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Full f particle simulation of internal transport barrier formation

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Introduction. Various mechanisms have been suggested as a cause of the ITB in LH ion heated low current FT-2 discharges. According to the ASTRA and BATRAC simulations, the shear in the poloidal rotation does not rise sufficiently according to the standard neoclassical theory by the increase in the pressure gradient [1]. However, by inclusion of the inductive toroidal electric field and the related Ware pinch and ion and electron viscosities, substantial changes in the calculated radial electric field were found [2]. On the other hand, by ASCOT Monte Carlo particle simulation of the neoclassical evolution of the FT-2 hydrogen discharges a strong onset of the poloidal rotation was found at low plasma current when the ion temperature was raised by LH heating over 150 eV at the steepest gradient region [3]. In the ASCOT simulations, the wide orbit effects and the proper treatment of poloidal rotation exceeding the Mach limit are included.

Full *f* particle simulation code ELMFIRE is a gyrokinetic version of ASCOT solving electrostatic turbulent plasma simulation in tokamaks allowing significant changes in plasma profiles during simulation. Applying the code in FT-2 tokamak configuration, the formation of internal transport barrier (ITB) -like structure was found in Ref. [4] with sufficient lower hybrid ion heating in accordance with the experimental observations of ion temperature profile and related transport coefficient interpretation. However, there the plasma was initially at high temperature. In the present work, the origin of the ITB formation in gradually heated plasma is investigated and more details are included in the simulation. The relative roles of the Ware pinch, Oxygen impurity effects on the turbulent modes, rotation shear by neoclassical poloidal rotation and turbulence driven Reynolds stress, and recycling details on the transport barrier generation are investigated for the rapidly evolving plasma pressure profile during heating and transport collapse.

Numerical model. In ELMFIRE, particles are followed in a toroidal annulus in an axisymmetric torus. Collisions are evaluated using a binary collision model and, thus, neo-classical physics included. Code includes kinetic electron and ion species, one impurity species and analytic neutral model. 3D electrostatic perturbations are solved using a direct ion polarization method [5] in quasi-ballooning (almost straight field line) coordinates while guiding centre

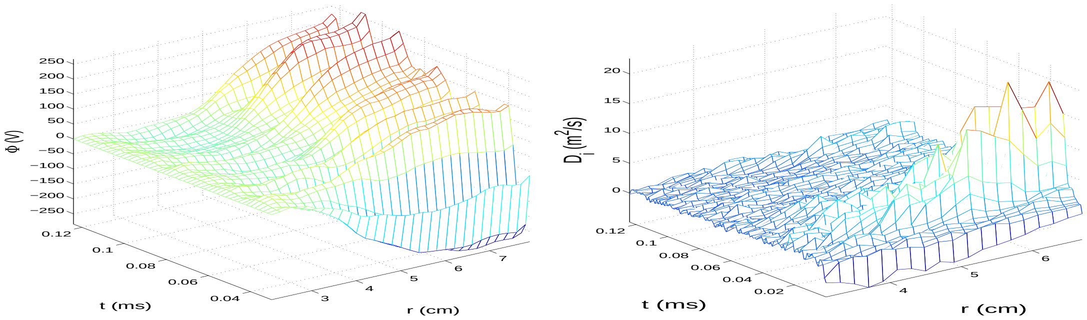

Figure 1: *a) Rapid growth in electrostatic potential is observed when ITB developes, b) particle diffusion coefficient D_i drops after initial transient*

equations are solved in straight field line coordinates. The code has been benchmarked against the other gyrokinetic code predictions for the Cyclone base case linear mode characteristics and nonlinear saturation level of χ_i in both adiabatic and kinetic electron simulations. Moreover, detailed predictions of neoclassical properties, including the radial electric field, in the presence of turbulence have been performed. More numerical details of the code and benchmark tests are given in [6].

Results. In FT-2 tokamak [1], internal transport barrier has been observed with some 100 kW LH heating of ions. To model this experiment, simulations in a hydrogen or deuterium plasma with a minor radius of $a = 8$ cm, major radius of $R = 55$ cm, magnetic field $B = 2.2$ T, and plasma current of $I = 22$ kA have been conducted. Here, 5×10^6 ions and 5×10^6 electrons are simulated in $N_r = 31$, $N_\chi = 200$, $N_\phi = 4$ grid using timestep $\Delta t = 5\times10^{-8}$ s. At the outer edge, recycling (100 %) boundary condition is used and at the inner boundary potential is set at zero. In Ref. [4], evidence of ITB generation was observed starting from well heated plasma with $T_e \sim 300$ eV, $T_i \sim 250$ eV and impurities were not taken into account. Here, instead, ion temperature is initially only $T_i \sim 150$ eV and is gradually heated to transition temperature. Lower hybrid off-axis (power deposition maximum at r=0.035 m) ion heating applied at the power level of 120 kW, and the density and temperature profiles are taken to be close to the experimentally measured ones at the simulation start. Oxygen impurity ($Z = 8$) with concentration $n_{O8+}/n_e = 0.05$ is assumed. In Fig. 1a, evolution of the magnetic surface averaged plasma potential is shown together with the time evolution of main ion diffusion coefficient in Fig. 1b. After some 50 μs when the radial electric field increases significantly in the middle of the plasma leading to a relatively strong shear in the $E_r \times B$ velocity at the radius $r \sim 5$ cm as shown in Fig. 2 while E_r at outer radius remains in lower amplitude. Heat transport coefficient χ_i clearly follows the oscillation of E_r while at the same time, Reynolds

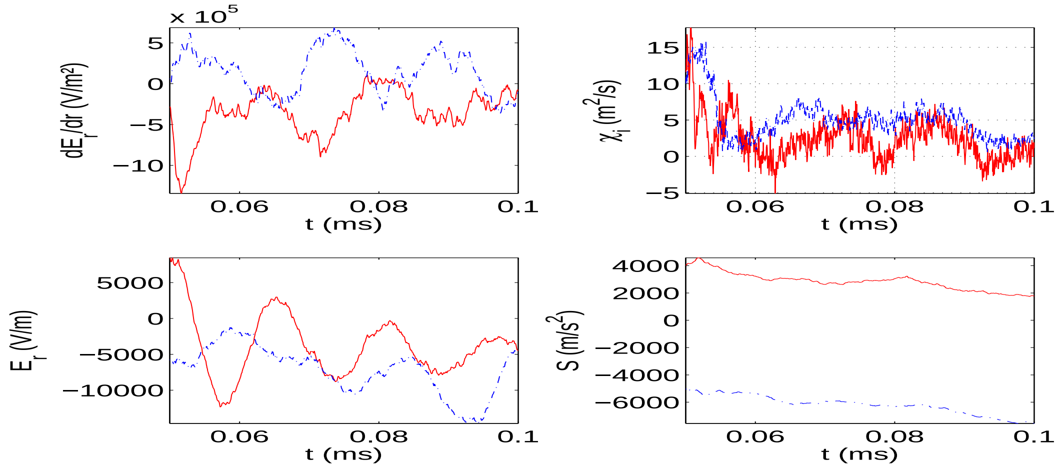

Figure 2: *dE_r/dr, χ_i, E_r and Reynolds stress at radii $r = 5$ cm (solid) and $r = 6$ cm (dashed) show clear correlation between large electric field and suppressed χ_i*

stress changes only slowly (only the Reynolds stress of main ions is shown in the figure). In Fig. 3, time traces of temperature profiles are shown together with time behaviour of heat transport coefficients. No rapid change is observed in χ_i which was the case in simulation without impurities in Ref. [4]. However, clear drop in heat transport coefficients of impurites is seen in the figure.

Effect of Ware pinch has also been tested. However, in the present case with the oxygen impurity (with measured concentration) included in the ELMFIRE simulations, the loop voltage of 2 V was not able to provide significant changes in the poloidal rotation profile in spite of the inclusion of the Ware pinch effect. In contrast, a slight increase in the anomalous transport coefficient was observed which is also seen as a more modest growth of the poloidal rotation and radial electric field than in the case with no impurities. On the other hand, without impurities the deuterium discharge shows a strong increase of poloidal rotation after the LH ion heating has raised the ion temperature over 150 eV at the steepest gradient region. This result is obtained even with a zero loop voltage indicating that the Ware pinch effect is not a strong mechanism, at least for a constant loop voltage.

A similar behavior was also seen with hydrogen (which was used in experiments) ions. The oxygen concentration n_O/n_e radial profile was there set more close to the measured one by accounting for the off-axis maximum of the concentration. In spite of the lesser dilution of hydrogen in the core and the related steepening of the hydrogen density profile off axis, no similar growth of the poloidal rotation was observed with impurities as in the case of deuterium with impurities. The charge exchange losses of the ions and the ionization energy losses of the electrons were also incorporated in the model according to a neutral and recycling model for

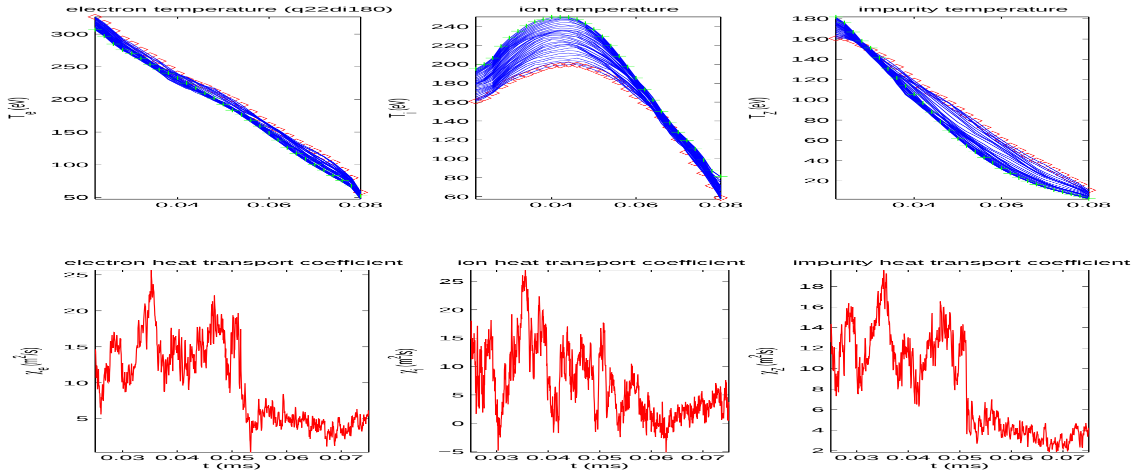

Figure 3: *Top row: Time traces of temperatures T_e, T_i and T_Z. Here, diamonds denote the start and "+" the end of simulation ($t = 0.08$ ms). Bottom row: Sudden drop in heat diffusion coefficient of electrons and impurity ions is observed at radius $r = 5$ cm.*

the FT-2.

It is therefore of importance to investigate the role of turbulence in the neoclassical behavior of the plasma. While the turbulent structures and related poloidal rotation as found from ELMFIRE appear to be in good agreement with the Doppler reflectometry measurements [7] in L-mode discharges, a similar comparison has not yet been made with LH heating included.

Conclusions. Formation of ITB-like structure in a gradually heated plasma with realistic impurity concentration was found in accordance with the experimental observations of ion temperature profile and related transport coefficient interpretation. Here, sudden drop was not clearly observed in χ_i, but rather in χ_e and χ_Z. Clear correlation between time behaviour of radial electric field and suppressed transport coefficient was observed.

The computing facilities of CSC – Scientific Computing Ltd. were usedfor this work.

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