H-mode characterisation for dominant ECRH and comparison to dominant NBI heating at ASDEX Upgrade

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Introduction

Present day fusion experiments are heated mostly by neutral beam injection (NBI) with beam energies around 100 keV. Depending on the plasma temperature and beam energy this method deposits roughly half the heating power to the electrons and half to the ions. Future plasma experiments like ITER or DEMO will be predominately electron heated. This comes with the higher particle energy of the NBI systems and the increased use of electron cyclotron resonance heating (ECRH) and alpha particle heating. The ECRH system at ASDEX Upgrade was recently upgraded and can now provide up to 3.9 MW of heating power. This, in combination with the broad range of high temporal and radial resolution diagnostics available at ASDEX Upgrade, offers the opportunity to analyse the influence of different ratios of electron to ion heating on global and local plasma characteristics like confinement, kinetic profiles and radial heat transport coefficients. For this purpose, experiments have been performed in high density H-modes with total heating powers between 3 and 8 MW, which is about two to five times the H-mode threshold. In each discharge the total heating power was kept constant, while the NBI was substituted stepwise by ECRH up to the maximal available power level.

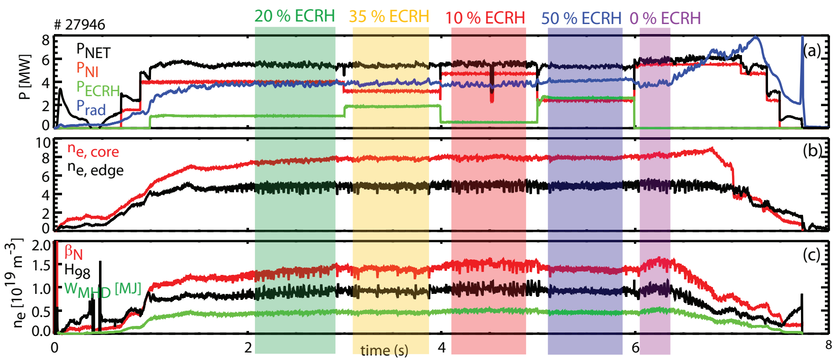

Figure 1: *Global plasma parameters: (a) total auxiliary, NBI, central ECRH and radiated power; (b) line averaged density in the core and at the edge; (c) normalised beta, confinement factor and stored energy*

Comparison of NBI vs. ECRH

Discharge # 27946 is a lower single null type I ELMy H-mode with a central magnetic field of -2.5 T and a plasma current of 1 MA which leads to a safety factor at the edge (q_{95}) of around 4. It has a high central density of around $9.5 \cdot 10^{19} m^{-3}$, a constant total heating power of 6 MW. Figure 1 shows the time traces of the most important plasma parameters. In the uppermost plot the total auxiliary heating power, which is kept constant over the entire plateau phase of the discharge, is shown in black. The phases of different ratios of NBI (red) and ECRH (green) power are highlighted with vertical bars. The global plasma parameters like radiated power ($P_{rad} \sim 4.3 MW$, blue, figure 1 (a)), stored energy ($W_{MHD} \sim 500\ kJ$, green, figure 1 (c)), normalised beta ($\beta_N \sim 1.4$, red, figure 1 (c)) and confinement factor ($H_{98} \sim 0.9$, black, figure 1 (c)) do not change significantly when the heating mix is changed from pure NBI heating to 50 % ECRH power. While the ELM behaviour does not show a variation with heating mix, the frequency of the sawtooth oscillation increases with increasing ECRH fraction. The effective collisionality, $\nu_{eff} = 0.1 \frac{n_e Z_{eff} R}{T_e^2}$, computed with local central values ($\rho_{pol} \sim 0.1$) also remains constant around 0.09 for the mixed cases with central ECRH.

Figure 2 shows the core kinetic profiles from the different phases of the discharge. Each was averaged over a 700 ms stable period highlighted with vertical bars in Figure 1. The data is fitted with a splinefit for easier comparison. Previous experiments with low total heating powers of 3 MW and an effective collisionality at $\rho_{pol} \sim 0.1$ of around 0.4 [1] have shown an increased density peaking with increased ECRH fraction, which is typically observed in this parameter range [2]. In contrast, the density data in Figure 2 (a) does not change with changing heating mix outside the uncertainties of the measurement. The electron temperature T_e (2 (b), solid lines) shows an increase in the core by 30 % when only 900 kW of NBI are replaced by ECRH. When increasing the ECRH power further the increase of T_e is only marginal. On the other hand T_i decreases slightly but steadily with increasing ECRH fraction, though the change is hardly outside the uncertainties of the measurement. This could indicate an increasing ion heat diffusivity χ_i due to a larger amount of power in the ion channel due to high density and higher energy exchange between electrons and ions by Coulomb collisions Q_{ei}. The toroidal rotation, however, decreases drastically with decrease of NBI heating due to the reduced torque input by the beams.

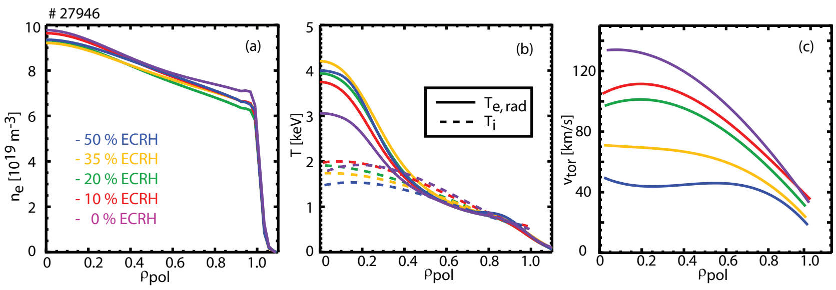

Figure 2: *Averaged kinetic profiles of the different heating mixes. (a) electron density; (b) electron (solid) and ion (dashed) temperature; (c) toroidal rotation*

Comparison of ICRF vs. ECRH

As presented in reference [1] in more detail, discharges were also carried out which are very similar to # 27946 but with a total heating power of 5.5 MW and ICRH instead of NBI heating. They show a similar behaviour as the low power cases replacing NBI heating by pure electron heating (ECRH). The electron density exhibits an increased peaking when applying more and more electron heating. The toroidal rotation stays at low levels and almost constant throughout the various heating mixes due to the missing torque input by neutral beams. The electron temperature exhibits an increase when adding a little amount of ECRH, while the ion temperature decreases slightly. Comparison of phases with similar heating mixes of NBI + ECRH and ICRF + ECRH show very similar density and temperature behaviour both in the core and at the edge despite great differences in rotation.

Modelling

In addition to the experimental observations of high power discharges the data of discharge # 27247 presented in [1] is also analysed with various codes. This discharge was performed very similar to the one presented here, but with a total heating power of 3 MW. First presented is the analysis with an interpretative transport model (power balance) inside the ASTRA code package [3]. The major findings are an increased heat exchange between electrons and ions with increasing ECRH fraction. This results in an electron heat flux Q_e that goes towards zero at the edge and Q_i, which is independent on the heating scheme when P_{rad} is considered. As a result of this power balance analysis χ_e is independent on the heating method, while χ_i increases by a factor of two over the whole radius when going from pure NBI heating to pure ECRH. Predictive transport calculations with the trapped gyro-Landau fluid transport model (TGLF [4]) within ASTRA were performed to calculate the theoretically expected electron and ion temperatures. This theory based transport simulation uses the heating profiles as inputs and the measured kinetic profiles as initial conditions. The experimental values of the kinetic profiles at $\rho_{pol} = 0.85$ are taken as boundary condition. Figure 3 shows the simulation results for the two extreme cases of mostly NBI heating and pure ECRH. Both the simulated electron (blue) and ion (red) temperatures show a significant flattening in the centre by sawtooth activity (Kadomtsev-type reconnection model for a single q=1 resonance surface) and the features created are the signature of an extremely low transport in a region where the strongly localized ECRH deposition is

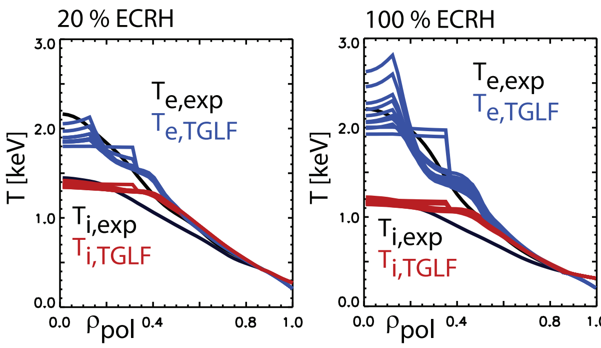

Figure 3: *TGLF simulations of T_e (blue) and T_i (red) and comparison to experimental values (black) of discharge # 27247*

slightly off axis. The sawtooth inversion radius of $\rho_{pol} \sim 0.2$, the experimental values (black) of the electron and ion temperatures in the core and at the edge and the increased value of T_e/T_i with increased ECRH fraction in the core are reproduced by the modelling. Only the position of equipartition between electrons and ions lies slightly too far inside. Simulations including and excluding the influence of the ExB shear on the radial transport show no difference in the resulting profiles. Therefore the similarity between NBI (high toroidal rotation) and ICRF (low toroidal rotation) heated phases is not surprising.

Linear calculations with the gyrokinetic code GS2 show that the dominant instability, which is expected to produce turbulent transport in these plasmas, is the ion temperature gradient mode. Figure 4 shows the maximal growth rates in the ion gyroradius sized wave number range (ITG or trapped electron mode), the maximal ETG growth rates normalized to the electron gyroradius and the frequency of the ion branch. The most unstable modes lie always in the ion branch and rotate in the ion diamagnetic drift direction, which depicts them as an ITG. The comparison of different heating mixes shows that the fundamental instability remains the ITG mode. However, the growth rate increases with increasing electron heating which is in line with the increased χ_i found in the power balance analysis. Parameter scans of the various destabilising effects show that the difference in growth rate is mainly produced by the differences in T_e/T_i, R/Ln_e and R/LT_i and only slightly by the change in R/LT_e. The difference in rotation or rotational shear has no influence on the growth rate, which is in line with the observation that NBI and ICRH heated discharges behave very similarly despite the strong differences in rotation. In conclusion one can say that the codes used to model the discharge reproduce the experimental data from the phases with different heating mix quite well and grasp the major trends of plasma behaviour.

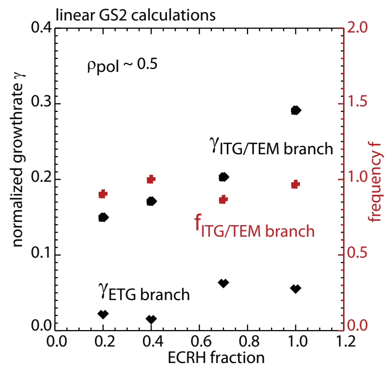

Figure 4: *Maximal growth rates of ITG/TEM and ETG modes of discharge # 27247 in relation to the ECRH heating fraction (black); mode frequencies for ITG/TEM branch (red)*

Acknowledgments

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