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Simultaneous Attainment of High Electron and Ion Temperatures in ITB-Discharges with ECCD on ASDEX Upgrade

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Introduction. Internal transport barriers have been observed in various experiments in which current rise and heating pulses were controlled to produce low or reversed central shear. This has previously been successful in two extreme regimes, in which ion temperature gradient driven (ITG) modes should be either stable, or relatively easy to stabilize by rotational shear, namely in cases with pure electron heating (e.g. in [1]) and relatively cold ions, and in discharges with strong ion heating and T_i significantly larger than T_e [2, 3]. Internal transport barrier (ITB) discharges with $T_i \approx T_e$ have been obtained on JET transiently, but this feature was lost, when strong ion heating was applied [4]. As the mode considered responsible for anomalous transport in discharges with strong ion heating - the ITG mode - is destabilized by increasing the ratio T_e/T_i, these observations have to be viewed as very critical for the prospects of a reactor based on advanced confinement modes, as α-particle heating will predominantly heat the electrons, resulting in $T_e > T_i$.

We report on first experiments on ASDEX Upgrade, in which central ECRH heating was applied during the ITB phase of NBI heated discharges with controlled current ramp. In these discharges an ECRH power of 1.25 MW was launched in the second harmonic X-mode. The toroidal injection angle of the focused ECRH beams was varied so as to produce, in addition to electron heating, also co- or counter current drive. The discharges presented here were limiter discharges, leaning on the high-field side protection shield, with an L-mode edge. At constant applied ECRH power, marked differences were observed between the three cases of co-, pure heating and counter-current drive, with the latter giving the best performance and the longest lasting internal barriers for both ions and electrons. This was to be expected, as the counter-current drive was conceived to compensate for the tendency of the central q-value to decrease, leading in turn to the disappearance of the reversed shear region. In fact, the co-injection case, in which this unfavorable current profile development should be even accelerated, shows values of $T_e = T_i$, which for T_i are much lower compared to the case without ECRH power application. In this co-case, measurements of the q-profile based on the motional Stark effect (MSE) diagnostic and the equilibrium code CLISTE [5] show the disappearance of the reversed shear region about 500 ms after the application of the electron cyclotron current drive (ECCD).

Negative central shear configuration. In the discharges presented in this paper, a central reversed shear configuration is attained by a reduction of the current diffusion by applying 5 MW of NBI during the current ramp-up phase at line averaged densities between $2-3\times 10^{19} m^{-3}$ [6]. The resulting shear is strongly reversed in the plasma center with inital q_0 values exceeding 6 and $q_{min} \approx 4$. However, due to the reduced but still continuous current diffusion q evolves towards a monotonic profile with q_0 finally approaching one, if MHD instabilities do not terminate the discharge earlier. Without ECRH an ITB is formed, which is reflected in central T_i values in excess of 10 keV corresponding to a ion thermal diffusivity χ_i at neoclassical level. While T_e is a factor of two to three below T_i in the plasma core, the central χ_e is also $\leq 1\,m^2/s$. At the time when q_{min} reaches 2 a (2,1) mode is observed which at least transiently deteriorates the confinement properties, resulting in a sharp drop of T_i. Analysis with linear and non-linear resistive MHD codes predict (2,1) double tearing modes to become unstable for the q-profiles measured in these plasmas [7]. To investigate the effect of electron heating and current drive on stability and confinement, central ECCD was applied at a time when q_{min} approaches 2, either to support the shear reversal or accelerate its decay.

Central co- and counter-ECCD. Figure 1 shows the time traces of the central T_i (at ρ_{tor} = 0.06) together with the ECE measurements at ρ_{tor} = 0.2 (the innermost ECE channel available during central ECRH power application) for three different cases: without ECRH, and with co- and counter current drive.

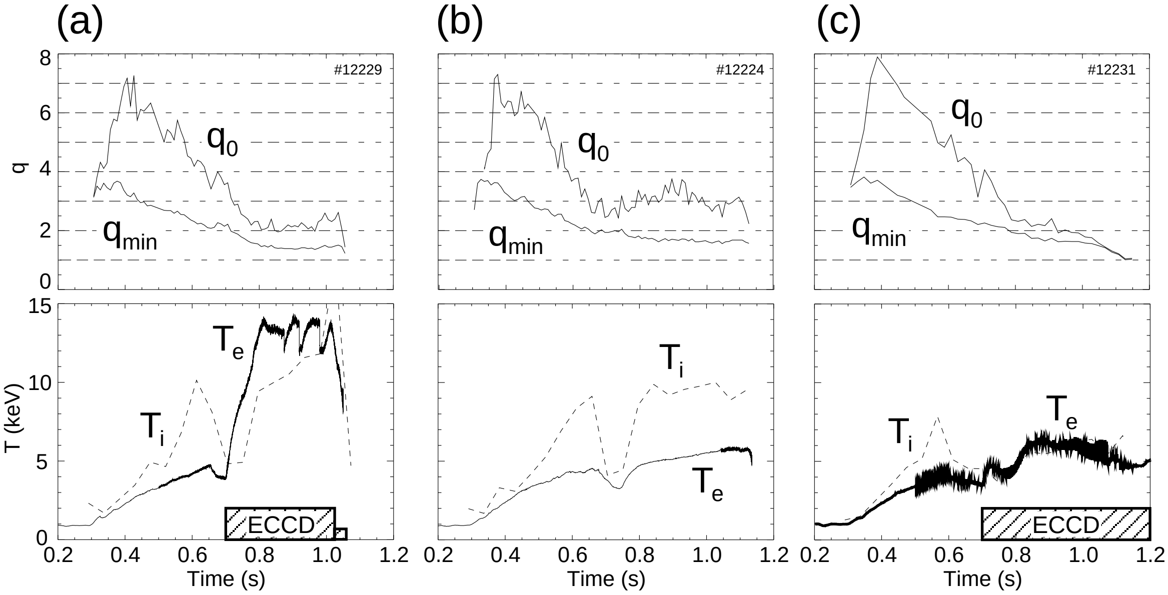

Fig. 1.: Comparison of three types of discharges with heating in the current ramp-up phase: (a) NBI and counter-ECCD, (b) reference case with NBI only, and (c) NBI and co-ECCD. Shown are the evolution of central and minimum q, the difference of which reflects the amount of shear reversal, and maximum values of ion and electron temperature from charge exchange recombination spectroscopy and ECE, respectively. The ECE channels are located at $\rho_{tor} \geq 0.2$ *because of the central ECRH deposition.*

For counter-current drive (figure 1(a)) the electron temperature, even 0.12 m from the center, reaches a value of 13 keV, which is confirmed also by Thomson scattering and is most of the time higher than the central value of the ions. The large drop of T_i before ECRH is switched on is attributed to the (2,1) mode, which disappears when q_{min} has passed through the q = 2 surface. Raytracing calculations with the TORAY code show an ECR deposition within ρ_{tor} = 0.2. Neglecting current diffusion, the calculated driven current initially is 82 kA and rises to 134 kA due to the strong increase of the electron temperature. The corresponding current density is of the order of the total current density measured with the MSE diagnostic in the plasma center. Depending on the exact location of the ECRH deposition, the diffusion times required for the build up of these currents vary between 50 and 200 – 300 ms. The temporal evolution of the central and minimum q exhibits a slowdown of the current profile decay shortly after the application of counter-ECCD. At 1.06 s the discharge is terminated by a disruption triggered by the accidental tripping of two gyrotrons.

Figure 1(b) shows the equivalent traces for a reference discharge without ECRH power, in which T_i reaches a similar high value, but the maximum T_e remains at 5 keV. The behavior of the q-profile derived from CLISTE using the MSE measurements is comparable to the counter-ECCD case. However, the slope of the central MSE polarization angles which is a measure of q_0 show a small but visible difference suggesting a larger q_0 with counter-current drive. Probably the parametrization of the current profile in the present version of the equilibrium code is not sufficiently flexible to bring out these small and very localized differences.

With the ECR current drive in co-direction (figure 1(c)) the (2,1) mode, which in the other two cases has disappeared again, develops into a continuous mode with decreasing frequency and exists throughout the ECCD phase which inhibits the recovery of the ITB. T_i being equal to T_e remains at relatively low values also in the plasma center. The increasing modulation of the T_e amplitude in figure 1(c) is caused by the (2,1) mode. 300 ms after the switch-on of co-ECCD, both, q_0 and q_{min} start to drop finally reaching unity. Two main effects may contribute to the faster decay of the reversed shear: On the one hand, the central current density is increased by co-current drive and, on the other hand, the boot strap current due to the deteriorated confinement is reduced.

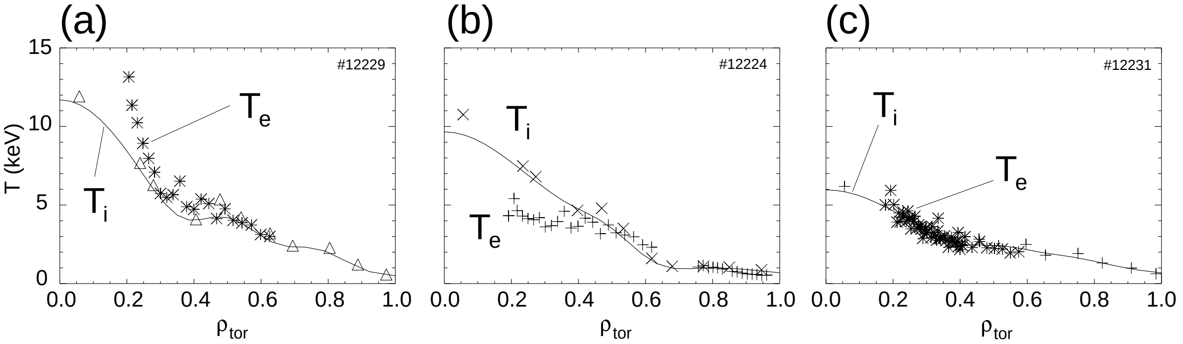

Fig. 2.: Comparison of the temperature profiles at 0.97 s of the three types of discharges with heating in the current ramp-up phase: (a) NBI and counter ECCD, (b) reference case with NBI only, and (c) NBI and co ECCD. The strong electron temperature gradient is only seen in case of counter-ECCD.

The temperature profiles of the three cases are shown in figure 2, evidencing the strong electron temperature gradients with counter-ECCD. Without ECRH the electrons are mainly heated through the ions and therefore do not follow the increase of T_i in the plasma center. For co-ECCD due to an increased radial transport $T_i = T_e$.

The comparison between the toroidal rotational velocities of counter-ECCD and NBI only discharges does not exhibit marked differences (figure 3). Before the ECCD is switched on v_{tor} is similar in both cases. During ECCD the rotational velocity of the plasma appears to rise more slowly, but finally reaches the same value as in the reference discharge (0.981 s). At this time also the radial profiles are of comparable shape.

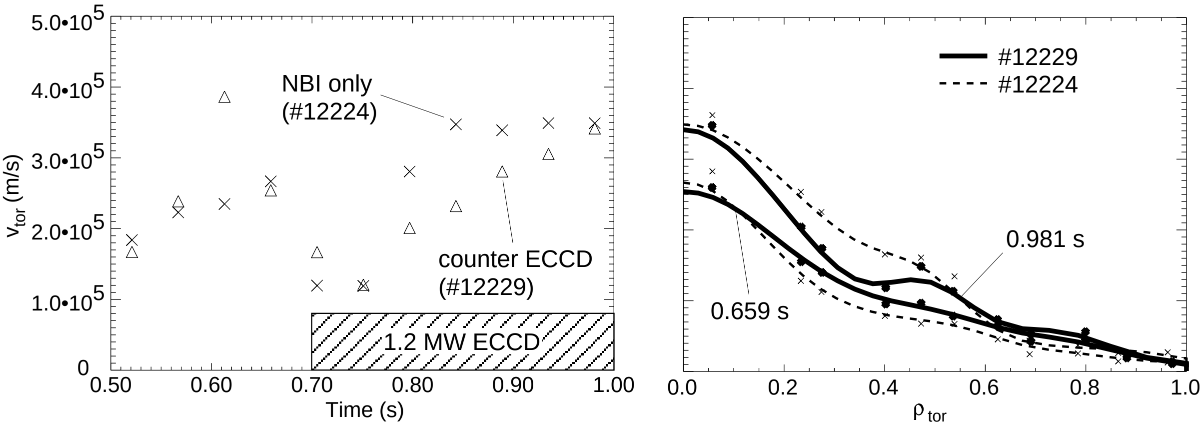

Fig. 3.: Time evolution and radial profiles of toroidal rotational velocity (v_{tor}), comparing the counter-ECCD with the reference discharge (NBI only) before and after the application of ECCD.

Summary. It has been demonstrated that with a combination of neutral beam injection and electron cyclotron current drive into plasmas with negative central shear it is possible to attain internal transport barriers for both electrons and ions simultaneously. In the cases presented, where during ECCD the minimum q-value has already dropped below two, the high central electron temperature in combination with the amount of shear reversal seems to play a critical role in the ability to avoid MHD instabilities which strongly deteriorate the improved core transport properties. Only if the high value of q_0 is sustained, supported by counter current drive, it was possible to reach high central electron temperatures. Here, the stabilizing effect of reduced resistivity on double tearing modes could serve as an explanation.

These experiments have addressed one of the most critical elements for the applicability of advanced scenarios to a fusion reactor, namely their behavior under simultaneous strong ion and electron heating, at $T_e \approx T_i$, with an outcome giving strong support to the case.

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