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ORIGINAL ARTICLE

Contributions to Plasma Physics

Effect of toroidal particle sources on SOL physics in the FT-2 tokamak

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Abstract

Two gas-puffs are used near limiters in the FT-2 tokamak for the purpose of hydrogen refuelling during plasma discharges. This creates toroidal and poloidal asymmetry in particle sources near limiters which has to be considered in modelling. Here, the effect of toroidal asymmetry is simulated using the gyrokinetic code ELMFIRE. Two slightly different toroidal particle sources are used in simulations, and their results are compared with each other, and with experimental measurements to understand the impact of toroidal particle sources on Scrape-off Layer (SOL) physics.

KEYWORDS

gyrokinetic simulation, particle sources, PIC, scrape-off layer, tokamak plasma edge, turbulence

1 | INTRODUCTION

The quantitative description of Scrape-off Layer (SOL) physics is difficult to be described by using analytical models. Thus, it is of vital importance to rely on numerical modelling to further the understanding of SOL physics. Full-f gyrokinetic codes are appropriate for studying SOL physics as they evolve the full distribution function and include kinetic effects. Many of these like Gkeyll,[1] GENE-X[2] use the continuum method (Eulerian approach) and solve for the gyrokinetic Vlasov equation directly. However, XGC,[3] PICLS[4] and the present tool, *ELMFIRE*,[5–7] use the so-called particle-in-cell (PIC) method where marker particles are integrated along characteristics of the gyrokinetic Vlasov equation. Flux-driven codes need to have proper heat and particles source and sink mechanisms for realistic modelling. Correct profile for particle sources can be difficult to implement for plasma discharges where the presence of gas-puffing near limiters can cause toroidal asymmetry in the particle source profile. This is evident from the fact that previous *ELMFIRE* simulations,[8,9] do not agree very well with experimental measurements. In this work, two toroidal particle

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source profiles are used to model the FT-2 tokamak limiter plasmas. These particle sources consider the fact that more particles will be born near limiters due to gas-puffing when compared to other toroidal sections. Simulations results are then checked for a better agreement with Langmuir probe measurements,[10] if profiles maintain their initial shapes at the end of the simulation, and to study the effect of two toroidal particle source profiles on SOL physics.

2 | *ELMFIRE* CODE

ELMFIRE is an electrostatic gyrokinetic code capable of studying micro, meso, and macro scale transport processes. Gyrokinetic equations are evolved in time in a 3D-grid by using the particle in cell (PIC) method. *ELMFIRE* uses constant magnetic field with circular concentric nested surfaces. The straight field line coordinate system is used to include the SOL region obtained by using limiters. The latest version of *ELMFIRE* uses logical boundary condition (BC)[5] for mimicking sheath physics. This enables one to incorporate sheath physics in gyrokinetic simulations without resolving the sheath region.

In *ELMFIRE*, particles gain energy via ohmic heating. The ohmic heating is done by driving a homogeneous plasma current through the magnetic axis. The Bremsstrahlung radiation loss of electrons is included by using the experimentally measured radiation profile. Particles are lost once they touch walls and limiters. Thus, walls and limiters are the only particle sinks in simulations. These lost particles are recycled back as ion and electrons pair in simulations by using particle source profiles based on experimental measurements. Particle source profiles can have radial and toroidal dependencies depending on the simulated plasma discharge. Ionization loss of electrons are not considered in simulations. More details of the code can be found in References [5–7].

3 | SIMULATION PARAMETERS

3.1 | The experimental setup

The experimental setup used for simulations is the FT-2 tokamak plasma discharge.[10] Experimental data for input profiles are calculated with the ASTRA code. The radial particle source and the radiation profile are calculated from the ASTRA code. The geometric parameters are as follows: $R_0 = 0.55$ m, $a = 7.8$ cm, $a_w = 8.7$ cm, are the major radius, plasma radius, and the minor radius at the wall. The magnetic field on axis, plasma current, and loop voltage are: $B_t = 2.3$ T, $I_p = 22$ kA, $V_{\text{loop}} = 3.865$ V.

3.2 | Simulation setups

Two simulations with different toroidal particle sources were run with all other parameters considered equal. The main ion species is H^+ and the main impurity species is O^{8+}, and both are treated gyrokinetically while electrons are treated as drift-kinetic species. Two limiters are used in simulations, and are 180 degrees apart in the toroidal direction. However, two limiters of FT-2 tokamak are located not 180 degrees apart, but 90 and 270 degrees. In one simulation, particles are recycled back into the simulation on only one side of the limiters and will be called as case 1. In the case 2, particles are recycled on both sides of the limiters. In both simulations, particle recycling in the toroidal direction is done only near the limiters. The case 1 lasted for 87 μs and the case 2 lasted for 82 μs, and in both cases, simulation results are averaged over the last 30 μs in the non-linear phase. The toroidal particle source used in two cases are shown in the Figure 1. The Figure 2 shows the radial distribution of particle source used in two cases. It can be seen that the particle source peaks well before the last closed flux surface (LCFS) region and drops towards the limiters. The experimental radial distribution of particle source is obtained from the ASTRA code.

4 | RESULTS

4.1 | Experimental comparisons

In this section, simulation results are compared with experimental measurements for checking if source and sink mechanisms are well balanced in simulations, and if there is a good agreement with Langmuir probe measurements. The Figure 3

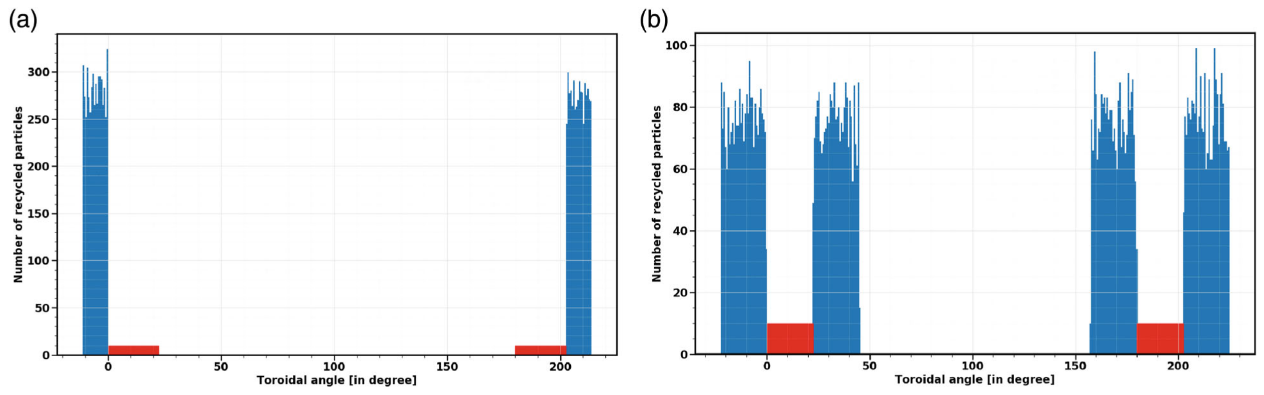

FIGURE 1 Schematic representation of the toroidal particle source: Plot (a) for the Case 1 and plot (b) for the Case 2. Yellow and red shaded regions indicate limiters while the width of blue stripes gives the angular extent of particle sources in the toroidal direction

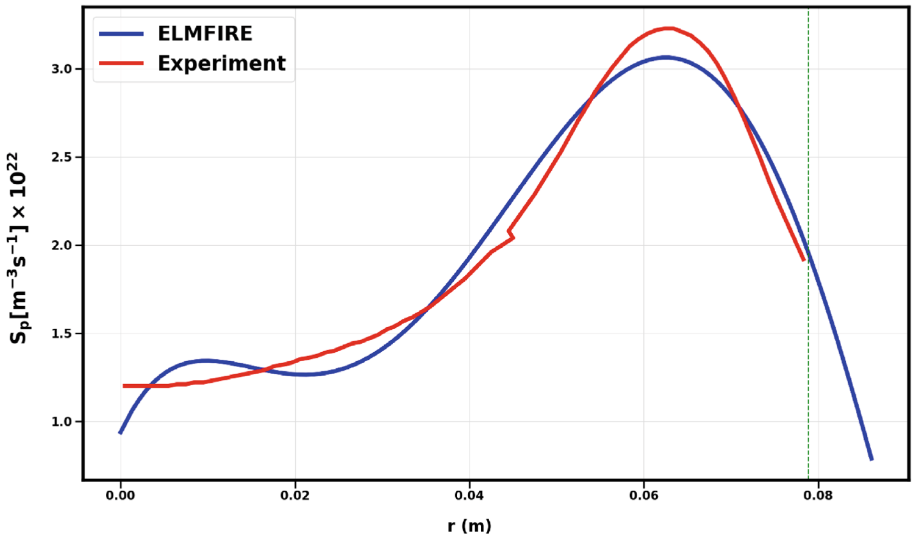

FIGURE 2 Radial distribution of particle source used in two cases. The vertical dashed line indicates the last closed flux surface

shows a good agreement between density profiles of all species, and input density profiles for both cases at all radial locations except near the core region, where density rises for all species. This rise in density indicates that there are more particles recycled back near the core region in simulations when compared to recycling of particles near the core region in the experiment. The electron temperature shows a relaxation near the core region but rises near the last closed flux surface (LCFS). While, Hydrogen temperature profile has a good agreement with the input profile. The rise of electron temperature near the LCFS can be attributed to the fact that ionization loss of electrons is not considered in simulations. In the rest of the paper, results are shown only for the case 1 unless there is a considerable difference between two cases. Density and temperature values from simulations at certain poloidal angles are compared to Langmuir probe measurements in the Figure 4. Both temperature and density measurement matches well with simulation results at all poloidal angles.

4.2 | Radial electric field

The radial electric field in the simulation crosses the LCFS region at the zero point and grows towards a positive value while approaching the sheath region. The value of the electric field inside the LCFS region is almost zero except near the LCFS where there is a high shear of the electric field needed for turbulence suppression. This is in agreement with the Hinton-Hazeltine analytical estimate[11] for neoclassical physics. Similarly, in the SOL, there is a good agreement with the - $3\nabla T_e$ value as predicted by the sheath physics.[12] These comparisons are shown in the Figure 5.

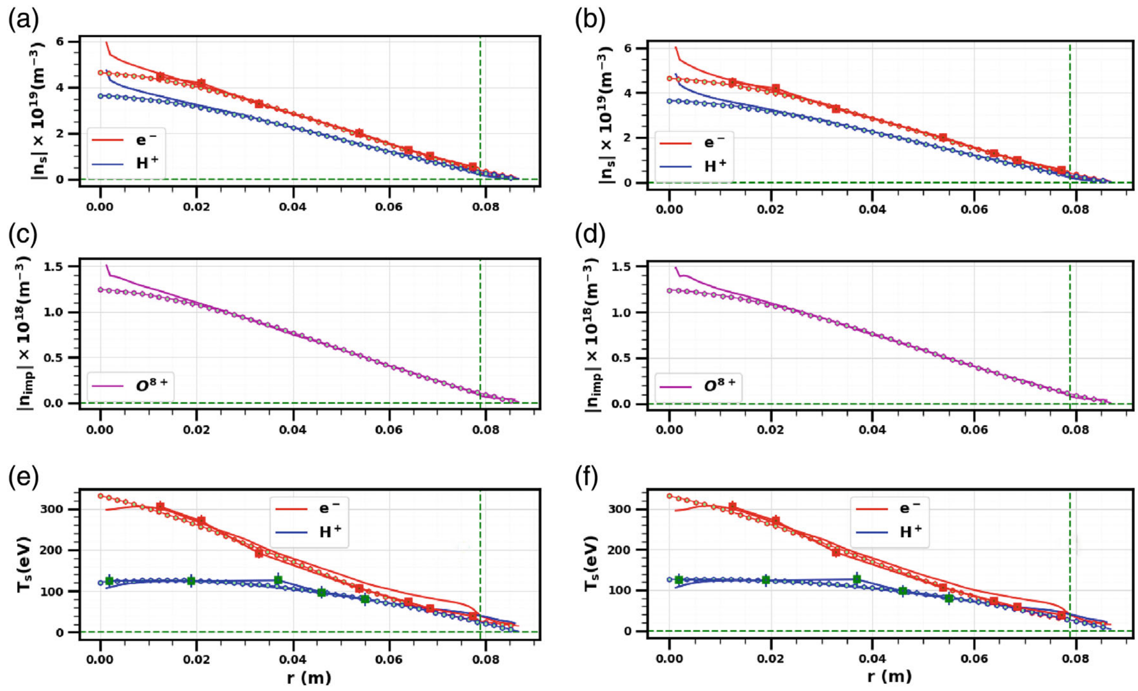

FIGURE 3 Radial profiles (flux surface averaged) of densities, and temperatures averaged over the last 30 μs in the saturated phase. Plots (a, c and e) are for the case 1 and plots (b, d, f) are for the Case 2. Lines with hexagons are input experimental profiles obtained from the ASTRA code and lines with squares are experimental measurements. The vertical dashed line on all plots indicate the last closed flux surface

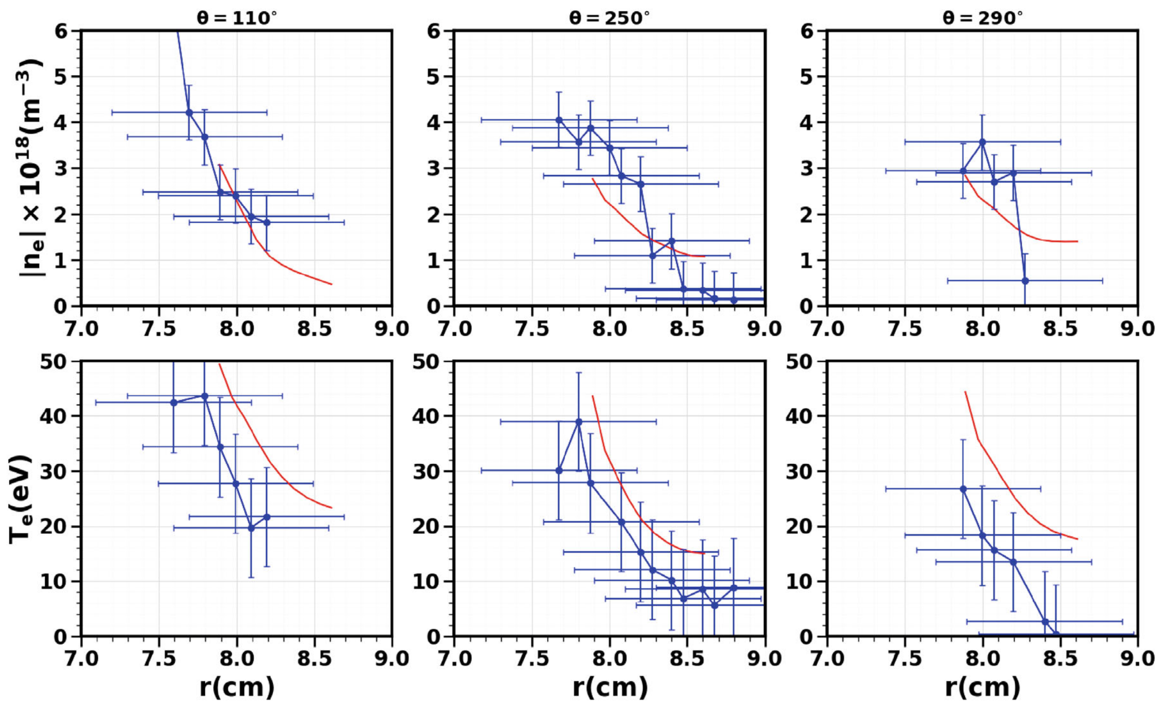

FIGURE 4 Density and temperature comparisons between ELMFIRE results and Langmuir probe measurements for the Case 1

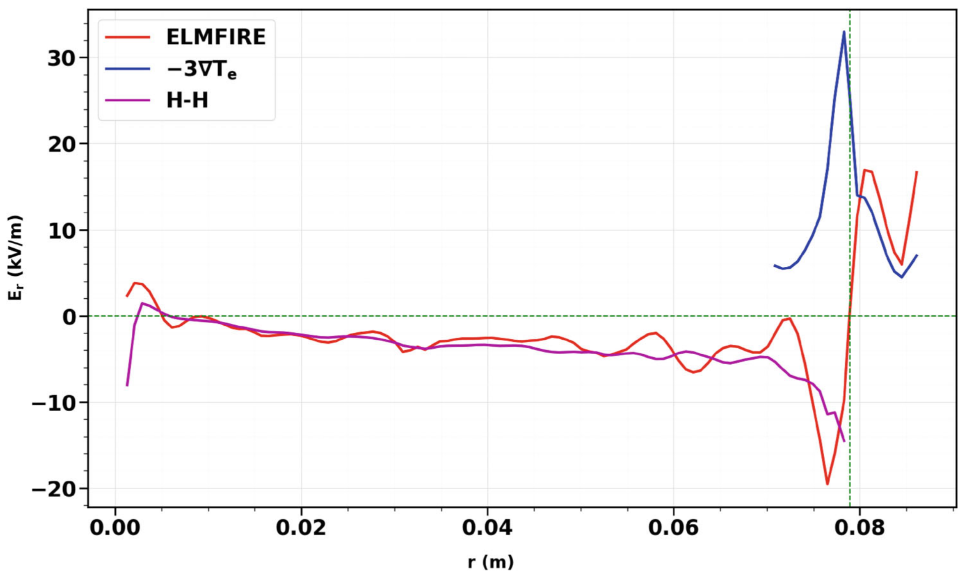

FIGURE 5 Radial profiles of electric field for the Case 1. The vertical dashed line indicates the last closed flux surface

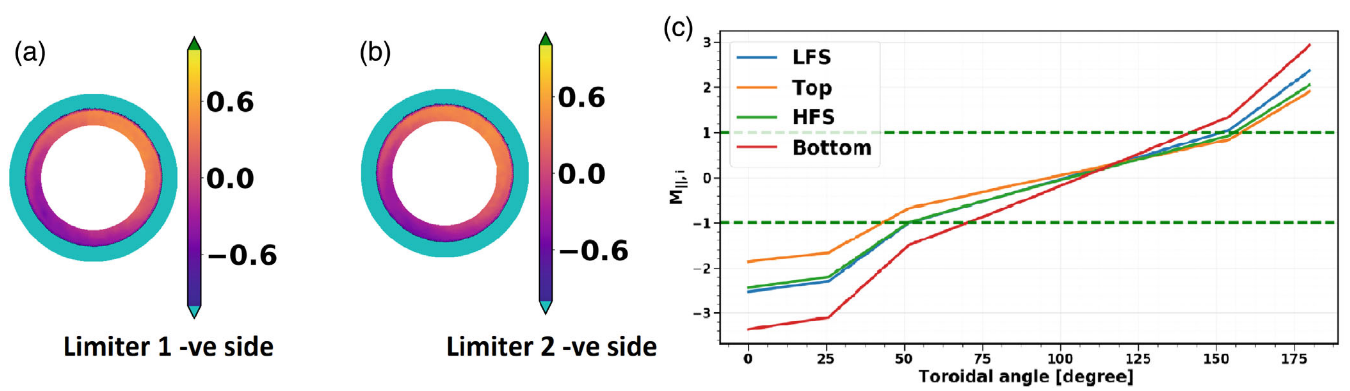

FIGURE 6 Plots (a) and (b) are poloidal sections of M||,i at one side of the limiters. The plot (c) shows profiles of the parallel ion Mach number in the SOL in the toroidal direction, averaged over four different poloidal positions: Top, Bottom, HFS, and LFS. Dashed lines shows the value of $M_{\|,i} = \pm 1$

4.3 | Mach number

The presence of sheath at limiters accelerates particles along field lines in the SOL region. As a result, the velocity of ions reaches a value greater than the ion sound speed c_s, where c_s^2 is $\frac{T_e}{n_e}\left(\frac{n_H}{m_H} + \frac{n_O Z^2}{m_O}\right)$. Thus, a term called ion mach number $M_{\|,i}$ can be defined as v_i/c_s, where v_i is the ion velocity, and the value of $M_{\|,i}$ should cross one as particles approaches limiters, indicating a transition to supersonic flows.[13] In Figure 6a,b, ion mach number crosses the value of 1 all over the poloidal cross section of limiters, and thus there is a global transition to supersonic flow. The Figure 6c, show the transition to supersonic flows near limiter plates at the negative side of the limiter 1 and the positive side of the limiter 2.

4.4 | Toroidal variation of profiles

The Figure 7 shows that there is a drop in the electron density and temperature near limiters when compared to other toroidal sections. This decrease in density could be due to the reason that there are less particles getting recycled near the limiters than getting lost at the limiters. While, the decrease in temperature can be due to the fact that particles are

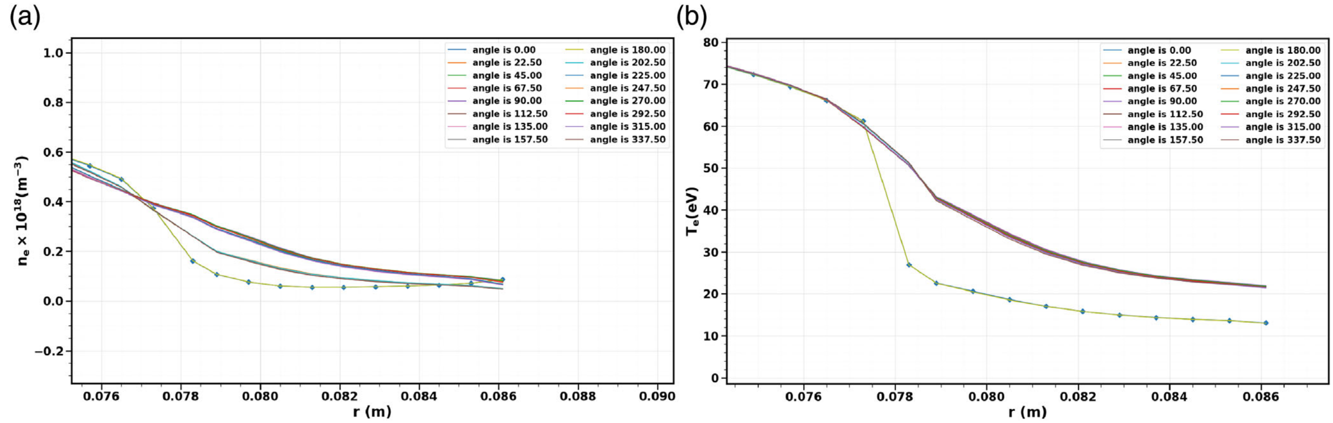

FIGURE 7 Plots (a) and (b) are radial profiles of electron density and temperature across different toroidal sections for the Case 1. The line with blue diamonds indicates the toroidal section corresponding to 0 degree

recycled with a cold temperature (5 eV). There is no drop in density at toroidal sections corresponding to angles 22.50 and 202.5 degrees, which corresponds to other sides of the limiters.

5 | CONCLUSION

Using experimental radial particle source profile, and recycling particles near limiters in the toroidal direction, gives a better agreement with Langmuir probe measurements, and profiles in simulations are close to initial values in most of radial locations when compared to the previous study,[9] where the particles were recycled uniformly between the region 2 cm from the wall in the radial direction and on one side of poloidal limiters in the toroidal direction. However, density was observed to increase near the core region. Similarly, electron temperature increases near the LCFS region and drop near the core region, which can be due to the fact that ionization loss of electrons are not considered in simulations. The radial electric field is well-behaved inside and outside the LCFS, and transition to supersonic flows is observed all over poloidal cross sections of limiters. Both electron density and temperature profiles decreases at only one side of the limiters due to more particles getting lost than getting recycled near the limiters and the particle balance near the limiter is mostly determined by how transport processes at LCFS bring new particles to the SOL.

In future works, ionization loss of electrons needs to be considered for limiting the temperature rise near the LCFS region. Particles need to be recycled disproportionately between two limiters as in experiments where only one of the gas-puffs near the limiters is the main particle source. Recycling side of particles on either side of the limiters needs to be identified by developing a synthetic diagnostic, and based on that particles needs to be recycled on that side of the limiters accordingly. Spectral analysis of turbulent flow in the SOL could be done and compared with Langmuir probe measurements. Propagation of blobs from LCFS to SOL region could be studied along with their dynamics and compared with experiments.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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