Influence of Electron Cyclotron Heating on Electron Density Behaviour

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SUMMARY

Understanding the coupling between heat and particle transport in tokamak plasmas with elongated and shaped cross-sections is essential for fusion devices. A consequence of the coupling between heat and particle transport is the drop of the central line integrated density, $\bar{n}_e$, (pump-out) which is observed during Electron Cyclotron Heating (ECH) in many tokamak experiments [1]. Despite the importance of this effect, there is little understanding of the underlying physical phenomena.

On TCV (Tokamak à Configuration Variable, $R = 0.88\,\text{m}$, $a = 0.25\,\text{m}$, vacuum vessel elongation $\kappa = 3$ and vacuum central magnetic field $B \leq 1.43\,\text{T}$) a series of experiments has been carried out to investigate the electron density pump-out in sawtoothing plasma discharges under intense localised ECH. The steerability of the ECH launching system and the capability of TCV to produce a large variety of plasma shapes have allowed a detailed study of the pump-out under different heating scenarios. For these experiments, TCV was operated with up to six 82.7GHz, 500kW gyrotrons, with a 2s pulse length, for heating at the second cyclotron harmonic resonance (X2-mode). The 6 launching mirrors are separately orientable in the toroidal and poloidal direction. The vertical microwave beam width near the plasma centre is $w \approx 2.5\,\text{cm}$ in free-space (beam intensity $\propto exp[-2(r/w)^2]$, where r is the distance transverse to the direction of the beam propagation). Local ECH power densities in excess of 10MW/m^3 have been obtained.

These experiments showed that in sawtoothing discharges the electron density response to heating conditions is dependent both on the plasma shape and the injected power, P_{ECH}. In low triangularity plasmas for central ECH and ECCD, particles are expelled from the plasma core during the sawtooth reheating phase resulting in a flattening of the electron density profile. This phenomenon produces inverted sawteeth [2] and is accompanied by strong $m/n = 1$ mode activity. Hollow electron density profiles are sustained during the whole sawtooth cycle in the ECCD case. The particle outflux is terminated by the sawtooth crash, during which the central electron density rapidly recovers. The relative amplitude of the recovery strongly depends both on plasma shape and heating conditions, increasing with injected power and decreasing with the plasma triangularity. At high triangularity, no pump-out and no mode activity are observed during the sawtooth reheat phase.

The correlation between pump-out and the presence of central mode activity suggests that the mode activity is responsible for this coupled transport phenomenon.

EXPERIMENTAL OBSERVATIONS

The electron density and the sawtooth shape response to a sweep of the EC injection angle is shown in Fig. 1. In what follows, the plasma parameters are taken at the Last Close Flux Surface and in the present case are: $\delta_a = 0.18$, $\kappa_a = 1.3$, $I_P = 193\,\text{kA}$, $q_a = 4.55$, $P_{ECH} = 500\,\text{kW}$. The EC power absorption location is scanned through the plasma along the vertical resonance position for the X2-mode (Fig. 1a) at a velocity of 3.5cm / 100ms. The plasma shape remains constant, albeit with a varying incidence poloidal angle, ϑ, and beam width. The time behaviour of the central line integrated electron density $\bar{n}_e$ depends on the ECH power deposition location. The interval [A,B] highlighted in yellow in Fig. 1e, corresponds, within the experimental uncertainties, to power deposition inside the sawtooth inversion surface as determined from the tomographic inversion of soft X-ray measurements. For injection angles outside the interval [A,B], $\bar{n}_e$ increases during the sawtooth ramp and then drops at the crash on a fast time scale (typically $\tau_{crash} < 100\,\mu s$), Fig. 1g. The relative crash amplitude is $\Delta\bar{n}_e/\langle\bar{n}_e\rangle \sim -1\,\%$, where the brackets $\langle\ \rangle$ indicate the average of a quantity evaluated before and after the sawtooth crash (see Fig. 1g). During the sawtooth ramp, the soft X-ray emissivity is poloidally symmetric with no detectable MHD mode activity. At the sawtooth crash, $m/n = 1/1$ precursor oscillations are seen ~100μs before the sawtooth crash, Fig. 1f.

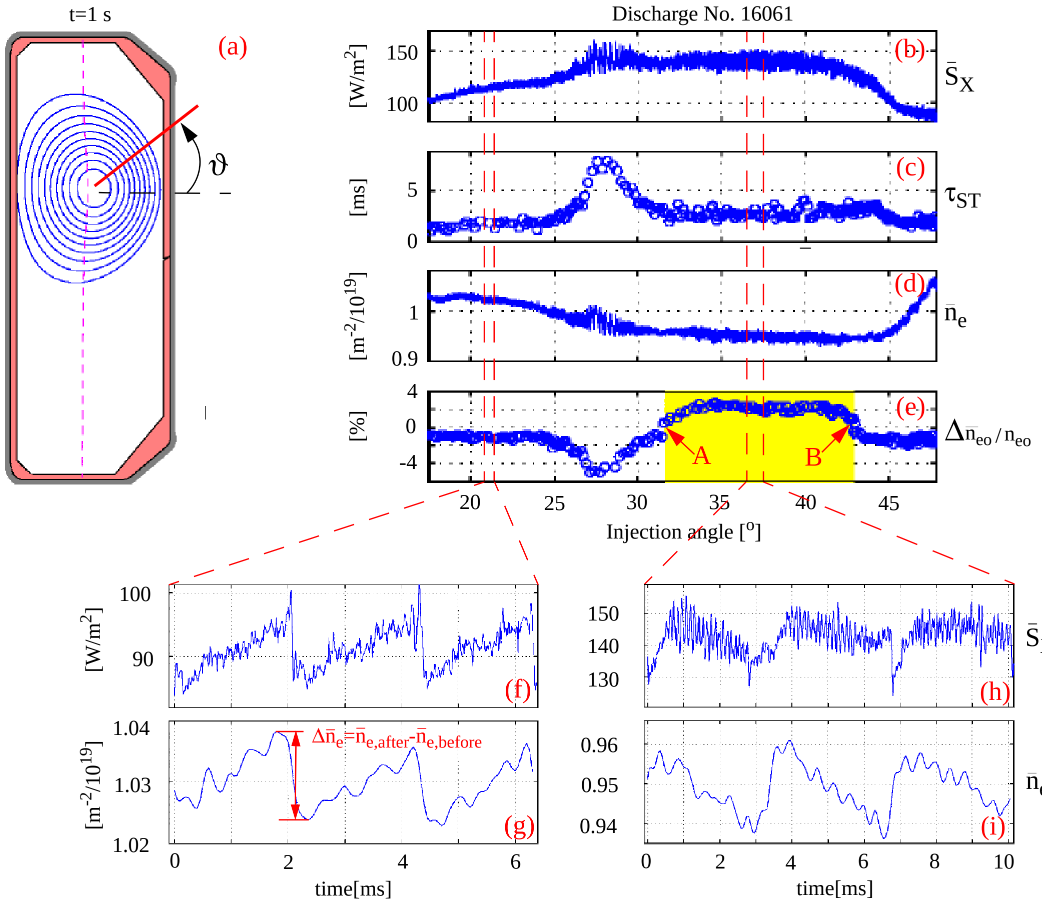

Fig. 1 Top: (a) Poloidal cross section of the plasma. The absorption layer for the X2-mode and the ECH launching geometry are shown. (b) Central line integrated soft X-ray signal. (c) Saw-tooth period. (d) Central line integrated density. (e) Relative variation of $\overline{n_{e0}}$ *at the sawtooth crash. Bottom: two types of sawtooth shapes from a central line integrated soft X-ray channel (f, h) and from a central line integrated electron density (g, i).*

When the ECH power deposition moves inside the interval [A,B], particles are expelled from the plasma centre during the reheat phase, resulting in inverted sawteeth on the central electron density, Fig. 1i. The central soft X-ray emissivity remains almost constant or even decreases until the following sawtooth crash, Fig. 1h. This saturated phase is accompanied by a strong $m/n = 1$ mode rotating in the electron diamagnetic drift direction. The particle outflux is terminated by the sawtooth crash, during which the electron density rapidly

recovers (typically $\tau_{recover} \sim \tau_{crash}$). The relative amplitude of the recovery, $\Delta\bar{n}_e / \langle \bar{n}_e \rangle = 2\%$, is approximately constant for injection angles inside the interval [A,B].
The dependence of sawtooth behaviour on the injected ECH power is presented in Fig. 2. The temporal evolution of the central electron density n_{e0} from Abel-inverted multichord interferometer measurements, Fig. 2(d, e, f), is shown together with the central soft X-ray emissivity, Fig. 2(g, h, i). Plasma parameters are: $\delta_a = 0.23$, $\kappa_a = 1.54$, $I_P = 393\,\mathrm{kA}$, $q_a = 2.9$. The EC resonance position is located inside the sawtooth inversion radius, Fig. 2a, and P_{ECH} is increased in three steps from 0.5MW to 1.4MW, Fig. 2b. For this plasma shape, the central ECH deposition strongly perturbs the triangular Ohmic sawteeth. With $P_{ECH} = 1.4\,\mathrm{MW}$, the sawtooth period, $\tau_{ST} \sim 3.9\,\mathrm{ms}$, is significantly longer than the Ohmic sawtooth period $\tau_{ST} \sim 2\,\mathrm{ms}$ and the n_{e0} behaviour changes from triangular (Fig. 2f) to inverted (Fig. 2i). In the inverted sawtooth case, the electron density recovery $\Delta\bar{n}_e / \langle \bar{n}_e \rangle$ increases from 1.6% at $P_{ECH} = 0.8\,\mathrm{MW}$ to 2.3% at $P_{ECH} = 1.4\,\mathrm{MW}$. During the associated inverted sawtooth ramp, the decrease in n_{e0} results from a flattening of the electron density profile and is correlated with the presence of $m/n = 1$ mode activity. With higher P_{ECH}, partial collapses of the soft X-ray emissivity are observed during the particle pump-out which result in a flattening of the soft X-ray emissivity profile.

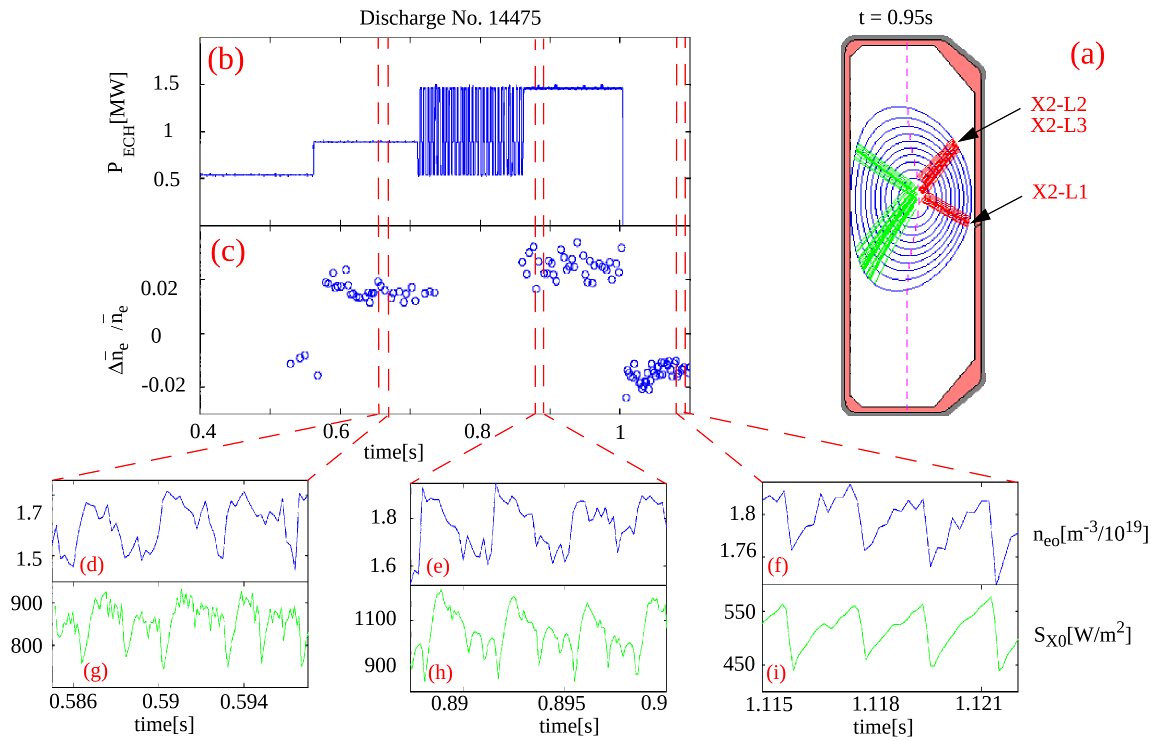

Fig. 2 Top: (a) Poloidal cross section of a plasma and ECH launching geometry for central power deposition. The absorption layer for the X2-mode and the ECH beams are indicated. (b) Stepping up of the ECH power. (c) Relative variation of $\bar{n}_e$ at sawtooth crash. Bottom: sawtooth shapes at different injected ECH power on local soft X-ray emissivity (g, h, i) and from Abel-inverted central electron density (d, e, f).

An extreme example of electron density pump-out has been obtained in the case of full current replacement [3] with Electron Cyclotron Co-Current Drive at an injected power $P_{ECH} = 2.7\,\mathrm{MW}$. In this case, hollow electron density profiles are sustained during the whole sawtooth cycle. Figure 3 shows the electron density profile relative to a time just before the sawtooth crash where $n_e(r_{inv})/n_e(0) \sim 1.42$. At the sawtooth crash, the density recovery is

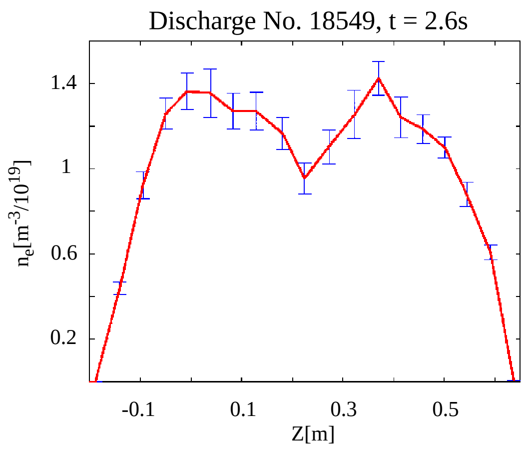

Fig. 3 Electron density profile the TCV discharge No. 18549 (I_P = 210 kA, δ_a = 0.42, κ_a = 1.62, q_a = 7.8, n_{e0} = $9.8 \cdot 10^{18} m^{-3}$. The profile is relative to a time just before the central electron density recovery at the sawtooth crash.

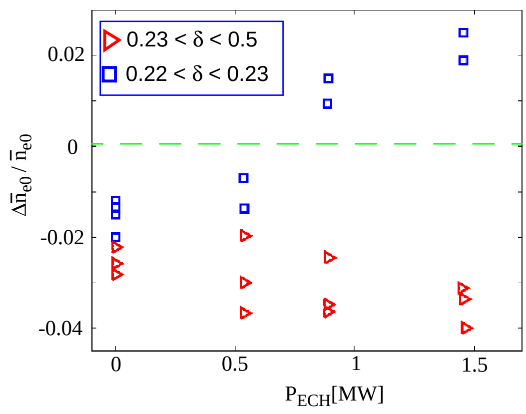

Fig. 4 Relative variation of $\bar{n}_e$ at the sawtooth crash for different plasma shape and injected ECH power. Positive and negative $\Delta\bar{n}_e/\langle\bar{n}_e\rangle$ values indicate respectively inverted and normal sawteeth.

such that $\Delta\bar{n}_e/\langle\bar{n}_e\rangle$ ~5.5% and results in flatter n_e profiles (not shown in the figure) with $n_e(r_{inv})/n_e(0) \sim 1.08$.
The effect of the plasma shape on the electron density behaviour has been studied by varying the elongation from 1.06 to 2 and the triangularity from -0.28 to 0.5. Since high elongation and low triangularity reduce the sawtooth amplitude [4] resulting in barely detectable sawteeth on the electron density, the data presented in Fig. 4 are in the following parameter range: $0.2 < \delta_a < 0.5$ and $1.02 < \kappa_a < 1.62$. In order to separate the afore mentioned dependences, the electron density, temperature and current profiles have been kept similar. The last condition was fulfilled by adjusting the average current density, in order to keep the sawtooth inversion radius constant and thus the broadness of the current profile [5]. The ECH power was increased in three steps. For all the discharges, the power deposition region was inside the sawtooth inversion surface. Figure 4 shows the dependence of $\Delta\bar{n}_e/\langle\bar{n}_e\rangle$ as a function of P_{ECH} for different plasma shapes. In strongly triangular plasmas (triangles in Fig. 4), the $\Delta\bar{n}_e/\langle\bar{n}_e\rangle$ increases from ~2%, in the Ohmic phase, to ~4% with P_{ECH} = 1.4 MW and no MHD activity is detected during the sawtooth ramp. Low triangularity plasmas (squares in Fig. 4) show normal sawteeth below $P_{ECH} \sim 0.6$ MW and inverted sawteeth above this threshold. In all this situations, the relative amplitude of the recovery increases with P_{ECH}.

Acknowledgements

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