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INTRODUCTION

Efforts have been made to develop advanced scenarios aiming at obtaining high confinement and stability in tokamak plasmas. Internal Transport Barrier (ITB) discharges are believed to be the most promising way to attain the goal. However, the ITB discharges require supplementary elaborate control of the pressure and the current density profile and of the MHD stability in order to fulfil the demand for advances scenarios. The improved H-mode scenario, so-called ITER hybrid scenario, cut a conspicuous figure as an advanced scenario to overcome such drawback of ITB discharges. It accomplishes high confinement (H_{98} up to 1.4) and stability (β_N up to 3) simultaneously in long pulse duration (~50 τ_E limited by the machine hardware). This scenario is established in many tokamak devices, such as ASDEX Upgrade, JET, DIII-D and JT-6OU, relying on low or zero magnetic shear in the centre of the plasma [1-4]. To access the improved H-mode regime in this scenario, it is a key to apply moderate heating avoiding the ITB formation in the current ramp up phase and to produce low magnetic shear in the central region of the plasma. Neutral Beam Injection (NBI) is the main heating tool for this scenario but in some discharges ICRH has been used to replace some of the NBI power. To avoid density peaking, which triggers serious NTM's and leads accumulation of impurities in the centre, ICRH or ECRH are used in addition to the NBI heating [5].

In this paper, transport analysis is performed for an improved H-mode discharge at ASDEX Upgrade with the aim of investigating the reason for the improved confinement in this scenario compared to the standard H-mode scenario. In addition, transport in an improved H-mode discharge at JET is analysed and compared to those in ASDEX Upgrade, particularly for the experiments with similar ρ^*, q-profiles and plasma configurations compared to ASDEX Upgrade.

1. TRANSPORT ANALYSIS IN THE IMPROVED H-MODE AT ASDEX UPGRADE

The ASTRA code [6] is employed for the transport simulations of improved H-mode discharges. It is a 1.5-dimensional transport code with realistic tokamak geometry but no divertor geometry. It calculates plasma equilibrium, current diffusion and heat transport self-consistently. Particularly, the Weiland transport model [7] is employed for the heat transport calculations in this work. Remarks should be given here that the Weiland model employed for this work inherently has a limit to its application to the regime with low or zero magnetic shear. Neo-classical electrical conductivity is assumed and no MHD activities are included in the simulations. Boundary conditions are given at $\rho_{tor} = 0.8$ for ion and electron temperatures since the ITG instability is not expected to dominate transport in the H-mode edge barrier region. No particle transport calculations ($n_e = n_e^{exp}$) are included for the simulations. The initial q-profile is used from the MSE measurements. The heat transport simulations are performed for ASDEX Upgrade pulse 17870 at two time points. One is chosen in the premature improved H-mode regime with the 5MW heating power (2.14sec),where H_{98}~1, β_N ~1.8 and the other in the fully developed improved H-mode regime with the 7.5MW heating power (4.71sec), where H_{98} ~1.4, β_N ~2.8. The experimental and calculated temperature profiles for the two time points are shown in figure 1 (a) and (b) for ion and electron, respectively. The Weiland model predicts the experimental temperature profiles reasonably well. The ion heat conductivity is presented in figure 1(c). The calculated conductivities by the Weiland model are similar to the power balance ones computed using experimental measurements. The heat conductivities in the central region of the plasma, where $\rho_{pol} < 0.4$, are very close to the neoclassical ones. This could result from the high E×B shearing rate as shown in figure 1(d) and little volume integrated heat source at the centre due to the off-axis beam heating.

It is worthy to note that the ion temperature gradient length in the fully developed improved H-mode regime is not changed compared to that in the premature improved H-mode regime although the ion temperature is increased globally due to the higher value on top of the pedestal. This implies that further improvement in the confinement and stability at the fully developed improved H-mode regime is not originated from the improvement in the ion heat transport. It is supported by the experimental observations. First, turbulence level measured by O-mode heterodyne reflectometry reveals that no dramatic change is observed at $\rho_{pol} = 0.6\text{-}0.7$ between the premature regime and the fully developed regime. In addition, the ion temperature gradient length stays the same in this discharge although temperature gradient changes as presented in figure 1(a).

Second, it is observed that the ion temperature and the toroidal rotation velocity profiles [8] in improved H-mode discharges are stiff with the same gradient length as standard H-mode. As shown in figure 2, improved H-mode discharges lie on the same solid line $T_i(0.4) = 1.9 \times T_i(0.8)$ as standard H-mode discharges do. It implies that the improved H- mode discharges are still turbulence dominated, similar to the standard H-mode. If $T_i(0.0)$ versus $T_i(0.4)$ is plotted in the similar way, both improved H-mode and standard H- mode discharges are located on the line, $T_i(0.0) = 1.7 \times T_i(0.4)$ although points are more scattered. Therefore, in the central region the improved H-mode discharges also have a similar behaviour as standard H-mode discharges although most of standard H-mode discharges locate below of the line, $T_i(0.0) = 1.7 \times T_i(0.4)$ due to sawtooth.

2. TRANSPORT ANALYSIS IN THE HYBRID SCENARIO AT JET

In a similar way, heat transport simulations are carried out for a JET hybrid scenario, Pulse No: 58323, and the results are shown in figure 3. Here, the simulation is performed at 13sec in the fully developed improved H-mode regime. As shown in figure 3(a), the Weiland model fails to predict temperature profiles well. Particularly, it underestimates ion temperature. The calculated ion heat conductivity by the Weiland model is much higher than that of ASDEX Upgrade as presented in figure 3(b). Also the heat conductivity from the power balance calculation is higher than the neo-classical one. Both the E×B shearing rate and the linear growth rate are lower compared to ASDEX Upgrade (see figures 1(d) and 2 (c)). The E×B shearing rate is not high enough to surpass linear growth rate.

Similar to the improved H-mode discharges at ASDEX Upgrade, ion temperature profile stiffness is observed in JET hybrid scenarios, which is shown in figure 4. The trend of hybrid scenarios is generally follows the behaviour of standard H-mode discharges and different from that of ITB discharges. However, few hybrid scenarios are positioned above the solid line similar to ITB discharges.

CONCLUSION AND DISCUSSION

Transport in improved H-mode at ASDEX Upgrade and JET is analysed by the modelling using ASTRA with the Weiland model and by the experimental observations. Both show that ion heat transport is not improved in the improved H-mode regime. The confinement region is still turbulence dominated accordingly, stiff ion temperature profiles are observed as in typical H-mode discharges. However, some discharges have lower ion temperature gradient length, indicated some points above the solid lined in figures 2 and 4, which could imply that some improved H-mode discharges have weak ITB's. This needs more investigation. Consequently, the improved H-mode regime can be characterised as a high confinement regime with turbulence where the core ion heat transport is similar to standard H-mode but very close to the criterion of ITB formation. And it needs more investigations to find the reasons for the improvement in improved H-mode discharges without ion heat transport improvement, for example the role of edge pedestal and peaked density profiles.

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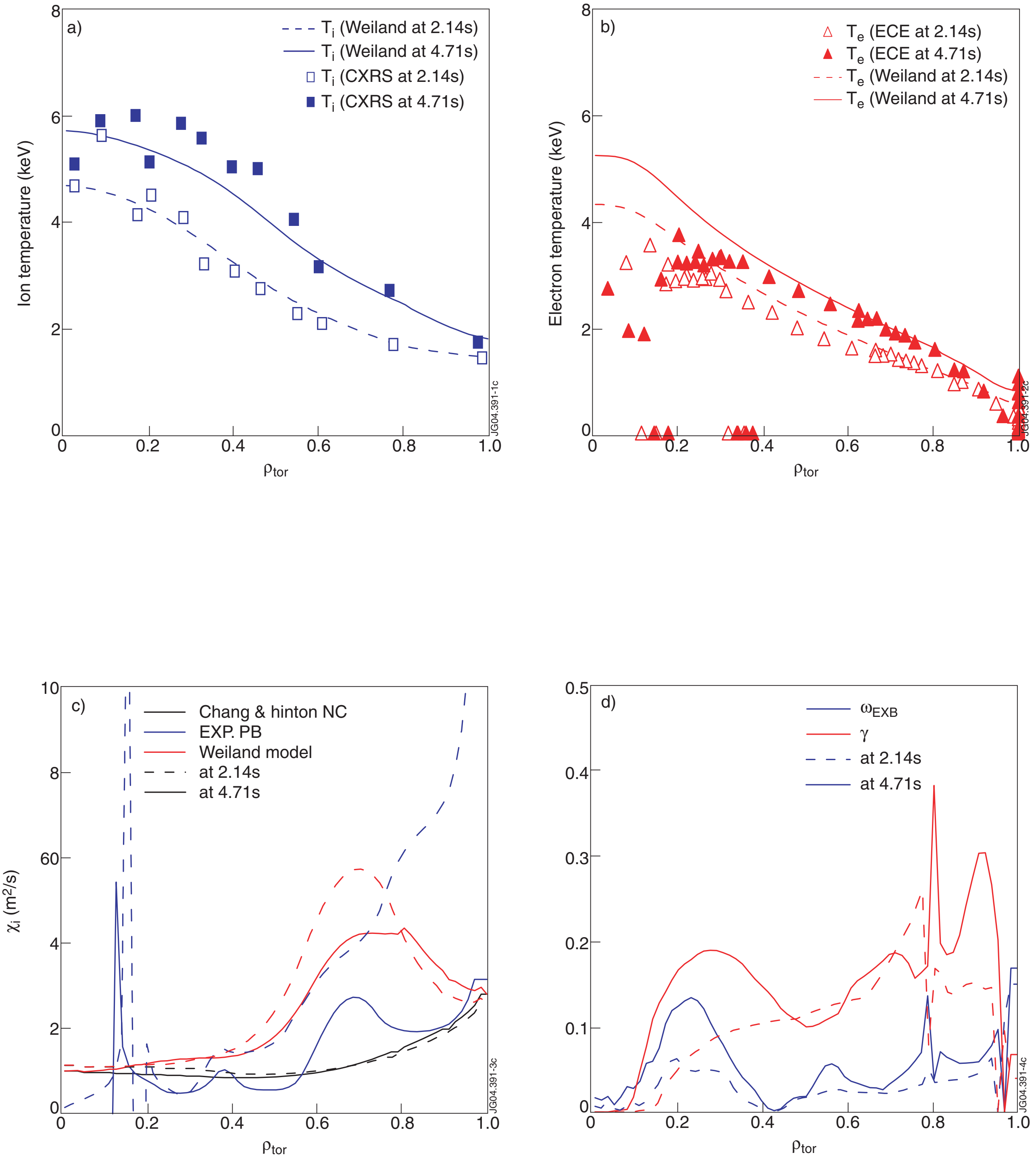

Figure 1: Pulse No: 17870 at ASDEX Upgrade; experimental and calculated ion (a) and electron (b) temperature profiles, corresponding ion heat conductivity (c), E×B shearing rate and linear growth rate (d) at premature and fully developed improved H-mode regime. For $\rho_{tor} > 0.8$, the transport calculation is not performed.

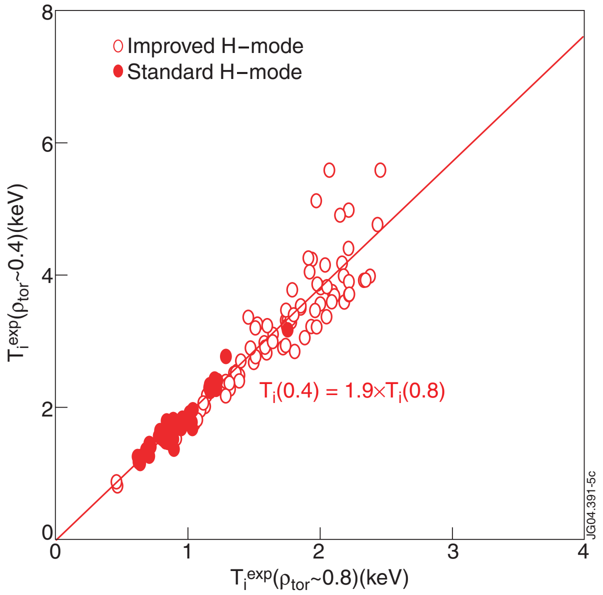

Figure 2: Experimentally measured ion temperature at r_{tor} = 0.4 versus those at r_{tor} = 0.8 for standard and improved H-mode discharges.

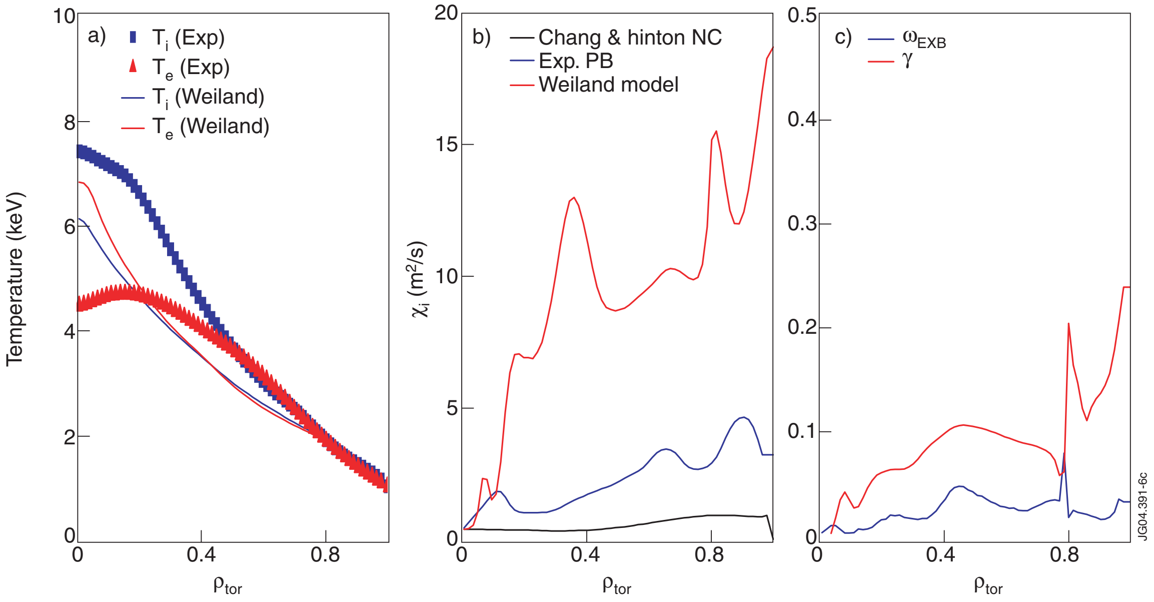

Figure 3: Pulse 58323 at JET; experimental and calculated ion and electron temperature profiles (a), corresponding ion heat conductivity (b), E×B shearing rate and linear growth rate (c) at premature and fully developed improved H-mode regime.

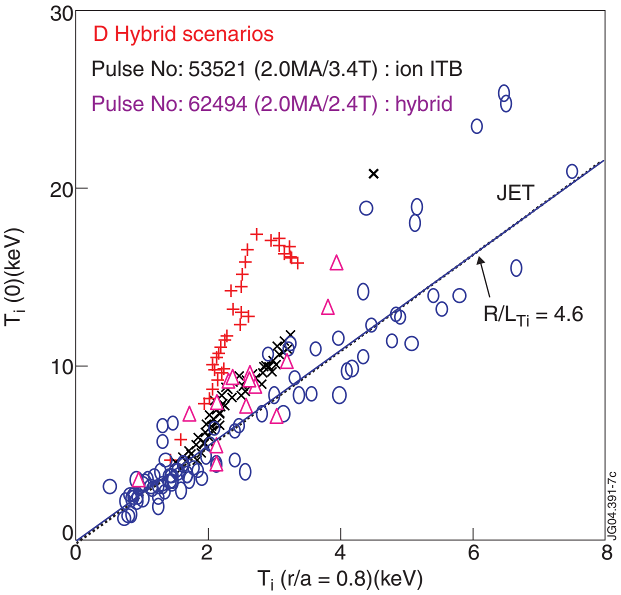

Figure 4. Experimentally measured ion temperature at r/a=0 versus those at r/a=0.8 for ion ITB discharges, standard and improved H-mode discharges,