Investigation of internal transport barrier in OH mode with sawtooth oscillation and in discharges where sawtooth are suppressed by off-axis ECRH.

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In this paper certain aspects of ITB physics in OH and ECRH plasmas in the T-10 tokamak are described.

Introduction

The formation and evolution of internal transport barriers (ITB, i.e. local regions with decreased heat and particle transport coefficients or heat and particle flows) has been the subject of many studies over the last decade. The underlying mechanism(s) of ITBs are still not fully understood. Therefore core plasma diagnostics are being modernized, while new ones are being developed to resolve this problem [1, 2]. These efforts bring out on a new higher level understanding of the processes which lead to formation and existence of ITB.

In this paper measurements are aimed at resolving the characteristic features of ITBs as well as their relation with rational values of the safety factor (q). This is done in T-10 tokamak discharges with ohmic heating (OH), central and non central electron cyclotron resonance heating (ECRH). In the latter experiments sawtooth oscillations have been stabilized. The experiments were carried out with the aid of electron cyclotron heating waves from two gyrotrons: 130 GHz (550 kW) and 140 GHz (900 kW) in the T-10 tokamak (R=1.5m, a = 0.3m, B≈2.4 T, I ≈ 150 kA, $n_e \approx 1.4 \div 2{*}10^{19}$ m^{-3}). The ECRH waves were launched into stationary OH plasmas, perpendicular to toroidal magnetic field. The cold resonance zone was placed on the plasma axis (for 130 GHz) or at half radius at the high magnetic field side (for 140 GHz).

The following diagnostics were used: a 21-channel radiometer using the 2nd harmonic X-mode of the electron-cyclotron emission (ECE, Δr = 2÷3 cm, Δt = 0.02 ms), a single pulse Thomson scattering system (TS, Δr = 0.6-1.2 cm), a semiconductor soft x-ray pulse height analysis system (PHA, T_e(r = 0), Δt = 50ms) for electron temperature (T_e) measurements. The PHA system was mainly used for the absolute calibration of ECE in the point r = 0, with a successive relative calibration of all other channels on the known T_e distribution in the OH stage. The soft x-ray emission (SXR) was also registered by a multi-wire proportional detector (Δr =1–1.5 cm and Δt = 0.05 ms). These chordal measurements were less noisy and more sensitive to T_e changes in the core plasma, and have been used in non-abelized form.

Results

To check hypothesis of ITB existence, central ECRH was switched on in the stable phase of an OH discharge, and the response on T_e profile, measured by ECE and SXR, was studied.

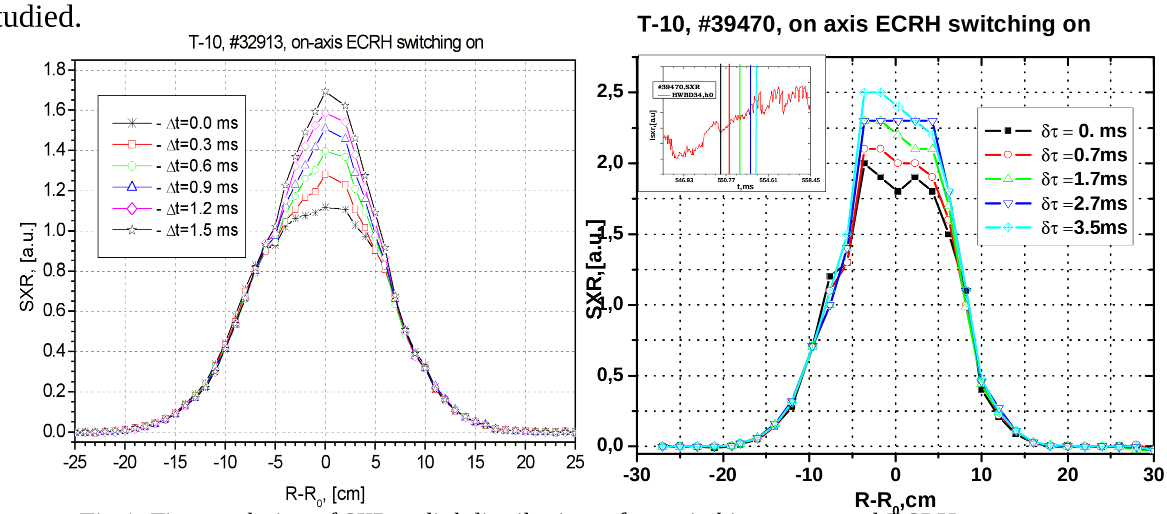


Fig.1. Time evolution of SXR radial distribution, after switching on central ECRH.

The SXR signal increases after ECRH switch-on during ≈1.5 ms. This occurs only inside the radius limited by -7cm and 7cm (shot # 32913, $<n_e> = 1.4*10^{19}m^{-3}$), see fig.1. The radius of +/- 7 cm corresponds to the calculated q=1 radius. In pulses like #39470 ($<n_e> = 2.*10^{19}m^{-3}$) the SXR signal increases inside the zone -5 <r<+7.5 cm within a time interval Δt ≈ 4.5 ms. The sawtooth inversion radius (r_{rs}) is -5 and +5.5 cm according to the SXR data.

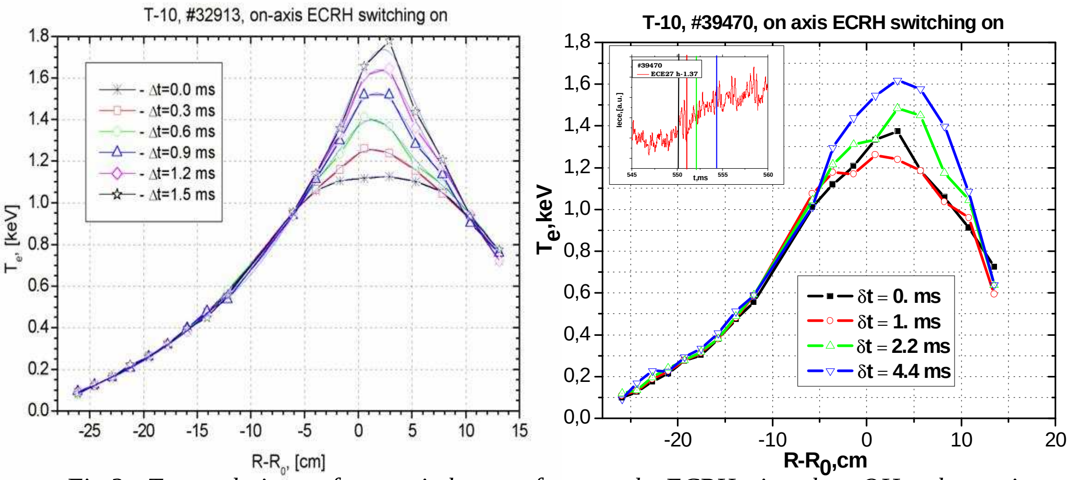
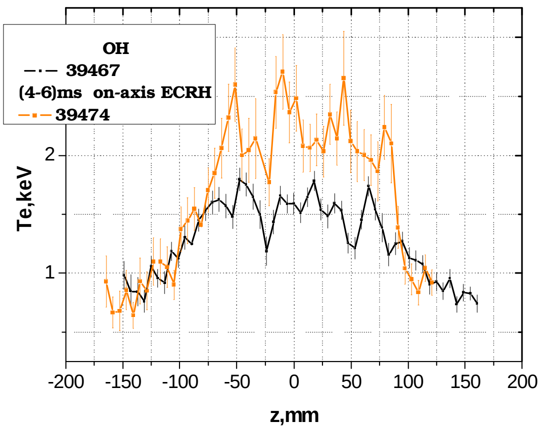


Fig.2 T_e evolution after switch-on of central ECRH in the OH phase in two shots.

The electron temperature measured by ECE showed a similar behavior (fig.2): during Δt ≈1.5 ms after switch-on of on-axis ECRH, the electron temperature increases by a factor ~1.7.

This happens only in the region between -6.0cm and 10.4cm (# 32913). The temperature gradient increased approximately by a factor of 5-6 times in this shot (fig.2).

Estimations for the thermal conductivity in the barrier region (4÷10 cm) yielded χ_{eff} ~0.03-0.10 m^2/sec. In discharge #39470 a similar T_e increase is observed between -6cm and 13cm during $\Delta t \approx 4.5$ ms (~ one sawtooth period) after on-axis ECRH switch on. In this shot the electron temperature increased by a factor of ~1.4; its gradient approximately by a factor of 3.



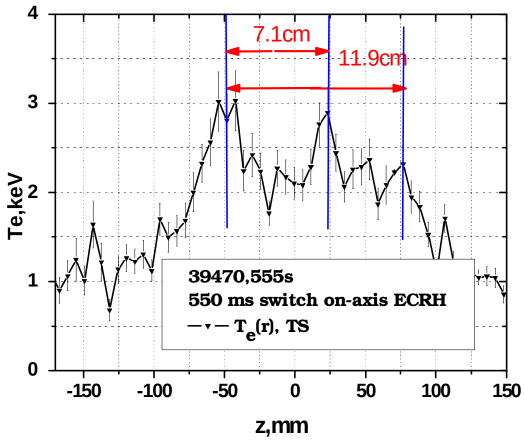
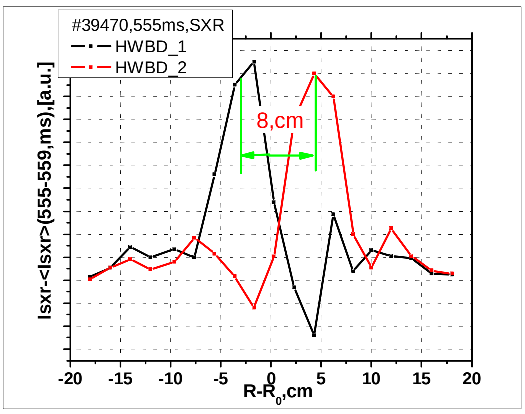


Fig.3 T_e (TS) in OH and 4 ms after on-axis ECRH. *fig.4 T_e (TS) at 5ms after switch-on of on-axis ECRH.*

Thomson scattering was applied in discharges with <n_e> = $2{*}10^{19}m^{-3}$ to obtain the T_e profile in the OH stage and during the first ms of central ECRH. The existence of a zone with high dT_e/dr (ITB) is apparent in fig.3. but growing temperature scope in first ms restricted within -10cm< z <6cm.(a systematic T_e (TS) excess over T_e (ECE) is observed: ~400 eV in OH and ~600eV in ECRH plasmas, but it doesn't affect our conclusions on ITBs).

Fig.5 Odd mode SXR oscillation, period ~500 µs.



Non-monotonous T_e(r) profiles were distinctly seen within the ITB zone in OH and ECRH discharges. The typical radial position of local T_e peaks ("ears") is around r = r_{RS}, while islands on SXR signals were present on r< r_{rs} inside the barrier (fig.4,5).Under off-axis ECR heating the T_e profile becomes more flat but conserves typical for OH and on-axis ECRH appearance (also "ears" near ECRH deposition radius), see figure.6.

A similar picture was observed on TEXTOR [3], fig.7. In this case the T_e profile is hollow in the centre with two maxima near the deposition zone of off-axis ECRH (≈700kW, 140 GHz near q(r)>≈1, on 45 ms after the start of ECRH).

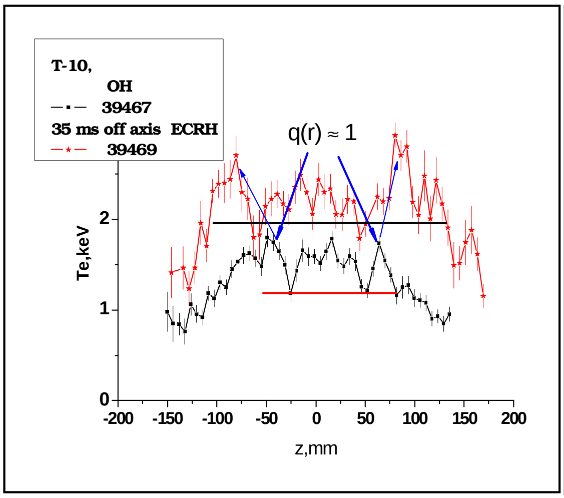


Fig.6 T_e (TS, T-10) in OH and steady-state off-axis ECRH.

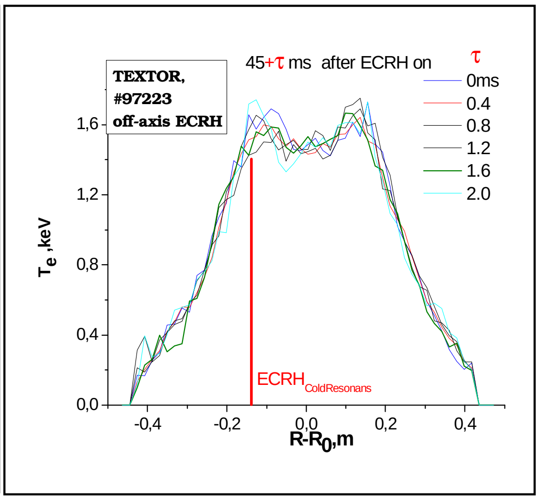


Fig.7 Hollow T_e profiles (TS, Textor) averaged over two pulses and four spatial points.

Conclusions

During the first few ms (~one sawtooth period) of on-axis ECRH the temperature increases only inside q ≈ 1, outside this radius T_e rise starts after this time lag. Three different diagnostics have measured a clear electron temperature increase inside the sawtooth inversion radius during this time interval. The Thomson scattering displays non monotonous behavior $T_e(r)$ inside the region limited approximately $r = r_{rs}$ in OH and on-axis ECRH. Traces of such $T_e(r)$ behaviour are also observed on SXR (in OH and on-axis ECRH mode) and ECE signals. The explanation for this could be the presence of MHD islands. Analysis of the transient process after off-axis ECRH switch-on indicates that immediately outside the resonance surface q=1 a zone with reduced heat transport exist. The estimations of the heat conductivity coefficient result in an inference: χ_{eff} has minimum in this region immediately after ECRH switch-on in OH mode.

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