Ion Temperature Fluctuations in ELMy H-mode of the X3 EC-heated Plasmas on TCV

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Abstract. This paper focuses on interpreting variations in the NPA measured energy distribution of neutral fluxes from the TCV high density H-mode plasma discharges with strong third harmonic electron cyclotron heating (P_{X3}>P_{Ω}). Two quasi-stationary regimes: ELMy H-mode and ELM-free H-mode, routinely and reproducibly obtained in TCV, with a plasma density 5-10×10^{19} m^{-3}, electron temperature 2-3 keV and ion temperature of 0.7-1.0 keV. The ELMy X3-heated H-mode plasma on TCV is significantly perturbed by ELMs, sawteeth activity and modes. In X3-heated plasmas ELMs are characterised by increased amplitudes and lower frequencies than are typical in ohmic H-modes with strong sawteeth synchronised with ELM cycle. The energy losses per ELM can exceed the 15% of the total stored energy and the plasma density and electron temperature profiles were resolved during the ELM cycle. NPA measurements in the presence of ELMs and sawteeth cannot be explained with the classical theory of two-body Coulomb electron-ion collisions alone. Additional effects (such as a modification of the ion temperature radial profile and/or ion redistribution in the coordinate and velocity space due to plasma perturbations) must be considered.

Keywords: Tokamak plasma, H-mode, ELMs, Neural particle analyser, Ion temperature.
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INTRODUCTION

The Tokamak à Configuration Variable (TCV) [1,2] is a medium-sized tokamak (R=0.88 m, a=0.25 m, I_p < 1 MA, B_T < 1.45 T, plasma elongation 1-2.8) able to produce a plasma with the central electron density 0.5-15×10^{19} m^{-3}, an electron temperature over 10 keV (with X2 ECH heating) and bulk central ion temperatures of 0.25-1.0 keV. TCV is equipped with 3 MW of electron cyclotron heating (ECH) power at the second harmonic (X2: X-mode; 87.4 GHz, 6 gyrotrons, low field side launch) and 1.5 MW of a third harmonic ECH system (X3: X-mode, 118 GHz, 3 gyrotrons, top launch).

The operational domain of the H-mode plasma with and without edge localised modes (ELMs) has already been reported in [3]. The low-density (n_e~4.2×10^{19} m^{-3}) cut-off of X2 waves, prohibits exploring H-modes with X2 heating, where the working density is often too high. The higher cut-off density for X3 waves, n_e~11×10^{19} m^{-3}, permits the study of auxiliary heated H-modes on TCV. In the contrast with limited electron and ion temperatures coupling in low density X2 heated TCV plasmas (T_e/T_i in the range of 5-30) X3 ECH heated discharges show increases in both (electron and ion temperatures) from ~1.0/0.5 keV to 2-3/0.7-1.0 keV, respectively [4,5].

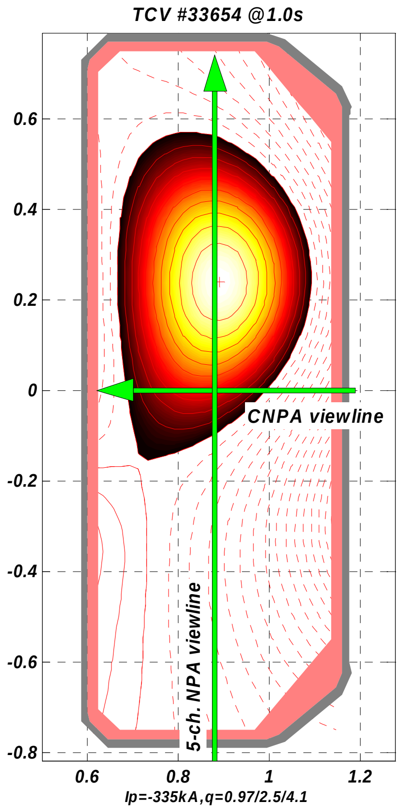

FIGURE 1. Poloidal cross section of the TCV Plasma configuration.

The EC power deposition and current drive profiles are calculated using the TORAY ray-tracing code with magnetic equilibrium obtained from the LIUQE reconstruction code using measured Thomson scattering (TS) electron temperature and density profiles [6]. The total plasma energy content on TCV was calculated from a diamagnetic loop diagnostic.

Two Neutral Particle Analysers (NPAs) are used on the TCV to obtain energy spectra of energetic neutrals escaping plasma resulting from the charge exchange of plasma ions with neutrals in the plasma. A "Five-Channel Energy Analyser of Atomic Particles" (5-ch.NPA) [7], operated on TCV in double electrical analysis mode, detects particles without atomic mass discrimination in the energy range 0.6-6.5 keV, with a time resolution up to 50 µs. A 28-channel "Compact Neutral Particle Analyser" (CNPA) [7] with mass and energy separation in E||B field simultaneously detects two mass species (11 channels for hydrogen and 17 for deuterium) in the 0.5-50 keV energy range with a time resolution in the 0.5-4.0 ms range. The DOUBLE-TCV numerical code is used to model the energy spectra of neutrals leaving the plasma and entering the NPAs [8]. The main carbon impurity C^{VI} ion temperature radial profiles were available from the CXRS [9] diagnostic. To improve the statistical accuracy, a coherent averaging technique [10] over several ELM events is been used in the analysis.

X3-HEATED ELMY H-MODE PLASMA

An Ohmic ELMy H-mode plasma in single null down diverted magnetic configuration (Fig.1), with ~220 kW of OH power and electron density of $5\text{-}7\times10^{19}\ m^{-3}$, was used as target for X3 heating. 700-800 kW (two gyrotrons) of X3 EC power was used to sustain quasi-stationary plasma conditions, where an increase of the X3 power typically provokes a transition to an ELM-free regime [5]. The plasma current was 300-350 kA and the electron temperature 1.9-2.1 keV before an ELM (and sawteeth crash) falling to 1.2-1.6 keV afterwards. Figure 2 shows some of the main plasma

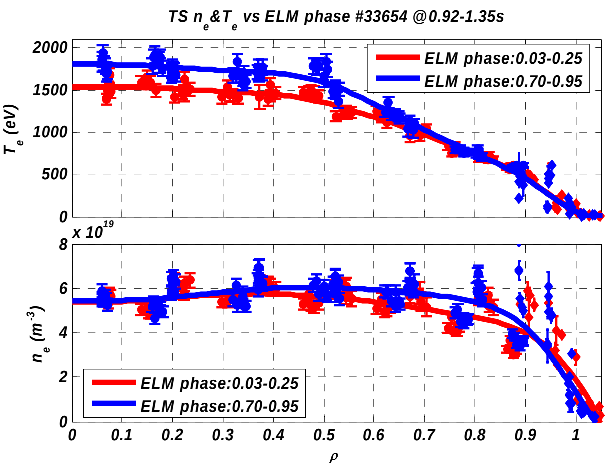

FIGURE 3. Variation of electron temperature and density profiles during the ELM phase

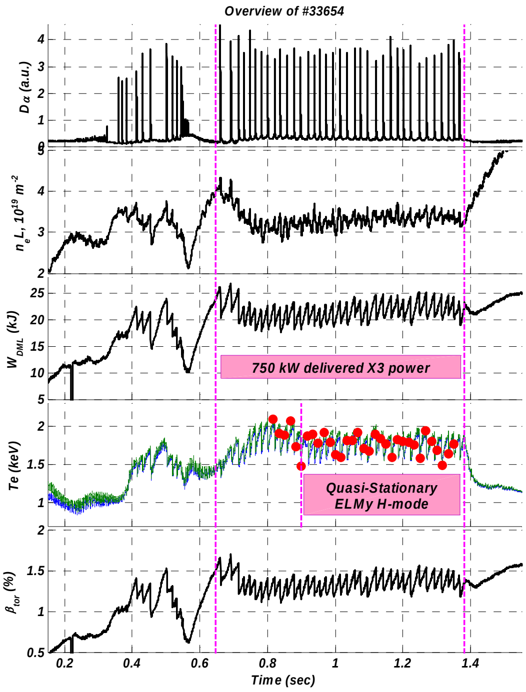

FIGURE 2. Overview of TCV shot 33654 with quasi-stationary ELMy H-mode with X3 ECH. From top to bottom: the D_α light, line integrated density (vertical view line), the stored energy (magnetic – DML), electron temperature (Soft X-ray foil absorption flux – lines, Thomson scattering – dots) and β_{tor}.

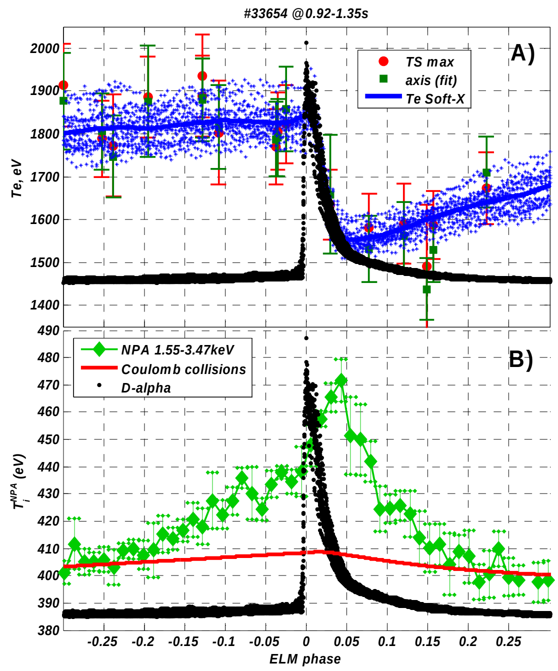

FIGURE 4. Electron temperature (A) and T_i^{NPA} (B) variation during ELM-phase: “0” on x-axis – ELM, maximum of D_α emission; -1 – previous ELM; 1 – next ELM, ~20.5 ms.

parameters in a TCV discharge with a quasi-stationary ELMy H-mode phase (0.92-1.35 sec). Strong sawteeth activity together with ELMs with a period of 20.5±2.6 ms result in a loss of ~15-20 % of the total plasma energy per ELM (values in the range 4-5 % being typical for ohmic H-mode ELMs). According to TS [6] measurement (Fig.3) ELMs leads to a small (<15%) decrease of electron density at intermediates plasma radii (0.3<ρ<0.9) and to a fast (~2 ms) decrease of core electron temperature from 1.8-2.0 to ~1.5 keV followed by a relatively slow (~10 ms) recovery time (Fig.4-A). The edge electron temperature profiles do not change significantly (Fig.3).

NPA MEASUREMENT

The technique described in [7], and references within, has been used for interpretation of the NPA data. In this paper we use a "CX spectra" defined as

$$F_{dc}(E) = J(E)/(\sigma_{cx}(E)\times E)\,, \tag{1}$$

where σ_{cx} is the cross-section for charge exchange. The energy spectra of the passive atomic flux *J(E)* emitted from the plasma into the NPA is the sum of fluxes in the plasma column along the view line of the analyser :

$$J(E) = \Omega\cdot S\cdot \int_{-a}^{a} n_a\cdot n_i\cdot f_i(E)\cdot\langle\sigma_{cx}(v_{ia})\cdot v_{ia}\rangle\cdot\gamma\cdot dz\,, \tag{2}$$

J(E) is proportional to the number of pulses detected by a given NPA channel (count-rate) *N(E)*: $J(E) = N(E)/(\Delta t\cdot\Delta E\cdot\alpha_{\det}(E))$. The temporal evolution of NPAs count-rates at several energies in quasi-stationary ELMy phase are shown in Fig.5. Fast ELM-driven (<1 ms) flux-spikes are clearly distinguishable from the 5-ch. NPA followed by decrease in the count-rates with a few ms decay time to below pre-ELM values. The increase of neutral density caused by the ELM related transient increase in the plasma-wall interaction is sufficient to explain these temporal flux-spikes.

For low density plasmas with a Maxwellian ion energy distribution, the ion temperature should be proportional to the logarithm of the F_{dc} slope; in most situations, including ELMy H-mode on the TCV, the plasma does not exhibit a single ion temperature and since attenuation may not be neglected the ion temperature, inferred from the slope of (F_{dc}), depends on the neutrals' energy:

$$1/T_i^{NPA}(E) = d\ln(F_{dc})/dE \tag{3}$$

T_i^{NPA} from the NPA CX spectrum, with TCV plasma conditions typical for ELMy H-mode, is 1.5-2 times lower than core ion temperature (Fig.6). There is a significantly larger variation of the neutral fluxes at high energy (>2.5 keV) than for lower energies (characterised by T_i^{NPA}) during an ELM cycle (Fig.5, 4-B).

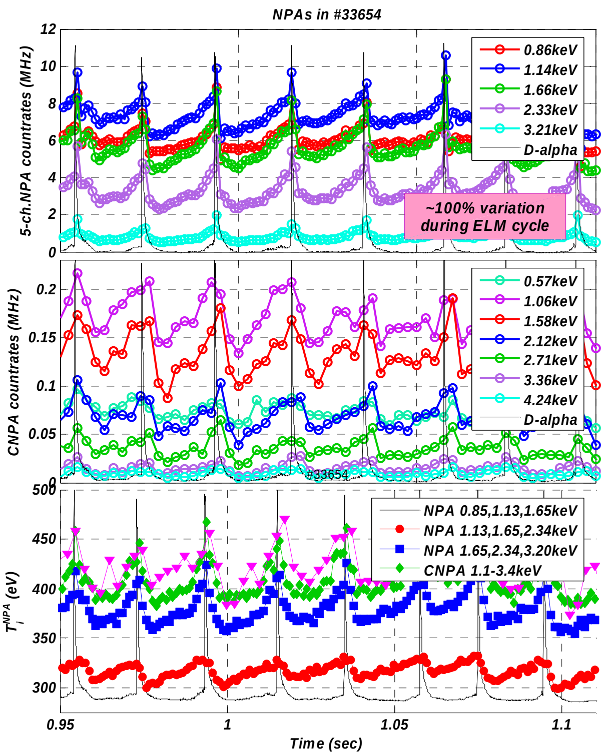

FIGURE 5. Variation of NPAs count-rates and T_i^{NPA} during a quasi-stationary ELMy phase.

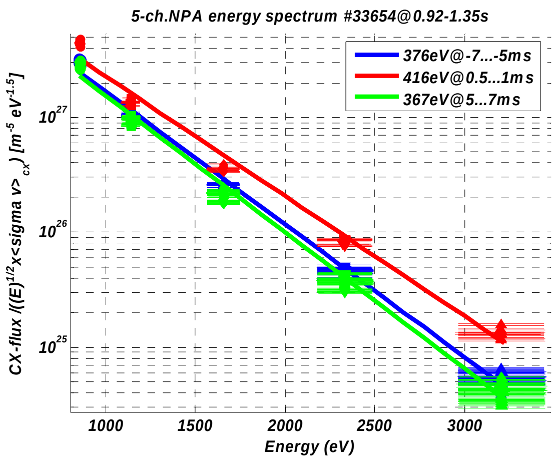

FIGURE 6. Measured energy distribution function ("NPA CX-spectra") before (-7…-5 ms), during (0.5…1 ms) and after (5…7 ms) ELM.

DISCUSSION

The correlation of the neutral flux ($J(E)$, eq.2) with ELMs could be caused by a several plasma effects: (a) increase of neutral density (n_a) due to ELM related transient increase of plasma-wall interaction; (b) plasma density (n_i) variation; (c) variation of ion temperature (T_i) due to variation of electron temperature and power exchange between electrons and ions (Coulomb collisions); (d) modification of ion energy distribution function ($f_i(v^3,\rho)$) due to ion redistribution in coordinate and/or velocity space. DOUBLE-TCV simulations [8] show that for TCV ELMy H-mode discharges neutral fluxes with low (<1 keV) energies originate from the plasma edge (emissivity function have a maximum at $\rho\subseteq[0.85\ldots1.0]$), whereas high energy fluxes originate from the plasma core (intermediate plasma radii, $\rho\subseteq[0.75\ldots0.85]$ for 3 keV). The transient increase of neutralisation probability should result in a stronger and faster increase of the neutral fluxes at lower energies (whereas experimental observations are opposite) and can thus not explain the increase of T_i^{NPA} during ELM cycle and the dependence of temporal variation of neutral fluxes with different energies (Fig.5,7). A plasma density variation of 10-15% is not sufficient to explain the observed increase in the neutral flux from decreased attenuation of the escaping plasma neutrals (increase of probability, γ). An analysis of the temporal behaviour of the Coulomb collisional electron-ion power balance indicates only a 2-3 % change of ion temperature mainly due the electron temperature variation (Fig.4). The variation of the T_i^{NPA} during ELM cycle (Fig.4,5) is much stronger corresponding to a 10-15 % increase in T_i.

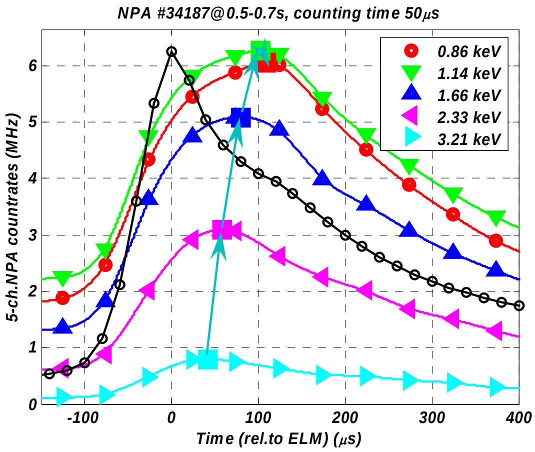

FIGURE 7. 5-ch. NPA count-rates in Ohmic ELMy H-mode with a 50μs time resolution

An ELM (or/and sawteeth) induced redistribution of ion remains the only considered candidate to explain NPA observations in the TCV ELMy H-mode plasma. Sawteeth crashes and ELMs are accompanied by a variation of the axial safety factor (q_0) around 1 and plasma vertical and radial displacements of a few mm. Modes excitation could then result in strong ion mixing, especially of trapped ions. A set of experiments with NPA observations at different toroidal angles of view line, various q-profiles, etc. is planned for the upcoming TCV experimental campaign.

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