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Gyrokinetic particle simulation of neoclassical transport in the pedestal/scrape-off region of a tokamak plasma

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Abstract. A gyrokinetic neoclassical solution for a diverted tokamak edge plasma has been obtained for the first time using the massively parallel Jaguar XT3 computer at Oak Ridge National Laboratory. The solutions show similar characteristics to the experimental observations: electric potential is positive in the scrape-off layer and negative in the H-mode layer, and the parallel rotation is positive in the scrape-off layer and at the inside boundary of the H-mode layer. However, the solution also makes a new physical discovery that there is a strong ExB convective flow in the scrape-off plasma. A general introduction to the edge simulation problem is also presented.

1. Introduction

A tokamak fusion reactor concept is based upon a toroidal plasma confinement provided by external coil arrays and an internal electrical current in the plasma. If the hot plasma, which has a density and temperature in excess of 1×10^{20} m^{-3} and 10 keV, respectively, is allowed to touch the material wall in an uncontrolled way, it can sputter the wall material into the plasma to degrade/extinguish the fusion burn and to shorten the wall lifetime to an unacceptable level. In order to control the problem, all the modern tokamaks, including the planned ITER (International Thermonuclear Experimental Reactor),

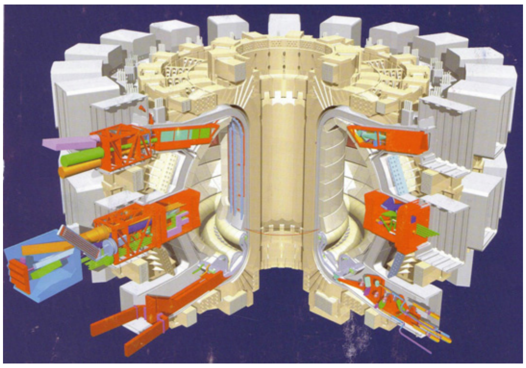

Fig.1a. Schematic picture of ITER tokamak, showing the toroidal main chamber, material wall, and the small divertor chamber at the bottom of the main chamber

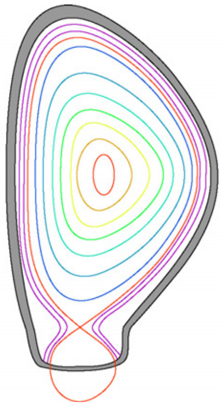

Fig. 1b. Cartoon Picture of diverted magnetic field

have been designed to divert the escaping edge plasma to a specific location called ‘divertor chamber’ (see Fig. 1a and b). The wall plates in the divertor chamber are periodically replaced, giving the main wall a much longer life. The contamination of the burning plasma by the sputtered wall material is also dramatically reduced by active pumping at the divertor chamber out of the device.

Since the plasma flows mainly along magnetic field lines, it can be diverted into the divertor chamber by using external coils to bend near-wall magnetic field lines into the chamber (see Fig. 1b). The overall magnetic field lines are then divided into two groups: one forming nested surfaces without touching the material wall in the main chamber, and the other being diverted to the divertor chamber. The two groups are physically separated by the magnetic separatrix surface. The region outside the separatrix surface with diverted field lines is called the ‘scrape-off’ region and the region inside the separatrix surface with nested magnetic surfaces is called the ‘confined core’ region. The plasma in the core region is hot and dense, while the plasma in the scrape-off region is cold and diluted.

When the heating power to the core plasma is above some threshold, it has been observed experimentally that there forms a thin plasma layer just inside the separatix surface in which the plasma is almost free of turbulence, with the cross-field transport rate down to the neoclassical level (neoclassical transport is a collisionally driven transport in an inhomogeneous magnetic field) [1]. This layer is called the “H-mode” layer, where H-mode is an abbreviation for “high confinement mode.” Since the cross-field transport rate in the thin H-mode layer is much lower than the ambient transport rate, the local plasma gradient becomes very steep. As a result, the plasma forms a distinct pedestal from the scrape-off into the core, with most of the gradient existing in the H-mode layer. Figure 2 shows experimental pedestal data from DIII-D device at General Atomics, CA. This pedestal raises the fusion probability dramatically. Under usual conditions, the rise of the pedestal triggers edge localized mode (ELM) instabilities, which destroy the plasma pedestal and simultaneously dump the plasma energy to the material walls in the divertor chamber, shortening the wall’s life time. The onset of ELM is known to be dependent upon the physical properties of the edge pedestal. Neither the pedestal growth property,

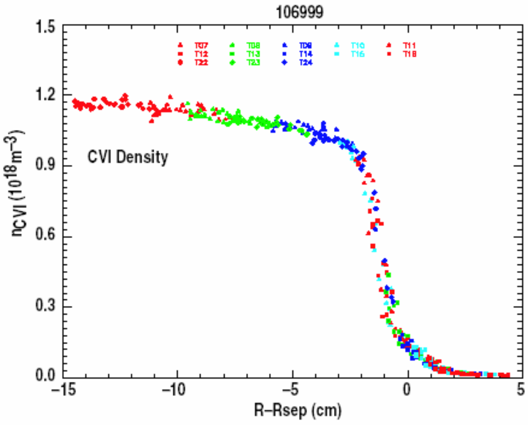

Fig. 2. An experimentally measured edge plasma density profile in a Quiescent H-mode in DIII-D (K. Burrell, 2002)

nor the ELM physics is sufficiently known at the present time. The success of ITER is highly dependent upon the existence of a reasonable pedestal height without a dangerous ELM. The physical understanding and prediction capability of the edge plasma pedestal are at the highest priority in fusion plasma research.

Understanding tokamak edge physics has been difficult for many reasons. First of all, the usual equilibrium thermodynamics physics laws do not apply to the edge plasmas. Equilibrium thermodynamics requires sufficient isolation of the physical information between different confinement domains. In the core region, plasmas at different flux surfaces are sufficiently confined within the flux surface and isolated from each other (weak radial transport). However, in the pedestal, the gradient scale length is on the same order as the radial particle excursion width, and in the scrape-off layer, the plasma is ill confined. Secondly, the effect of neutral species on plasma turbulence and transport, which in turn affects the neutral generation and distribution, is not well-understood. Thirdly, the existence of the magnetic separatrix and the material wall creates unconfined single particle orbits [2] in both pedestal and scrape-off regions, giving rise to another cause for non-equilibrium physics. All these phenomena require that edge plasma is non-Maxwellian and highly kinetic, which may not be easily handled by analytic theories or fluid equations. The existence of the magnetic separatrix and X-point makes even numerical simulations difficult since the convenient, conventional description of the particle motions in a flux coordinate system becomes singular. These are the reasons why an existing core kinetic code cannot be used on the edge plasmas.

2. Edge simulation with XGC-1 code

XGC-1 is a full-f gyrokinetic ion-electron particle code, specifically designed for edge plasmas. It is a more advanced version based upon the XGC-0 code [3], which is a massively parallel guiding center ion neoclassical particle code. In order to avoid the complications associated with the separatrix geometry, it uses the cylindrical coordinate system when evaluating the Lagrangian guiding center particle motions [4]. For a physics evaluation, however, the code uses a field-line following coordinate system. The usual four-point-averaging technique is used to include the finite gyroradius effects [5]. Neutral particles, from wall-recycling and gas puffing, are simulated together with the plasma particles, providing a self-consistent solution incorporating plasma-material interactions and atomic physics effects. In order to accommodate the X-point geometry and the arbitrary wall geometry, an unstructured triangular mesh is used for evaluation of the physical observables.

The XGC-1 code is designed for integrated simulation of neoclassical and electrostatic turbulence physics using massively parallel processors with mixed (particle and spatial) domain decomposition. The electromagnetic turbulence will be considered in the next version, XGC-2. The gyrokinetic Poisson equation [6] solves the four-point gyro-averaged charges deposited at the mesh nodes using the PETSc solver library [7].

In this paper we will report the fluctuation-averaged macroscopic results, which is here called ‘neoclassical’ in the extended sense. The turbulence physics will be reported elsewhere in the future. Even though the simulation described here is not long enough to allow the profile to evolve on a transport time scale, it does represent the first ever kinetic solutions of the plasma in the edge region.

Figure 3 shows a 3D view of the initial development of the neoclassical and electrostatic turbulence potential distribution in the tokamak edge region from an H-mode like plasma profile (see Fig. 4) in DIII-D geometry. For this simulation, the material wall with zero potential boundary condition is placed along a flux surface in the scrape-off region as can be seen from the figure. The dark blue and red/yelow hues represent negative and positive potential values, respectively. The separatrix surface is at $\psi=1$ in Fig. 4. It can be seen that a negative potential forms in the H-mode layer (dark blue) and a positive potential in the scrape-off layer (yellow). The red color around the X-point represents the higher positive potential formed as a result of the vanishingly small poloidal magnetic field there and the consequent long residence time of the ions. In contrast, the lighter electrons are less affected. The fluctuating electric field includes the strong GAM (geodesic acoustic mode) and its nonlinearly coupled modes.

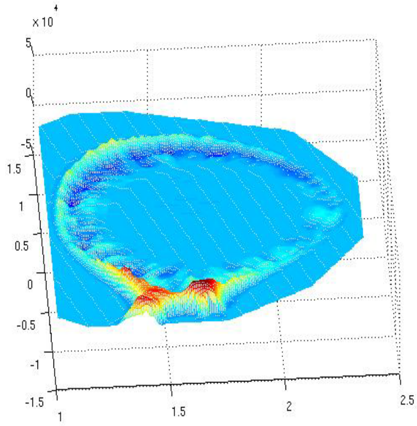

Fig.3. 3D view of an early time integrated solution of edge electrostatic potential. Sky blue is the zero potential

Fluctuations are then averaged over a significant poloidal extent to remove the turbulence. In Fig. 5, the figure in the left-hand-side represents the fluctuation-averaged electrostatic potential distribution (bright red color is zero, dark red is the positive, and the blue hue is the negative potentials). The right hand side is the fluctuation-averaged parallel flow distribution. Light green is zero, red hue represents flow in the direction of the plasma current (co-current direction), and the blue hue represents the opposite direction). We can see development of the negative potential (blue) to -2 keV inside the separatrix and positive potential (dark red) to 0.5 keV in the scrape-off layer. The pedestal temperature is 1 keV. We can also see formation of the co-current flow (dark red appears brown in the figure) to ~10^4 m/s in the scrape-off layer. These results are consistent with experimental observations, obtained for the first time from a first-principles kinetic simulation. It appears that the flow in the vicinity of the separatrix is sensitive to the neutral effect. However, flow at the pedestal shoulder/top is always in the co-current direction.

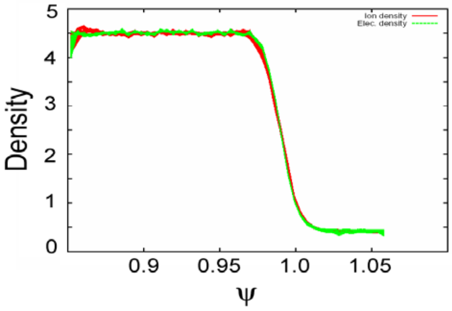

Fig.4. Plasma density ($x10^{19}m^{-3}$) corresponding to Fig.2, normalized to poloidal magnetic flux ψ

We find a possibly important implication from Fig. 5. The electrostatic potential distribution shows that there is a large scale ExB convective flow pattern in the scrape-off region of an H-mode plasma. Flow is in the counter-clockwise direction near the wall and co-clockwise direction near the separatrix, with the turn-around (direction reversal) occurring near the inner and outer divertor plates. This convecitive flow pattern in the scrape-off layer has been confirmed by visualization of particle motions. Our preliminary analysis shows that this ExB poloidal flow is more important to poloidal scrape-off plasma dynamics than the poloidal component of the parallel flow does, contrary to recent conjectures by some experimentalists. A more detailed study is in progress.

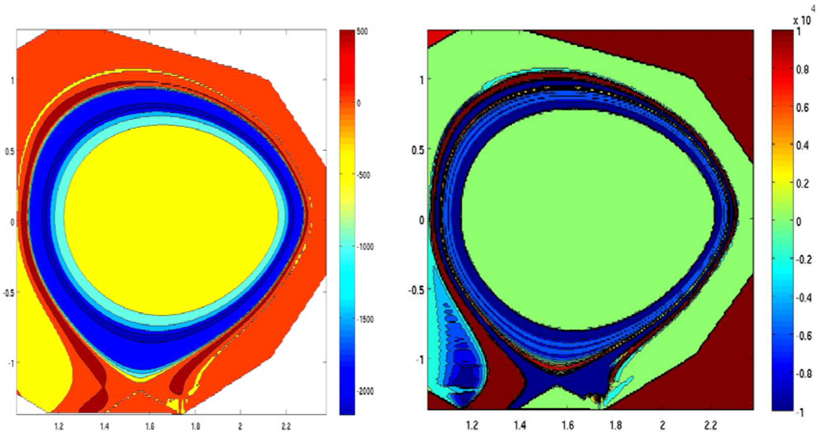

Fig.5. Neoclassical solutions for the electrostatic potential (left, in eV) and the plasma flow (right, in m/s) in the edge region of a tokamak plasma

3. Discussions

The present study produced neoclassical solutions of a diverted edge plasma for the first time, using massively parallel XT3 processors at Oak Ridge National Laboratory. The positive potential hill found here in the scrape off layer of an H-mode plasma may yield an important physical consequence for the particle and energy flow physics in the scrape-off layer. It shows that there is an ExB convective flow pattern in the scrape-off layer. Near the wall, the poloidal flow is in the clockwise direction. Near the separatrix, it is in the counter clockwise direction. The flow direction reverses in front of the inner and outer divertor plantes. Thus, the conventional simple conjecture that all the scrape-off flows hit the divertor plates is not consistent with the present findings.

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