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ORIGINAL ARTICLE

Contributions to Plasma Physics

Revisiting the improved core confinement simulations for FT-2 tokamak

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Abstract

In the present paper, we revisit observations performed in FT-2 tokamak from previous works. Improvements of core confinement are observed and believed to be caused by wide orbits going from collisionless to collisional regimes. Similar phenomena can occur whenever gradient lengths are comparable to the orbit widths at the top of the pedestal and the loss cone is continuously and increasingly filled by heated particles, collisions and turbulent effects. The lower hybrid heating operator is introduced into the ELMFIRE code to increase the ion temperature during the simulations while keeping the edge temperature low with logical boundary condition at the limiter. Particular focus is given on how the radial electric field deviates from the neoclassical value while introducing turbulent effects.

KEYWORDS

gyrokinetic simulation, neoclassical plasma, tokamak plasma, turbulence

1 | INTRODUCTION

The collisional and turbulent phenomena that occur in the presence of toroidal magnetic fields play a pivotal role when approaching tokamak physics. The neoclassical and turbulent effects affecting the dynamics of plasma flows have attracted a much deal of interest both experimentally and theoretically.[1,2] The study of confinement involves the understanding of various quantity of interest. The radial electric field E_r behaviour coupled with the turbulent cross field transport in different tokamak regions may give rise to different types of instabilities, such as ion temperature gradient turbulence (ITG) and trapped electron modes (TEM).

Standard neoclassical (NC) theory[3] provides estimates to the behaviour of E_r, even though limited to narrow orbits. Many numerical simulations of neoclassical electric field have been carried out by either employing the full f[4–6] or the delta f[7] method. However, when the effect of turbulence is also included, this has a direct effect to electric field, for example, through the Reynold's stress but also indirect effect in full-f simulations through the changes of density and temperature profiles in time.

When the codes are able to study plasma characteristics and dynamics with a much better resolution, faster relaxation time also appear. The present computing power allows to repeat the previous neoclassical work[1] now including turbulence and previous turbulence simulations[8] now with better resolution. Also, we discuss arguments if the previous work fall in the internal transport barrier physics or rather edge pedestal one. Such conclusions are supported by the fact that the orbits undergo different collisionality regimes and posses widths large compared with the gradient scale lengths, especially for trapped ions. Compared with previous works, more turbulent transport is generated and a relatively sheared $E \times B$ flow appears with on-axis LH-heating, while in the off-axis case it seems to disappear when ELMFIRE is run in NC mode.

In this paper, we present advances in the study of sheared $E \times B$ flow simulation results carried out for the geometry corresponding to the FT-2 tokamak conducted[1] by means of the Monte Carlo code ASCOT. The paper is structured as follows: in Section 2, the ELMFIRE code is described and a brief review of the importance of high sheared $E \times B$ flow for plasma confinement by suppressing the growth of instabilities. In Section 3 the newly implemented experimental settings of the code to allow for simulations are presented. The section also include the ELMFIRE simulations results corresponding to different radial profiles at time instants for different quantities as well as time behaviour for ad hoc radius values on the FT-2 tokamak. The final part covers the concluding remarks on this work.

2 | THE GYROKINETIC CODE ELMFIRE

ELMFIRE is a full-f gyrokinetic particle-in-cell (PIC) code that simulates both neoclassical and turbulent physics. Based on Sosenko's theory of quasi-particles,[9] the polarization drift is included in the particle drift orbit. The code includes ions gyrokinetically, while electrons are followed according to drift-kinetic equations of motion allowing for both ITG and TEM turbulence. Self-consistent electrostatic turbulence is solved via an explicit–implicit hybrid solver for the full distribution function. The model works in a flux-driven manner in the presence of prescribed particle, energy sinks and sources. Collisions are evaluated using a binary collision model, which enables the inclusion of neoclassical effects. The advantage that follow from using a full f code in neoclassical physics is such that given a sufficient number of simulation particles, the coupled turbulent and neoclassical transport phenomena are investigated by means of gyroaveraging procedures.

The simulation grid spans the whole plasma volume from the magnetic axis to the material wall, with the option of including the scrape-off layer. The static magnetic equilibrium with co-centric circular flux-surfaces is used according to a user-defined current profile. Further numerical details can be found in recent papers,[10,11] while a revised set of equations of motion for the new version of the code can be found.[12]

The first transport barrier simulations reported[8] were done with the early ELMFIRE code version.[13] After that, several upgrades have been done. The version extending from magnetic axis to scrape-off-layer was first reported[10] and it was successfully upgraded to include logical boundary condition[14] as shown.[2] At the gyrokinetic ordering, the logical boundary conditions allow to consider the plasma sheath infinitely small and at equilibrium at all times by assuming that the typical scales of the plasma sheath are small and fast compared with the scales of interest.

Early ASCOT simulations[5] recovered the Hazeltine–Hinton analytical expressions[3] of the neoclassical radial electric field. In these simulations, electrons were fixed background and E_r was solved from 1D polarization equation for ions. The present ELMFIRE simulations include electrons and the effect of binary collisions, which replicate the $E \times B$ shear disappearing in off-axis case when neoclassical mode, but in turbulent cases strong local shear appears. Particular interest is devoted to understanding whether a high or low sheared $E \times B$ flow appears in the simulations, both in neoclassical runs as well as in runs that include both turbulence effects and neoclassical physics. When $E \times B$ rotation with sufficiently strong shear manifests, it has been shown both experimentally and theoretically, see[1] for additional references, that the turbulent structures created by the correlation of small localized turbulence eddies are destroyed, restoring the transport to neoclassical level. Of particular interest is the analysis that correlates the growth rate of these turbulent structures with the $E \times B$ shearing, as higher shearing yields a better confinement and reduces the probability of uprising instabilities.

The initialization of the electrons temperature and their density profiles follow the same reasoning presented.[10] The average noise level in density fluctuations is approximately 1.1% based by Kiviniemi and Sauerwein[15] for $\Delta r = r\Delta\theta = \rho_i$ over the whole volume in this case. Noise is higher closer to the edge, where density is lower, as the number of particles per cell depends on density when using equal weights for all simulation particles. In addition to noise, the initial fluctuations include any poloidal variations arising from the initialization, which do not disappear with increased particle number. The code relies on a purely electrostatic theory with a non-time varying background magnetic field. It operates on a non-equidistant grid, depending on the Larmor radius of the particles, which means also that number of grid points in poloidal direction increases in radius.

The peculiarity of FT-2 tokamak is its low current, which increases the orbit width and seems to point out that previous works[1,16] fall under the edge pedestal physics rather than internal transport barriers. The orbit width parameter ρ_p appears to be of the order of the minor radius, see Figure 1a, but relatively large when compared with gradient scale

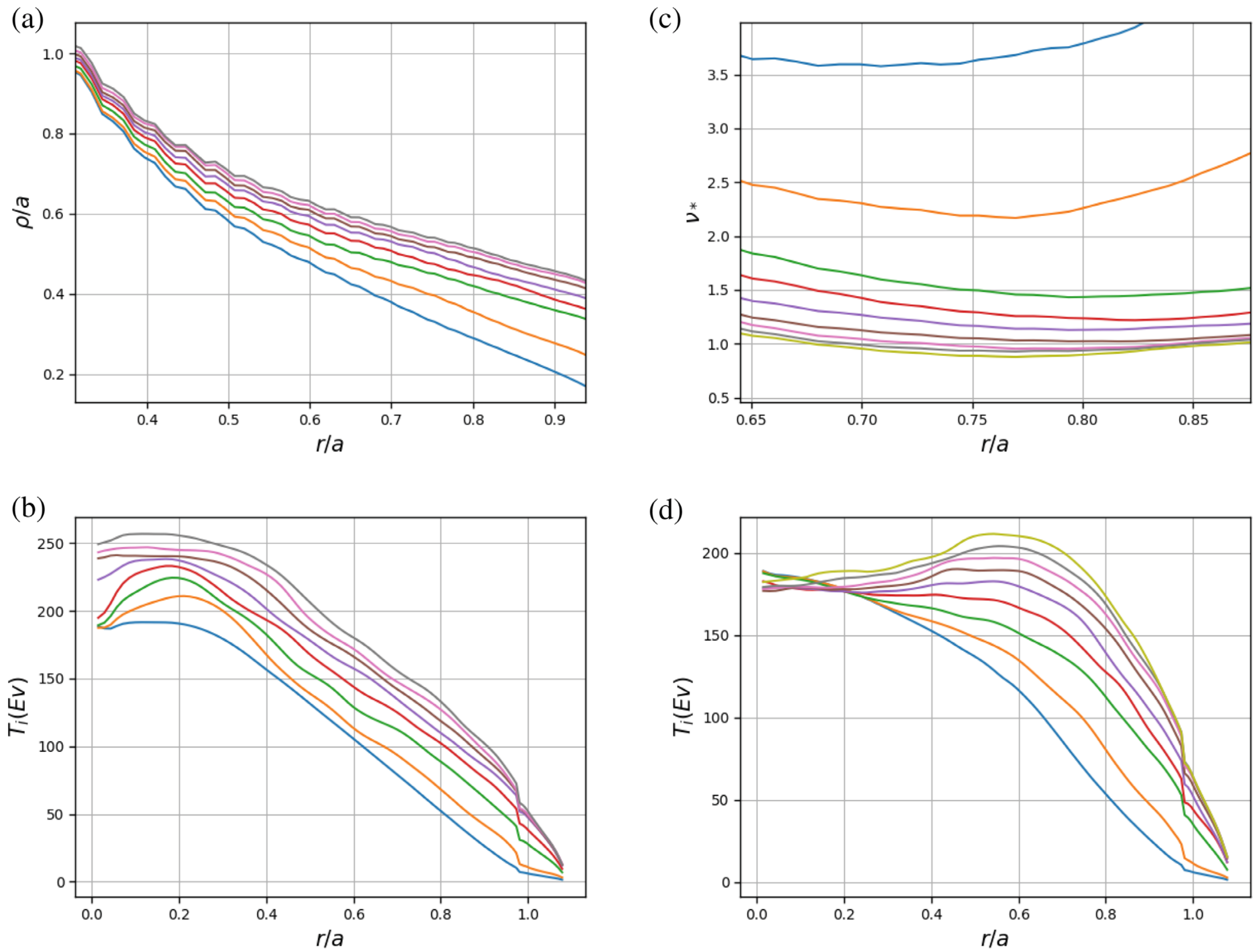

FIGURE 1 Radial profiles of the ion poloidal larmour radius, collisionality and temperature. Different lines colours correspond to different time instants. In particular the blue line corresponds to the first time instant while the gold colour to the last. (a) Poloidal ion larmour radius off-axis. (b) Ion temperature on-axis. (c) Ion collisionality off-axis. (d) Ion temperature off-axis

lengths L, making the analytic neoclassical theory invalid as ordering parameter ρ_p/L is not anymore small. Also, especially the banana orbits for energetic deuterium ions undergo different collisionality regimes ν_* Figure 1c. From a physical standpoint, the magnitude of such parameter relates the transport of particles to the rate of collisions. Specifically, when $\nu_* \ll 1$ one speaks of banana-plateau regime while when $\nu_* \gg 1$ we reach the Pfirsch–Schlüter regime. The banana-plateau regime is further subdivided into two regimes, the plateau regime $\epsilon^{3/2} \ll \nu_* \ll 1$ and the banana regime $\nu_* \ll \epsilon^{3/2}$, where $\epsilon = r/R$ is the large aspect ratio. The boundary case where $\nu_* = 1$ corresponds to the limit of the banana-plateau regime and is characterized by a low collisions rate between particles, which allow most circulating particle orbits to be completed while the trapped orbits are destroyed. These conclusions are valid only for trapped deuterium ions, which make up for only a third of the total number of ions present in the device. For passing ions the effect is much more modest. Due to their drift losses, in FT-2 tokamaks at lower plasma current $I_{pl} = 22$kA significant E_{rad} is formed.[1,16]

3 | EXPERIMENTAL SETTING AND SIMULATION RESULTS

In the following simulation results, we simulate the plasma of FT-2 tokamak (Ioffe Institute, Saint-Petersburg, Russian Federation).[17] The simulations use the same plasma initial profiles and parameters from an experimental LH-heated case.[1] except for main ion deuterium is assumed.[8] Here, $a = 0.08$ m, $R = 0.553$ m, $B_t = 2.2$ T, $U_{\text{loop}} = 0.5$ V, and $I = 22$ kA, where a is the plasma minor radius, R the major radius, B_t the toroidal magnetic field, U_{loop} is the loop voltage,

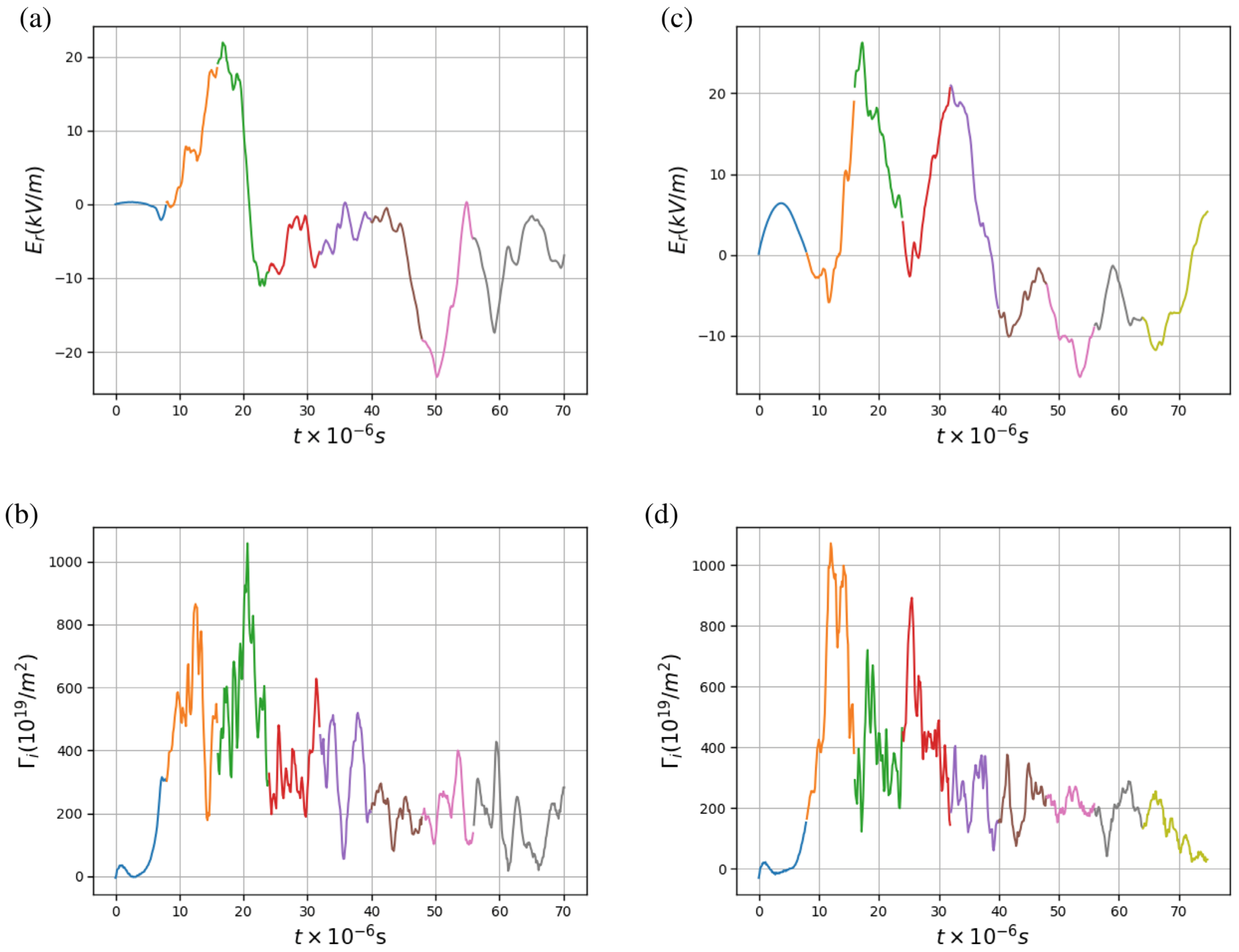

FIGURE 2 Time profiles of the electric and ion particle flux at a radius value of $r/a = 0.55$. (a) Electric field on-axis. (b) Ion particle flux on-axis. (c) Electric field off-axis. (d) Ion particle flux off-axis

and I the plasma current. The density of the plasma pulses in the area of interest, $n_e = (3\text{–}4) \times 10^{19}\ \mathrm{m}^{-3}$, is sufficiently high to disable any LH current drive. The plasma lies in the plateau collisionality regime according to the initial profiles. The normalized collisionality is calculated as $\nu_{*i} = \nu_{ii} Rq/(\nu_T \epsilon^{3/2})$. Here, $\nu_T = (2\ T/m)^{1/2}$ is the thermal velocity, with mass m, $\epsilon = r_{ce}/R$ is the inverse aspect ratio with minor radius r_{ce}, $q = \epsilon B_t/B_p$ is the safety factor with the poloidal magnetic field component B_p, and ν_{ii} is the ion–ion collision frequency. A total of 544 million electrons (1040 per cell on average) and 504 million ions (963 per cell) and 6 million impurities (12 per cell) are followed in a grid with $N_r \approx 107 \times N_{\theta,\max} = 700 \times N_\phi = 8$ (radial × poloidal × toroidal) points, totalling to 599,200 grid points. Grid cell size is matched to the ion Larmor radius in radial and poloidal directions, so the radial grid cell width and number of grid points in poloidal direction $N_\theta(r)$ vary as a function of radius.

The LH heating operators are assumed to have the same Gaussian intensity profiles and power,[1] which is centred either at $r_{ce} = 5$ cm (off-axis) or $r_{ce} = 0$ cm (on-axis). The ELMFIRE simulations are such that while electrons are kinetic, they are not heated directly with LH-operator but Coulomb collisions take place between electrons and the heated ions.

Figure 1b,d shows the radial temperature profiles for different time instants for off-axis and on-axis heating. The comparison between the two plots makes apparent the presence of a steep maximum around $r/a = 0.6$ when off-axis, which is generated due to the position of heating. In Figure 2, the time profiles of ion particle flux and electric field for a specific radial value are shown. In ELMFIRE simulations, the transport quantities typically oscillate in the frequency of electric field, the GAM frequency, as shown by the plots of the ion particle flux. The time-behaviour of radial profiles of the electric field, in Figure 3a,b, shows a formation of high sheared E_r in time around the value $r/a = 0.55$, which may explain the drop of particle flux in Figure 2b,d. Similar results were found in early ELMFIRE simulations showing

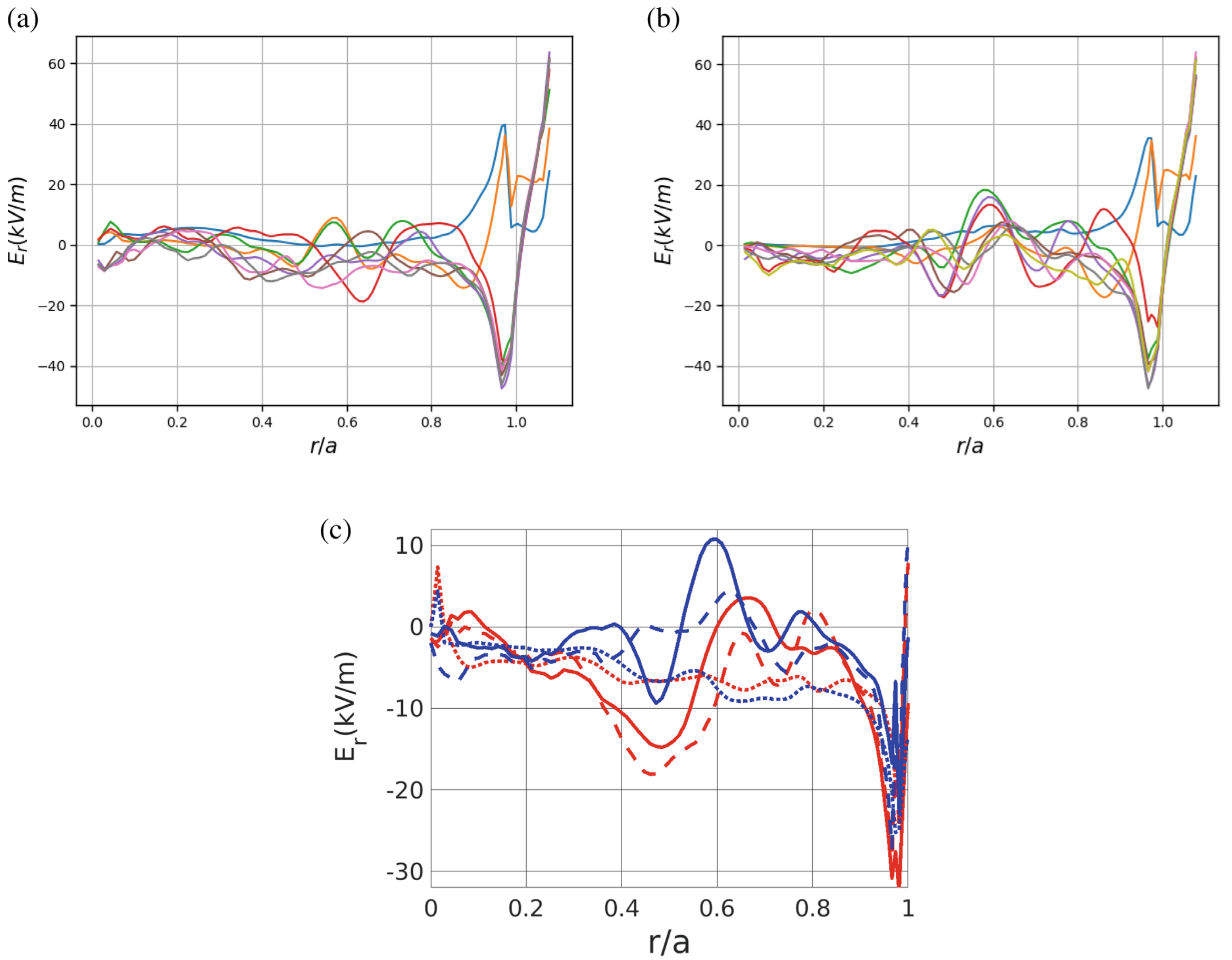

FIGURE 3 The plots (a) and (b) depict the time-behaviour of radial profiles of the electric field simulated by ELMFIRE, while plot (c) shows time-average of these same fields (solid line), time-average of NC field simulated by ELMFIRE (dashed line) and Hinton–Hazeltine field for the simulated profiles (dotted line). The blue and red colours indicate off-axis and on-axis simulations, respectively. (a) Radial Electric field on-axis. (b) Radial Electric field off-axis. (c) Turbulents versus neoclassical mode

high $E \times B$ shearing rate and subsequent drop of turbulent transport in LH-heated plasma, which was then interpreted to be an internal transport barrier.[8] Similar high shearing rate was also observed in neoclassical simulations[1] where the improved core confinement was thought to be caused by wide orbits going from collisionless to collisional regimes but not returning back due to collisional effects. ELMFIRE can be run also in neoclassical mode by combining toroidal averaging with coarse resolution in the poloidal direction, which prohibits turbulence to grow. In Figure 3c, we compare time-averaged radial electric field of ELMFIRE simulations run both enabling and prohibiting ('neoclassical run') turbulence growth and, also, the analytic neoclassical field.[3] A very high sheared $E \times B$ flow is formed in on-axis case in the neoclassical mode being strong enough to prevent the growth of instabilities and their correlation. Wide orbit effects and ion orbit losses may contribute to this phenomenon. At the same time, however, we see that even in the turbulent mode a strong high shearing flow is present. This shows that the results[1] are reproduced by ELMFIRE while also showing a strong shear even in the turbulent case. In the off-axis case, the shearing of E_r in neoclassical case is more modest but turbulence case shows strong local variation of E_r profile.

4 CONCLUSION

We reported the computational upgrades of the full-f gyrokinetic code ELMFIRE to reproduce and extend the previous investigations carried out by the ASCOT code. The study of the cases where LH-heating is on-axis or off-axis done with turbulence was repeated in neoclassical mode. Neoclassical simulations show a similar high $E \times B$ shearing while replicating the correct behaviours for the main quantities of interest. The orbits of trapped ions were shown to undergo different collisionality regimes and posses widths large compared with the gradient scale lengths suggesting similarities to pedestal physics. The previous works include simulation of both hydrogen and deuterium plasmas, so further work should repeat the present simulations for hydrogen plasmas to quantify the effect of isotope on conclusions.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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