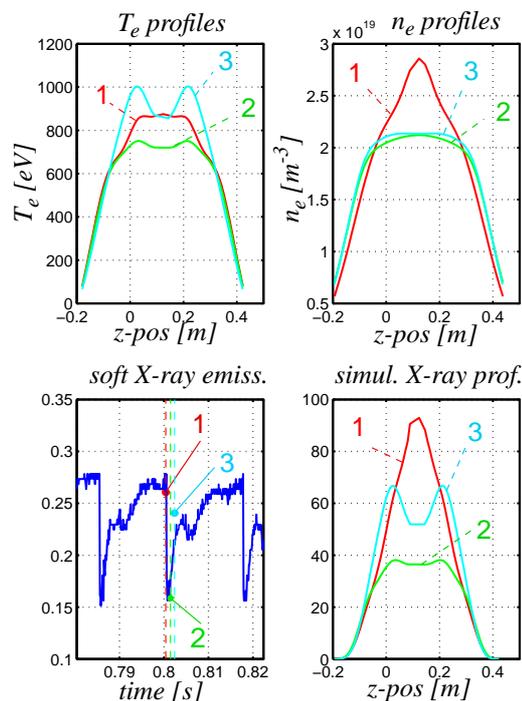
Due to the recent upgrade of the Thomson scattering system, it is now possible to take a series of measurements within a single sawtooth cycle. Fig. 3 shows a set of profiles measured within a 2ms time interval before and after a sawtooth crash. This type of sawteeth has been observed for EC power deposition close to the  $q=1$  surface. They are characterized by an unusually large variation of the central density and fairly rapid reheating after the crash. At the start of the reheating phase hollow profiles have been measured by Thomson scattering and soft X-ray tomography.

During “humpback”-type relaxation oscillations, the short crash in the soft X-ray emissivity is followed by a rapid recovery (see fig.4). The measurement closest to the crash reveals a clear drop of the central  $T_e$ , whereas the density profile remains almost unaffected. In this particular case, the rise in the soft X-ray emissivity after the crash is larger than would be expected from the measured increase in temperature. However, the  $T_e$  profiles during “humpbacks” show fluctuations which make it difficult to establish a clear trend.

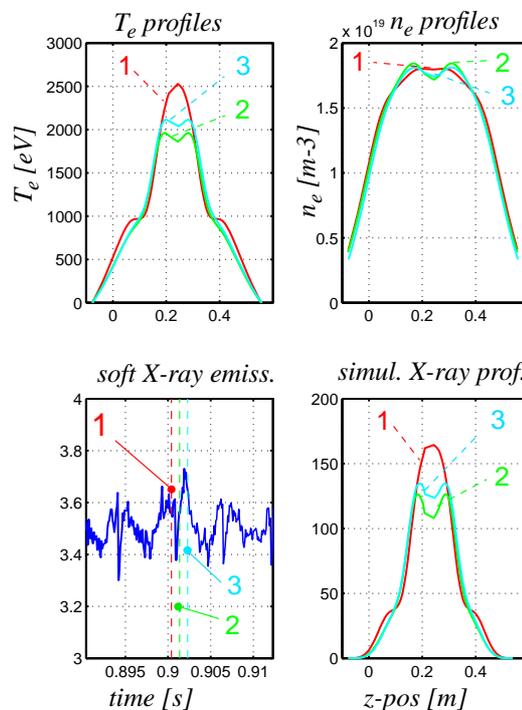
This work was partly supported by the Swiss National Science Foundation.

## REFERENCE

- [1] Z.A. Pietrzyk et al.  
Nucl.Fusion **39**(5), p.587ff, 1999



**Fig 3**  
Profile evolution during the cycle of a “partially saturated sawtooth”



**Fig 4**  
Profile evolution during the cycle of a “humpback”