

Improved core electron confinement on JET

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Abstract. Formation of core regions with reduced electron transport is reported in regimes with current profile shaping at JET. The electron heat diffusivity (χ_e) is reduced down to $0.5 \text{ m}^2/\text{s}$ in the region of low magnetic shear with an ICRH power of 1MW with no indication of a threshold. In the high performance optimised shear regime, obtained in scenarios dominated by ion heating, internal transport barriers on the ion temperature profiles are simultaneously accompanied by a significant reduction of the electron heat diffusivity at two-third of the plasma radius. In this regime, recent results and measurements obtained with the new gas-box divertor configuration are reported together with their transport analyses. The results indicate that χ_e is reduced by one order of magnitude in a spatially localised region.

Formation of internal transport barriers (ITB) with dominant ion heating schemes has produced high performance plasmas in JET [1-2]. In order to extrapolate this regime to fusion tokamak reactors one must establish whether an ITB can be formed and sustained with mostly electron heating and low particle fuelling rates as expected in burning plasmas. To address these long term problems, current profile control experiments performed at JET using dominant electron heating schemes alone together with their analyses are reported in the first section. Then, in the second section thermal electron transport in the optimised shear regime with clear ITB on the ion temperature profiles is described [3] in the light of the recent experiments performed with the recently installed gas-box divertor.

1. Improved core electron confinement with RF heating scheme

Improved core electron confinement is observed on JET when Ion Cyclotron Resonance Heating (ICRH) power using the helium-3 minority heating scheme is applied during the initial ramp-up phase of the plasma current. The plasma composition is a mixture of deuterium (D) and helium-3 (He^3) gas at low plasma density (the central electron density is $1.510^{19} \text{ m}^{-3}$). The ICRH antennae are operated in dipole configuration, the launched wave frequency is 37MHz at a toroidal magnetic field (B_0) at the centre of 3.4T. In the experiment shown on Fig. 1, up to 1MW of ICRH power is applied when the current is raised at a rate of 0.4MA/s to form a broad current density profile characterised by a low internal inductance ($l_i = 0.9$) without sawtooth activity. A significant peaking of the electron temperature profile ($T_{e0} = 7 \text{ keV}$) is produced when the ion-ion hybrid resonance layer is located close to the magnetic axis ($R_{\text{mag}} = 2.95 \text{ m}$) (Fig. 1). Formation of a core region ($3 \text{ m} \leq R \leq 3.3 \text{ m}$) with a steep electron temperature gradient, indicative of enhanced electron confinement is observed on the radial electron temperature profiles measured with the electron cyclotron emission (ECE) diagnostics (Fig. 1, right). For comparison, lower electron temperatures (dashed line on Fig. 1, right) are measured during experiments conducted with 1MW of ICRH power in the hydrogen minority heating scheme (H, $f=52 \text{ MHz}$) applied on a monotonic q-profile (see below and Fig. 3, right).

The He^3 concentration (n_{He^3}/n_{e0}) directly estimated from the input gas flows has reached 20%. For such high values, mode conversion from the fast magnetosonic wave to the slow ion Bernstein wave near the ion-ion hybrid resonance is predicted to play a major role and was also observed in other tokamaks [4]. We have analysed this heating scheme using the PION code [5] to calculate the ICRH power deposition profiles and to estimate the amount of mode converted power. In dipole configuration, i.e. with high n_{\parallel} , the resultant IBW is excited with a low parallel phase velocity and is assumed to be damped directly on the electrons in the vicinity of

the mode conversion layer. Consequently, very few suprathermal ions are produced in such case as confirmed by the low fast ion energy content. Indeed, the fast ion energy content estimated from the difference between the thermal energy and the diamagnetic energy represents less than the 10% of the stored energy, i.e. three time less than in the H-minority case.

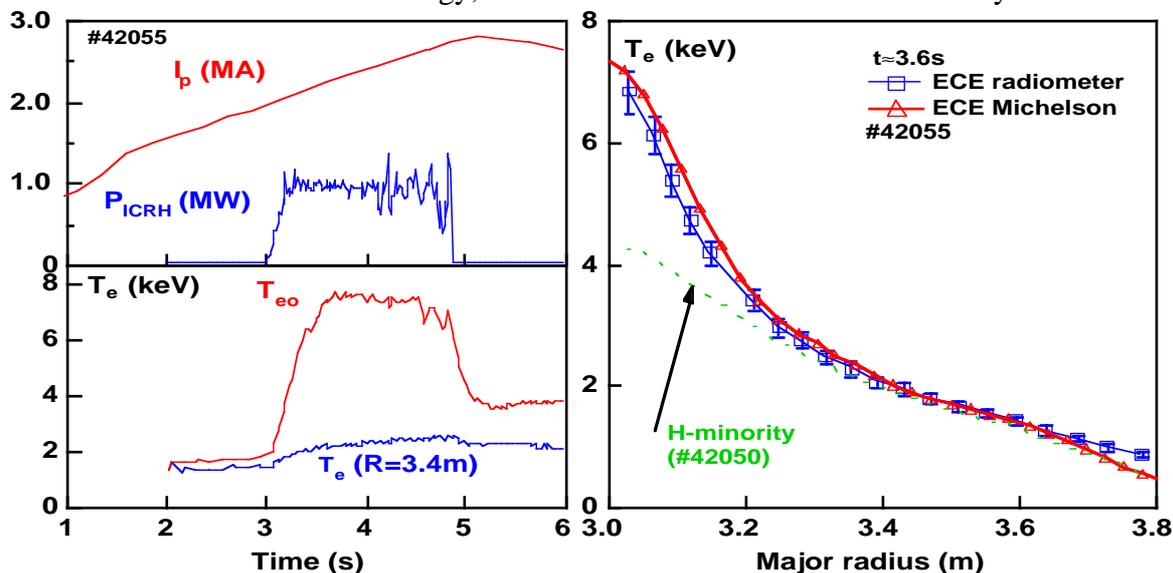


Fig. 1 : (left) Time evolution of plasma current, ICRH power and electron temperature in the He³ minority and on-axis case (42055). (right) T_e profiles using He³ (full curve,42055) and H-minority heating.

In the high concentration He³ minority heating scenario, the launched wave frequency has been varied at a constant toroidal field: the ion-ion hybrid resonance layer and the localised ICRH power deposition profile have been changed from on to off-axis locations. The ICRH power is also applied during the initial current ramp-up phase of the discharge. As shown on Fig. 2, the off-axis electron heating results in the formation of a broad electron temperature profile for $t \leq 3.7$ s. In this inductive regime, broad T_e -profiles correspond to hollow current density profiles. After the transient formation of a hollow q -profile at $t \approx 3.7$ s (see below), the electron temperature keeps rising up to 5 keV in the plasma core while its value at $R=3.3$ m is maintained at 3 keV. PION simulations indicate that the power deposited on the electrons (P_e) is absorbed (i) at the off-axis mode conversion layer (around 50% of P_e), localised at a normalised minor radius, $\rho=0.3$ and (ii) at the plasma centre due to the direct wave absorption on thermal electron (through transit time magnetic pumping and electron Landau damping).

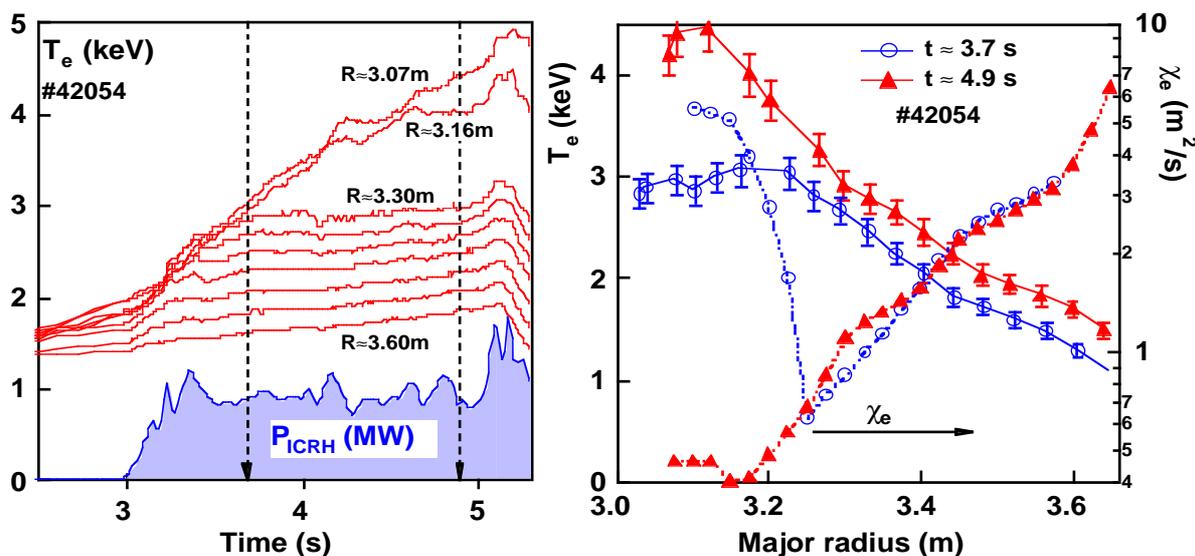


Fig. 2 : (left) Time evolution of electron temperature at various radii and ICRH power in the He³ minority and off-axis heating case (#42054). (right) T_e and χ_e profiles before ($t=3.7$ s) and after the core transition ($t=4.9$ s).

Interpretative electron transport analyses of these discharges reveal a reduction of the electron thermal confinement in the plasma core. In the on-axis electron heating case, the electron heat diffusivity is reduced from 1.4 m²/s down to 0.5 m²/s at $\rho = 0.3$ (Fig. 3, left). An upper limit of χ_e is obtained by assuming that (i) the electron-ion equipartition and radiated power densities are equal to zero, (ii) 80% of the injected power is absorbed on the thermal electron inside $\rho = 0.3$ as indicated by PION modelling. For comparison, the thermal diffusivities from the mixed Bohm/gyro-Bohm model [6] have been calculated using the experimental profiles and plotted on the same figure. The electron thermal coefficient is decreased from the anomalous Bohm level at mid-plasma radius down to the gyro-Bohm level inside the plasma core. Similar results have been obtained with the discharge shown on Fig. 2.

Current diffusion simulations show that broad or reversed q-profiles are produced in these experiments. In the on-axis and He³ minority heating case, the high T_{e0} value is sufficient to slow down the resistive current penetration of the off-axis ohmic current and form a region with low magnetic shear in the plasma core. For comparison, the current profiles deduced from the current diffusion simulation are monotonic in the H-minority case since these discharges have a lower T_{e0} and therefore a faster current diffusion time. In the off-axis electron heating case, the resistive current diffusion simulations indicate that q-profiles are hollow with a minimum q at $\rho = 0.3$ (Fig. 3, right) as anticipated on the initial broad shape of the T_e -profile.

We conclude that χ_e is decreased down to gyro-Bohm level in the low magnetic shear region as also observed on Tore Supra or previously on JET with lower hybrid waves [3,7-8].

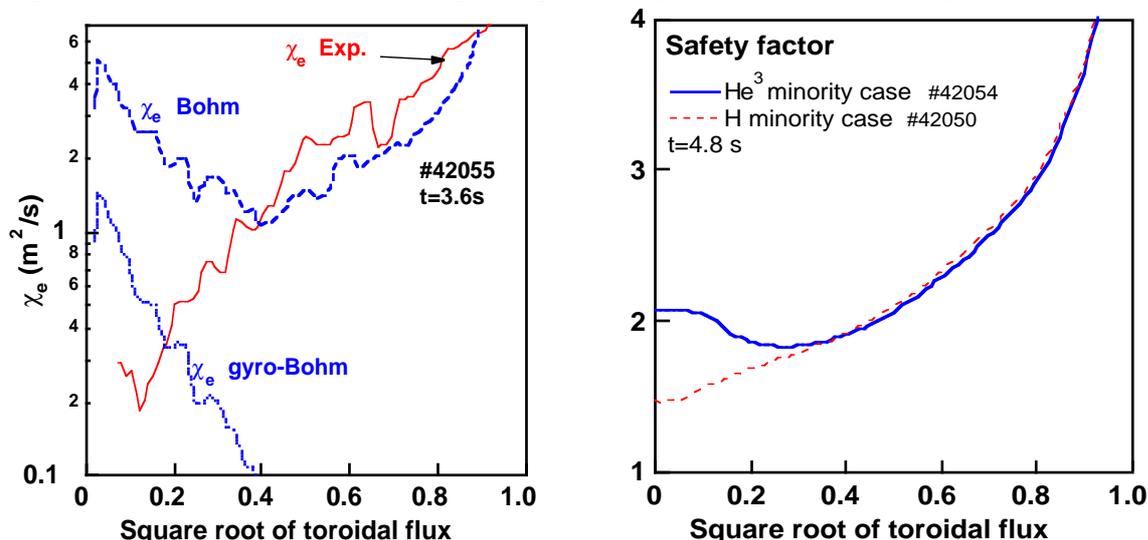


Fig. 3 : (left) Electron thermal diffusivity profile (#42055). χ_e values deduced from the Bohm/Gyro-Bohm model [6] are shown for comparison. (right) q-profiles from resistive current diffusion simulation (TRANSP).

2. Electron confinement in the optimised shear regime

The improved core electron confinement observed with RF heating alone has only been obtained at reduced power and plasma density corresponding to low performances in terms of normalised beta and fusion power. On the other hand, high-performance plasmas are produced in the optimised shear scenario at higher densities and powers in a regime with dominant ion heating, combining NBI (neutral beam injection) and ICRH [1-3]. In this scenario, significant reduction of the electron anomalous transport is systematically obtained when an ITB on the thermal ion heat diffusivity is triggered [3]. We report in this section on electron transport analyses of a standard optimised shear discharge obtained during the 98/99 experimental campaign with the gas-box divertor configuration at $B_0 = 2.5T$. Optimised shear discharges during this campaign were characterised by a combination of an ITB with an ELM'y H-mode edge [2] where the edge pressure pedestal is controlled by injecting Argon impurities at the plasma boundary as thoroughly described in [9]. The ICRH power in the H-minority heating scheme is first applied at a level of 1MW ($t=2.5s$), the NBI phase starts 1.2s latter and the full power is injected at $t=4s$ ($P_{ICRH} = 3.8MW$, $P_{NBI} = 13.5MW$) (Fig. 4). The current is ramped up to 2.5MA until $t=5.1s$. The ITB is formed during the high power phase ($t=4.2s$) at a major

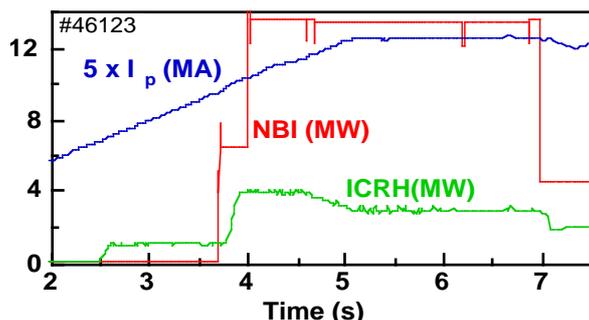


Fig. 4 : Current and power wave-forms, #46123.

applied χ_e is of the order of $4\text{m}^2/\text{s}$ in the confinement zone, and decreases at two-third of the plasma radius down to $0.2\text{-}0.4\text{m}^2/\text{s}$ after the ITB formation (Fig. 5). The region with low electron transport is spatially localised between $R=3.5\text{m}$ and $R=3.7\text{m}$. The localised nature of the transport barrier for the electron channel has also been observed in the ERS mode of TFTR [10]. Nevertheless, in the JET case the electron temperature profiles are not flat in the core and χ_e is maintained at a level of $1\text{m}^2/\text{s}$ inside the ITB region. This trend is generally not observed on the ion thermal diffusivities which continuously decrease close to the neo-classical level at the plasma centre. Explanations of the localised nature of the electron transport barrier are still investigated and we follow two hypotheses for future works : (i) either the thermal electron transport is sensitive to some weak level of MHD activity in the plasma core, or (ii) the micro-turbulence stabilisation mechanisms which reduce the ion transport in the plasma core does not affect in the same manner the thermal electron transport as suggested by recent density fluctuation measurements [11].

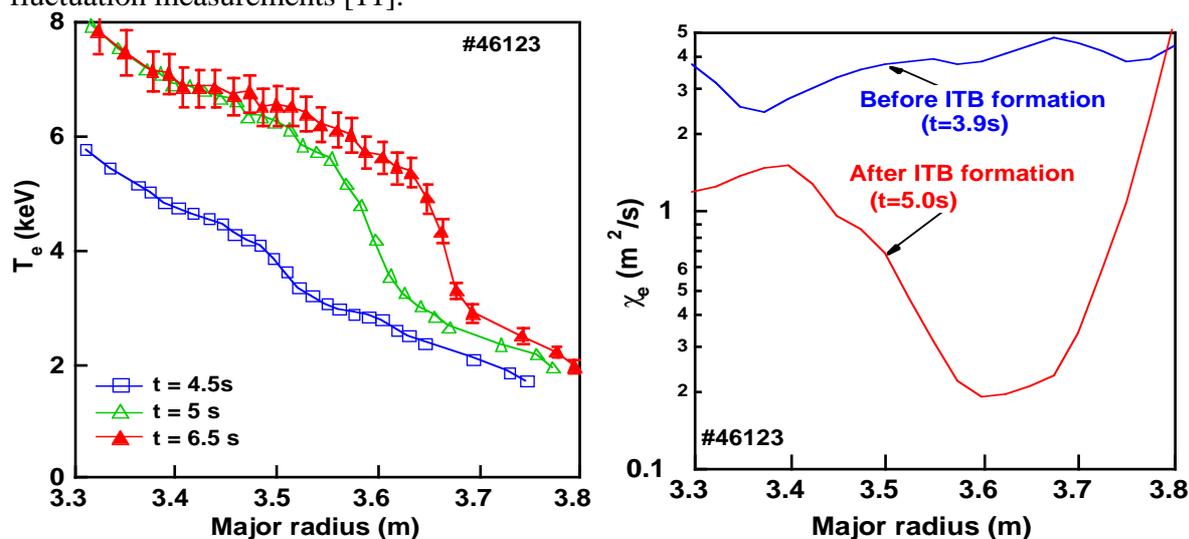


Fig. 5 : (left) T_e radial profiles measured with the ECE heterodyne radiometer diagnostic ($n_{e0} \approx 3.5 \cdot 10^{19}\text{m}^{-3}$). (right) Radial electron thermal diffusivity profiles (TRANSP) (#46123).

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