ELMFIRE gyrokinetic study of turbulence and equilibrium asymmetries at the FT-2 tokamak edge

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The study of the plasma edge is of great importance to sustain controlled magnetic fusion. The plasma boundary is both one of the main constraints on plasma scenarios, as well as the setting for rich physics combining plasma turbulence and self-organisation, magnetohydrodynamics, atomic physics and plasma-surface interaction [1–5].

We approach the modelisation of the plasma boundary from first-principles using the gyrokinetic (GK) turbulence code *ELMFIRE*, in conjugation with experimental studies on the circular-section, limiter tokamak FT-2.
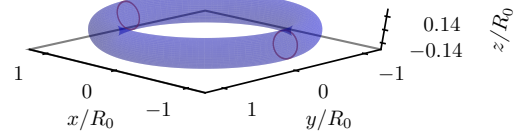

Figure 1: *Toroidal configuration for simulations of FT-2. The blue torus materialises the outer wall. The red circles are the poloidal limiter diaphragms (punctual in the toroidal direction, in simulations).*

We perform simulations with a fixed analytical magnetic background with circular concentric flux surfaces: $B = \frac{B_0}{1+\varepsilon\cos\vartheta}\left(\hat{e}_\varphi + \frac{\varepsilon}{q}\hat{e}_\vartheta\right)$, where $\varepsilon = r/R_0$ is the inverse aspect ratio, and q the safety factor.

ELMFIRE uses the particle-in-cell (PIC) method to simulate turbulence in a plasma of GK ions (including impurities) and drift-kinetic (DK) electrons with high $E \times B$ flows [6–10]. The non-linear polarisation of ions is included by accounting for shifts in the Lagrangian trajectories with an analytical form for the ion polarisation drift. The equations of motion—for (R,U) the gyrocenter position parallel velocity—and quasineutrality equation read:

$$\dot{R} = \frac{B^*U + E^* \times \hat{b}}{B^*_\parallel}, \quad \dot{U} = \frac{e_s}{m_s}\frac{B^* \cdot E^*}{B^*_\parallel} \tag{1}$$

$$\varepsilon_0 \nabla \cdot E(r,t) = \sum_s e_s \int F_s \left\langle \delta\left(r - x^{(1)}\right)\right\rangle d^3R\,dU\,dJ \tag{2}$$

with:

$$E^* = \left\langle E\left(x^{(1)}\right)\right\rangle - \frac{J}{2\pi m_s}\nabla B - \frac{m_s}{e_s}\frac{d}{dt}\left[\frac{\left\langle E\left(x^{(1)}\right)\right\rangle \times \hat{b}}{B}\right]$$

$$B^* = B + \frac{m_s}{e_s}\nabla\times\left[U\hat{b} + \frac{\left\langle E\left(x^{(1)}\right)\right\rangle \times \hat{b}}{B}\right]$$

In the above expression, $B^*_{\parallel} = B^* \cdot \hat{b}$, and $B = B\hat{b}$, J is the adiabatic invariant.
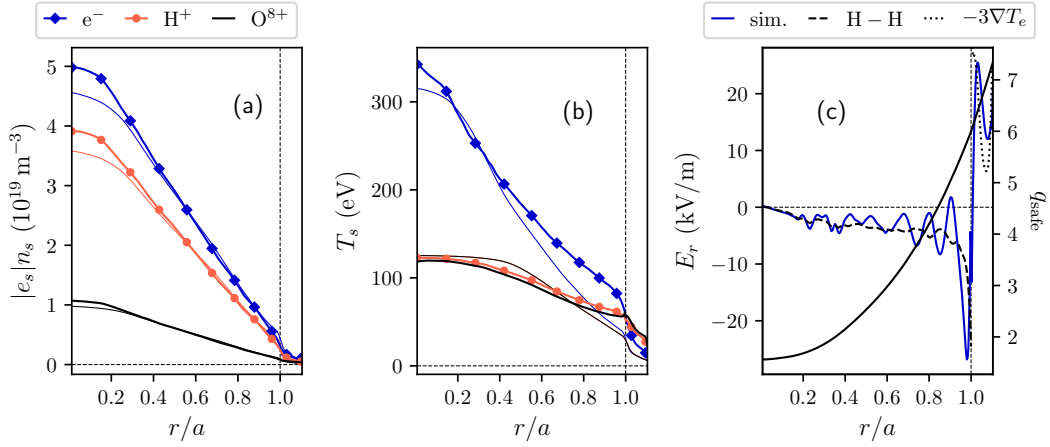

Figure 2: *a) and b) respectively show radial profiles of the charge densities and temperatures (thin: initial, bold/symbols: simulation result). c) shows the radial profiles of the radial electric field (left axis, blue: simulation result, dashed and dotted lines: analytical estimates) and safety factor profile (right axis, fixed during the simulation). All simulation results are averaged between* $100\,\mu s$ *and* $140\,\mu s$. *The last closed flux-surface (LCFS) is shown as a vertical dashed line.*

The simulation domain spans the entire plasma from the magnetic axis to the outer wall at $r = a_w$. It includes two poloidal limiter diaphragms at opposite toroidal positions, extending radially to the plasma radius $r = a$ (see Fig.1) [10, 11]. This is different from the actual configuration of FT-2, where the two main poloidal limiters are separated by $90°$ in the toroidal direction. The logical boundary condition is used at the limiters and wall [11–13].

We recall the FT-2 discharge of interest here [13], with the following parameters: $R_0 = 0.55\,$m, $a = 7.8\,$cm, $a_w = 8.7\,$cm, are the major radius, plasma radius and minor radius at the wall, respectively. The magnetic field on axis, plasma current, and loop voltage are: $B_t = 2.3\,$T, $I_p = 22.4\,$kA, $U_{\text{loop}} = 3.865\,$V. The main impurity is identified as O^{8+}, with $Z_{\text{eff}} = 2.5$. Fig.2 shows the profiles used for initialisation of ELMFIRE, and their time average over the last $40\,\mu s$ of the $140\,\mu s$ simulation (in the nonlinear regime). We compare the simulation to measurements of n_e, T_e and E_r carried out in the SOL with reciprocating Langmuir probes. The probes used

here access the plasma from the top and bottom of the machine, and perform measurements at a given poloidal angle θ and several minor radius positions, which is illustrated on Fig.3. The measurements are reproduced over several identical discharges.
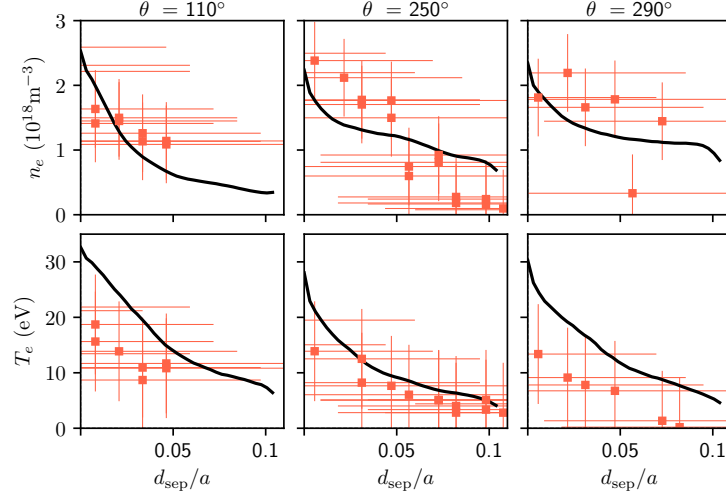

Figure 4: *Comparison of n_e and T_e at different poloidal angles θ between* ELMFIRE *(black line) and FT-2 reciprocating probe measurements (orange squares).*

We find a good agreement between measurements of density and temperature and the *ELMFIRE* simulation. The comparison is shown in Fig.4. There, we can see that the density in simulations (black line) agrees within error-bars with the probe measurements. We notice, in particular at $\theta = 250°$ that the limited radial extent of the simulation domain causes a raising of the density profile close to the wall boundary, resulting in a density gradient shallower than measured by the probes. The electron temperature in the simulation is consistently above the expectancy of the measurements, which is consistent with the relaxation of the temperature profile away from the initial value, as can be seen in Fig.2. Nonetheless the simulated values are mostly within error-bars of the measurements, and the gradients are comparable.
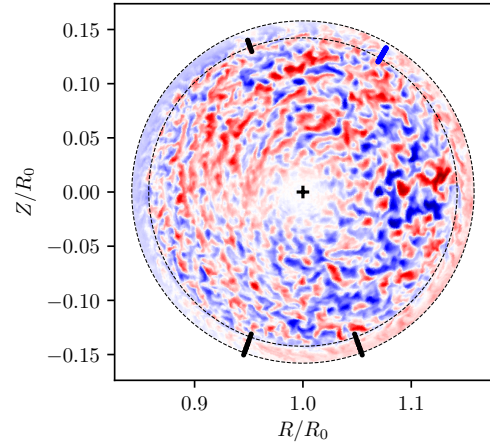

Figure 3: *Positions of the probe measurements in the poloidal plane. Black dots are (n_e, T_e) measurements, blue dots are E_r measurements. The dashed circles show the plasma radius a and wall radius a_w.*

Considering the radial electric field, we find the simulations show a strong in-out asymmetry in the SOL and edge, as illustrated in Fig.5a–b. In particular the maximum of E_r in the SOL at the high-field side (HFS) is much narrower and about twice the magnitude compared to the low-field side (LFS). A profile of E_r is measured with the reciprocating probe at $\theta = 60°$, shown in Fig.5c. Comparison with the *ELMFIRE* result shows that the magnitude of the E_r extrema astride the LCFS is well reproduced, but the simulation produces a sharper shear layer. We also notice that E_r at the LCFS is consistently strongly negative in the simulation, contrary to the experiment where the point of vanishing E_r is usually considered a reliable indicator of the LCFS position.
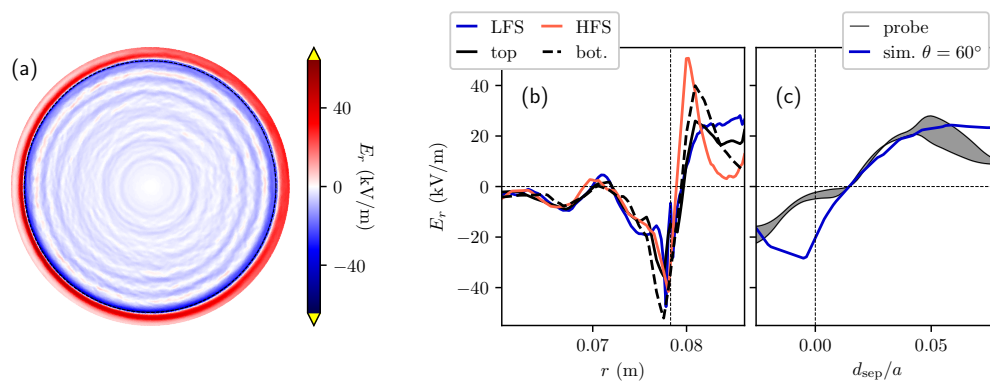

Figure 5: *a) Poloidal cut of E_r in* ELMFIRE *simulation. The dashed circle shows the LCFS. b) Radial profiles of E_r at the edge of the simulation for various poloidal positions. c) Comparison between E_r simulated by* ELMFIRE *(blue line) and FT-2 reciprocating probe measurements (black lines/grey range).*

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