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Transport Modelling of ASDEX Upgrade Plasmas with Internal Transport Barrier

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1. Introduction

Improved core confinement with internal transport barriers (ITB) in both electron and ion components has been observed in ASDEX Upgrade [1,2] with neutral beam (NB) and electron cyclotron heating and current drive (ECCD). With 1.2 MW counter-ECCD the central electron temperature T_e raises by a factor of two compared to a reference shot with NBI alone reaching a value of 10 keV which is comparable to T_i. With co-ECCD a high level of MHD activity results in freezing T_e and T_i at a lower level of 5 keV. Transport modelling has been performed in order to figure out (1) what a difference in evolution of the safety factor $q(\rho)$ for both cases can be responsible for such a pronounced difference in MHD behavior and (2) whether these experimental results are compatible with the assumption that the energy transport is governed by the ion temperature gradient (ITG) and trapped electron mode (TEM) instabilities. Results of the analysis are presented in this report.

2. Experimental regimes

Experimental results are described in detail in [1]. Here we outline the main features. In Fig. 1 the time evolution of central ion and electron temperatures for three types of discharges without EC heating, with counter-ECCD and with co-ECCD is shown.

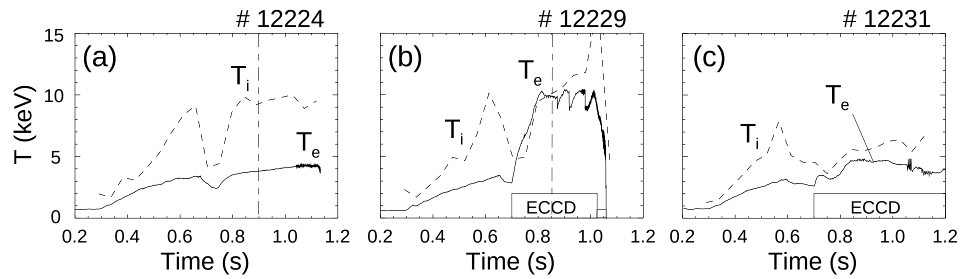

Fig. 1. Time dependence of central electron and ion temperatures: (a) Reference case with NBI only, (b) combination of NBI and counter-ECCD, (c) NBI and co-ECCD.

All three shots show a very similar behavior before the EC heating is applied at $t > 0.7$ s. They are obtained by early (2.5 MW at time $t > 0.3$ s, 5 MW at $t > 0.34$ s) NB heating during the current and density ramp-up phase. The plasma current increases at a rate of 7.5×10^5 A/s. MHD activity of (2,1) mode first appears at $t \approx 0.6$ s as short fishbone-like bursts which do not influence the plasma confinement. Approximately at $t = 0.67$ s it switches to a continuous mode of much lower frequency identified as the double tearing mode (DTM) [2]. The DTM causes a confinement deterioration and a drop in T_i and T_e is observed. Later the modes are stabilized and T_i recovers. In case of counter-ECCD, the stabilization happens even earlier and T_e also grows up to 10 keV. In case of co-ECCD, the MHD activity continues deteriorating confinement and resulting in a relatively low T_e and T_i.

3. Simulation of the current diffusion

As long as the current density modifications due to ECCD show a crucial influence on the MHD behavior and the energy confinement we start with a transport modelling of current diffusion. It was performed using experimentally determined profiles of the electron T_e and ion T_i temperature, electron density n_e and calculated profiles of NB and EC deposited power and driven current. The bootstrap current and plasma conductivity were calculated making use of the neoclassic code NCLASS [3]. The plasma effective charge was taken to be $Z_{eff} = 4$ what is a reasonable value for limiter discharges in ASDEX Upgrade and allows to fit the measured values of the loop voltage.

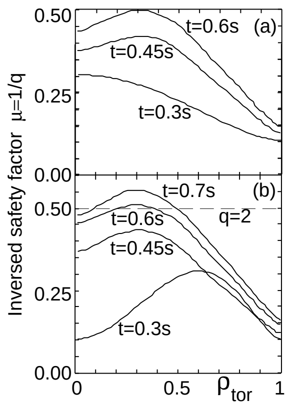

Fig. 2. Influence of initial conditions on the $\mu(\rho,t) = 1/q(\rho,t)$ evolution.
(a) $q_0(t_0) = q_{min}(t_0) = 3.25$,
(b) $q_0 = q_a = 9.3$.

Initial radial profile of the safety factor q was adjusted so that the observed time of first appearance of (2,1) MHD activity coincided with the time of occurrence of the $q = 2$ resonance surface in modelling. Although such an approach can introduce a non-physical dependence on the initial condition it will be seen that this dependence is rather weak and cannot affect the results discussed below.

An example of this dependence is presented in Fig. 2. One can see that with two quite different initial conditions, after 0.3 s of evolution, $q(\rho)$ arrives at nearly the same finite profile. The most significant difference between the two cases is a time delay of 0.03 s so that the q-profile of case (b) at $t = 0.57$ s closely coincides with that of case (a) for $t = 0.6$ s. If the simulation starts with a flat current density profile, $q(\rho, t_0) = 9.3$, then the picture remains similar to that shown in Fig. 2, however, $q = 2$ is first achieved at $t = 0.65$ s.

After appearance of the resonance surface, further expansion of the resonance radius is similar in all cases. It also coincides with the evolution of outer $q = 2$ surface derived from the ECE measurements. This gives a confidence that the adopted approach properly reproduces experimental q behavior and can be used as a reasonable starting point for further investigation.

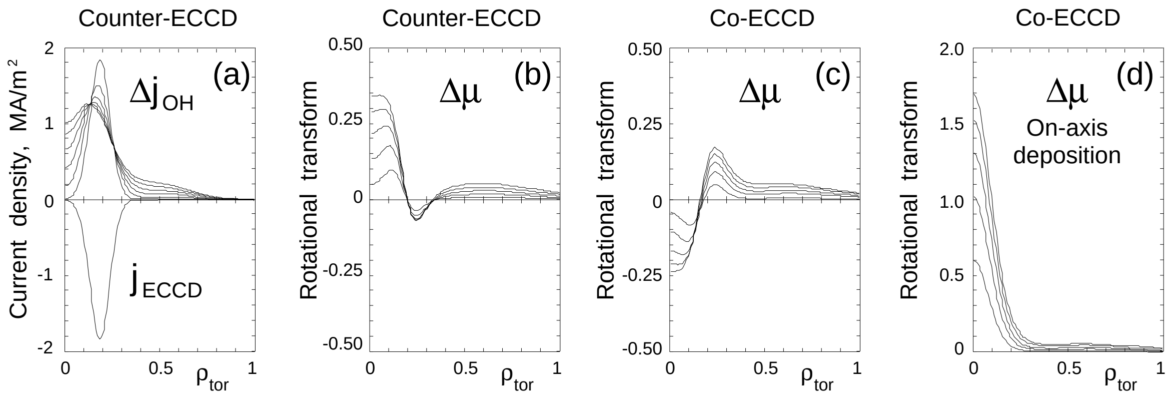

Fig. 3. Time variation of the Ohmic current density j_{OH} and the rotational transform μ starting from the outset of ECCD at $t_0 = 0.7$ s. Incremental changes of $\Delta j_{OH} = j_{OH}(\rho,t) - j_{OH}(\rho,t_0)$ and $\Delta\mu = \mu(\rho,t) - \mu(\rho,t_0)$ are shown with a time interval of 0.02 s. (a), (b), (c) off-axis ECCD, (d) on-axis ECCD.

As mentioned above (2,1) MHD activity continues about 0.1 s before the ECCD is applied. During this period, $\mu(\rho)$ grows monotonically in time as shown in Fig. 2(b). In [1] stabilization of MHD activity was attributed to the growing distance between two $q = 2$ resonances. In our modelling, it takes approximately 0.15 s from the first appearance of the resonance till the inner resonance point disappears on the magnetic axis. Obviously, a strong local ECCD can significantly affect this behavior.

In order to assess an influence of ECCD on this evolution we first consider relative changes in the rotational transform shown in Fig. 3. The EC driven current calculated with the TORAY code is shown in Fig. 3(a). For simplicity of comparison, plasma parameters and EC driven current profile are fixed at $t = 0.7$ s. In all cases, diffusion of the Ohmic current results in a substantial and rather fast variation of μ on the magnetic axis. One can see also a clear distinction between off-axis (the deposition width is smaller than the distance to the magnetic axis) and on-axis deposition.

We consider first the case of co-ECCD. Applying the procedure described above we obtain a μ-evolution shown in Fig. 4 which can be understood by adding the μ-variation shown in Fig. 3c to the μ-profile of Fig. 2b at $t = 0.7$ s. One can clearly see an additional delay of 0.2 s in disappearance of the inner resonance surface. The result is in agreement with the experimental observation that MHD dominated phase is extended by co-ECCD. However, this modelling is not comprehensive for the following reason. As shown in [1], (2,1) MHD modes clamp a profile of safety factor q in the region between two resonances so that μ_{max} is kept close to 0.5. On one hand, our diffusive model does not take into account this effect. On the other hand, decreasing $\mu(\rho = 0)$ just after switching co-ECCD on is caused by the current diffusion outside a zone affected by MHD. Therefore, this trend cannot be changed with allowance for any non-diffusive processes between the two resonance surfaces.

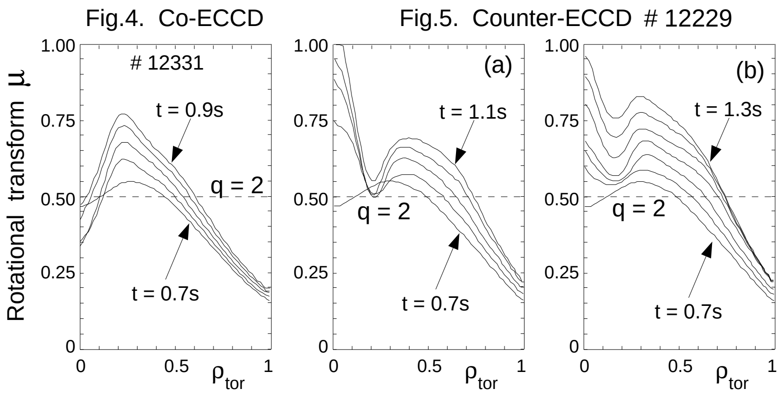

Fig. 4. Calculated time evolution of the rotational transform μ in shot 12331 for the succession of times $t = 0.7, 0.75, 0.8, 0.85, 0.9$ s.

Fig. 5. The same for shot 12229 with a time interval 0.1 s. (a) Narrow ECCD deposition, (b) broadened ECCD deposition.

For counter-ECCD (Fig. 3b), the negative change in μ is largely compensated by a positive increment due to the plasma current rise. Width of a zone where $\Delta\mu$ is negative and an amplitude of negative variation depend on many factors including the EC power applied, the width of the deposition zone and its location. Fig. 5a presents modelling similar to one shown in Fig. 4 but for the shot # 12229 with counter current drive. According to this modelling the inner resonance surface disappears 10 ms after the ECCD is switched on. This is in consistence with the experimental observation that MHD activity is stabilized by counter ECCD. However, under a simplified assumption that the EC current profile is fixed in time (Fig. 5a) after 0.15 s two new $q = 2$ resonances reappear and are present during the next 0.15 s. In a real experiment, the EC current deposition profile moves in time due to the movement of magnetic surfaces. This more realistic situation is shown in Fig. 5b where a broadening of the deposition profile due to displacement of magnetic surfaces is taken into account. In this case, only one $q = 2$ resonance is present in the plasma although multiple $q = 3/2$ resonances can be unstable.

4. Energy confinement

As shown in [4] plasma confinement in ASDEX Upgrade is well described with Weiland-Nordman transport model [5] based on ITG instability. However, a growth of the ratio T_e/T_i destabilizes the ITG mode and should result in enhanced anomalous transport. On the other hand, comparison of discharges 12224 and 12229 does not reveal this feature. Moreover, experimentally derived heat conductivities show the opposite trend.

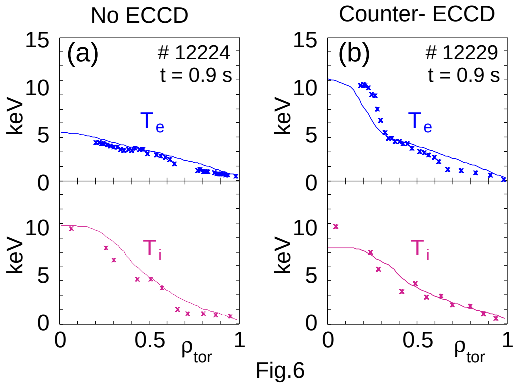

Fig.6

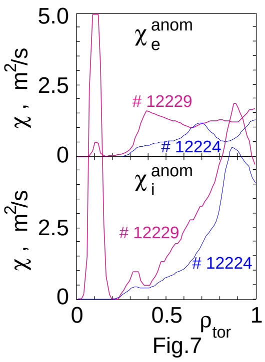

Fig.7

Fig. 6. Comparison of calculated (curves) and measured (dots) electron and ion temperature profiles at $t = 0.9$ s. (a) shot 12224 (NBI alone), (b) shot 12229 (NBI in combination with ECR heating).

Fig. 7. Anomalous heat conductivities according to Weiland-Nordman model.

In order to find out whether the new experimental results of [1,2] are consistent with the ITG induced anomalous transport a full simulation including the thermal transport of electrons and ions was performed for the discharges 12224 and 12229. The results are presented in Figs. 6 and 7. As expected, the electron and ion heat conductivities in the simulation (Fig. 7) are noticeably higher for the shot 12229 than for the shot 12224. Nevertheless, the experimental results are reproduced reasonably well both for pure NBI heating (shot 12224) and for combined NBI and EC heating (shot 12229). A significant enhancement of χ_i within a zone $\rho < 0.3$ does not deteriorate the plasma confinement substantially.

5. Conclusions

The current diffusion and energy confinement in ASDEX Upgrade discharges with 1.2 MW of ECCD were simulated making use of the transport code ASTRA. The diffusive current evolution model matches the measured loop voltage and the resonance surface location derived from ECE measurements. A strong influence of central ECCD on evolution of the safety factor profile was found which is in a qualitative agreement with observed MHD behavior and MSE current profile measurements.

The Weiland-Nordman transport model is shown to be applicable to ASDEX Upgrade plasmas with combined NBI and ECR heating when $T_e \geq T_i$. Although an increase of transport coefficients with a growth of T_e/T_i predicted by the model is not seen in the experiment a difference between the simulated and measured temperatures remains within experimental errors.

References

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