A Guiding Center Particle Simulation of Pedestal Buildup and Study of Pedestal Scaling Law in a Quiescent Plasma Edge

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Abstract

A discrete guiding-center particle code XGC (X-point included Guiding Center code) is used to study pedestal buildup and sheared E_r formation in a quiescent plasma edge of a diverted tokamak. Pedestal scaling law has been deduced, which shows that the density pedestal width is proportional to $T_i^{1/2}/B_t$ where T_i is the ion temperature and B_t is the toroidal magnetic field. Dependence the pedestal density or the poloidal magnetic field is found to be much weaker. Ion temperature pedestal is not as well defined as the density pedestal. Neoclassical electron transport rate, including the collisional heat exchange rate with ions, is too slow to be considered in the time scale of simulation (~ 10 ms).

I. Introduction

Understanding and predicting the edge pedestal behavior in H-mode is one of the most critical issues in ITER Physics. If the H-mode layer is quiescent, the buildup of a pedestal will be governed by the neoclassical physics. However, there is no analytic neoclassical theory to be used in a modeling, which is valid in the edge pedestal region where the gradient scale length is less than an ion banana width, where an unconventional orbit loss due to X-point (X-transport [1]) is dominant over the conventional neoclassical banana transport, and where the neutral collisions can be as important as the Coulomb collisions. The pedestal shape is closely tied to the orbit squeezing and X-transport in the self-consistent radial electric field (E_r) shear. Since most of these effects are highly kinetic, a pedestal buildup must be studied in a fully kinetic plasma-neutral system with a self-consistent radial electric field evaluation in a realistic flux-surface and first-wall geometry. There has been no known prior kinetic code in the literature for studying such an edge pedestal buildup by neutral ionization. A recent Monte Carlo kinetic code work reported by Heikkinen et al [2] simply evaluated an edge radial electric field profile from a prescribed plasma profile without the neutral penetration physics; hence, it was not able to study the pedestal formation physics.

In the IAEA FEC 2002 meeting, we reported the discovery of X-transport as a significant mechanism to create a sharp negative radial electric field in a thin quiescent layer just inside the separatrix surface [1]. We also reported the launch of a large numerical project to study the kinetic neoclassical pedestal physics. Using a primitive form of Coulomb operator (non-conserving pitch-angle scattering) and an analytically prescribed fluid neutral profile, a preliminary demonstration of the edge pedestal and E_r formation was presented. The first principles code XGC (X-point included Guiding-center Code) has recently been completed on a state-of-the-art physical and mathematical platform, and been producing a rather complete and self-consistent picture of the edge-pedestal buildup and other related physics in a quiescent diverted edge [3]. More importantly, XGC has recently been producing a neoclassical pedestal scaling law.

XGC is a massively parallel (typically, using over 2,000 processors) 3D ion kinetic code for a quiescent plasma. It is a full-f, Hamiltonian discrete-particle guiding-center-ion code in cylindrical coordinates, being five dimensional (three in the real and two in the velocity space) in a flux surface and limiter geometry provided by EFIT. It has the an advanced momentum and energy conserving Monte Carlo Coulomb collision scheme [4]. The background plasma evolves in time, following the evolution of the radial marker particle distribution. An axisymmetric 2D kinetic Monte Carlo neutral atom diffusion module is built into XGC for a more accurate accounting of the neutral penetration dynamics. Plasma and neutral particles experience charge exchange, ionization, and elastic collisions with each other species self-consistently. A continuous heat outflow from the core is included. E_r is evaluated dynamically from the flux-surface averaged Poisson's equation, consistently with the classical and neoclassical ion polarization currents, in the time-evolving plasma pedestal profile. In the current version, the electrostatic potential is assumed to be a flux function.

II. Pedestal buildup

A pedestal buildup is simulated after mimicking an L-H transition by turning off an artificially added anomalous diffusion coefficient D_A. D_A is incorporated into XGC by a random shuffling of each radial particle positions by a random-walk step size smaller than the density gradient scale length, and the shuffling frequency is determined by requiring the anomalously affected density slope being milder than a typical pedestal slope. $D_A = 1$ m^2/s is found to be adequate for a DIII-D edge plasma. The neutral atom density at a distance outside the separatrix can be kept constant after the L-H transition or made to be automatically adjusted according to the particle recycling. The poloidal neutral density distribution can be assumed analytically, to model a divertor dominant recycling, limiter recycling, or gas puffing at a specific poloidal location. The plots shown in this report is the simplest case, which uses a time invariant neutral density during the buildup with a uniform poloidal distribution. Effect of the spatiotemporally non-uniform neutral density will be reported elsewhere. However, those results are not much different from the simple neutral case presented here.

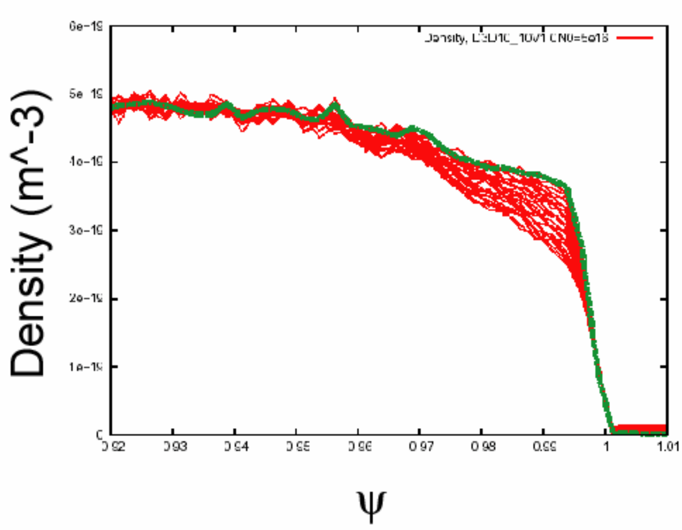

Fig. 1

Figure 1 shows buildup of plasma density pedestal by neutral ionization in a purely neoclassical stage after the anomalous diffusion is turned off. Neutral density of 5×10^{16} m^{-3} at ψ=1.04 is used. Total elapsed time is 40 toroidal transit time of a 200 eV passing D ion. The lines are drawn at one toroidal transit time interval. The green line is the density profile at 40 toroidal transit time. The density pedestal continues to build up after 40 toroidal transit time. If the simulation is left to go on for a long enough time, the pedestal buildup makes the edge density profile hollow. The radial location of the inner edge of the density pedestal does not change much as the pedestal density grows (seems to show a weak inward propagation with rising dendity). This observation does not agree with a recent study, which reports that the pedestal width decreases with pedestal density since the pedestal width is basically determined by the neutral penetration depth [5].

Figure 2 shows profile evolution of the electrostatic potential, ion temperature, ExB speed, and the parallel flow speed. The electrostatic potential basically shows wobbling motions, while the average potential becomes deeper very slowly, ending up to a little deeper than 2 keV for the ion pedestal temperature of 0.5 keV. The same trend is seen in the ExB speed. The fact that the electric field varies slowly assures us that we are in quasi-steady neoclassical state with vanishing net radial current profile. There is a GAM type of oscillation observed, which decays completely within the simulation time. We continuously add 0.5 MW of heating power to the ions at the inner most radial zone. The average ion kinetic energy K_i, though, shows some decrease at the inner most zone, indicating that the heat input was not enough to hold the inner most ion energy. The ion energy pedestal shows a much broader slope than the density pedestal. We believe that the broader slope in K_i at smaller minor radii is due to the usual neoclassical ion thermal conduction, while the steeper slope around the pedestal region is due to the X-transport phenomenon. It should be noted here that K_i does not drop to a much smaller value on the separatrix, like the density pedestal did. This is the ion orbit effect. It should also be noted that the K_i profile shows non-Maxewellian tail behavior at outside the separatrix. A close examination shows that the ion distribution function is anisotropic: the parallel component of K_i is greater than the perpendicular component. We find that the orbit squeezing effect causes this phenomenon. The fat banana ions cannot penetrate the high ExB shear layer, while the fat passing orbits can. This non-Maxwellian feature becomes more distinctive at lower ion collisionality. If the ion temperature is too low, and/or the scrape density becomes high, then the ion distribution function becomes almost Maxwellian.

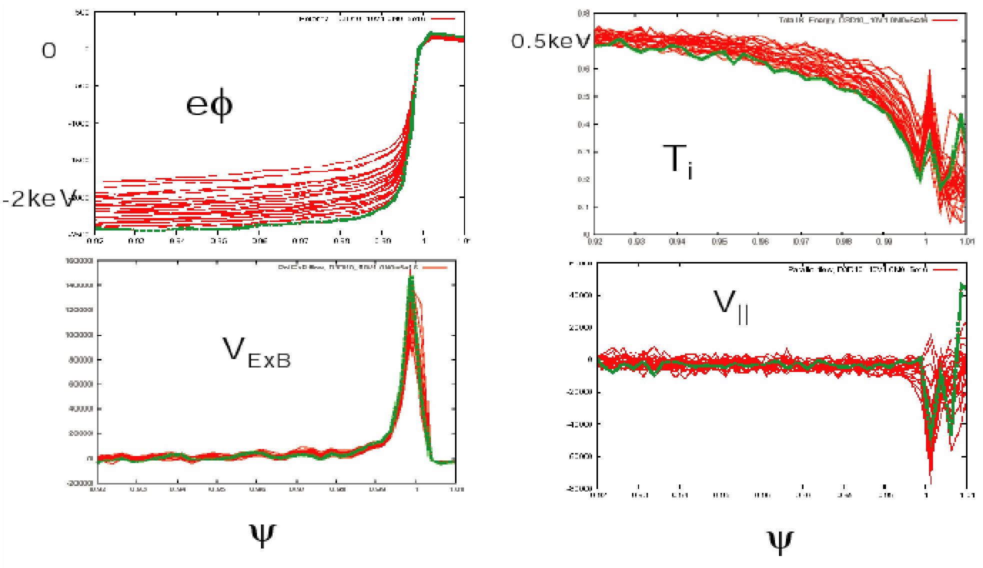

Fig. 2

We note here that the density profiles shown in the Fig. 1 may accurately defines the inner boundary of the density pedestal in a quiescent plasma. However, the outer boundary may not be accurately described in the figure. It is due to the facts that we do not include in the figure the distortion of the gyro orbits in a strong radial electric field (the static classical polarization density), even though we include the polarization current in the time dependent electric field evolution, and that the electric field is artificially set to zero at the first radial zone outside the separatrix (which may affect the foot of the density pedestal). The usual dynamic polarization density derived for plasma turbulence may not apply to this case, but implies that the static classical polarization density may not be negligible in the strong electric field region just inside the separatrix, where the electric field gradient length is not much greater than the ion gyroradius. Thus, the actual density pedestal may be somewhat broader.

The density and temperature pedestal structures show different responses. The density pedestal is controlled by neutral ionization dynamics together with the orbit dynamics of the newly ionized ions in a sheared radial electric field (orbit squeezing and expansion, and X-transport). On the other hand, the ion temperature is controlled by the heat out-flow from the plasma core, neutral cooling, and X-transport.

III. Pedestal scaling law

There are two ways to obtain a pedestal scaling law from the present simulation. The first one is to obtain data from numerous pedestal buildup simulations as shown in the previous section. The second method is to find a neoclassical profile solution at the steepest pedestal profile (find the maximal pedestal root) under a given set of pedestal temperature and density, assuming that a plasma pedestal builds up along the maximal pedestal root. In the second method, a convincing argument is that a density pedestal cannot grow steeper than a maximal pedestal due to the orbital effect, hence the density can only grow higher along the maximal pedestal root. Getting a data set from the first method is like getting a data set from experiments. It may require much more number of expensive computational runs than the second method. On the other hand, the second method can be extremely systematic, for we can choose the density and temperature pedestal heights. In the present report, we summarize the result from the second method.

To obtain the steepest density profile solution, we start with a step function density and temperature profile. The neoclassical orbital motions of the individual ions will immediately spread the ions in radius, reaching to an equilibrium profile solution eventually, where the radial ion current vanishes. It is not a real physical process, but only a mathematical process to find the steepest profile state. A proper amount of heat should be added to the ions at the inner most radial location to keep the ion temperature from falling, since the ions will lose energy by neoclassical thermal conduction.

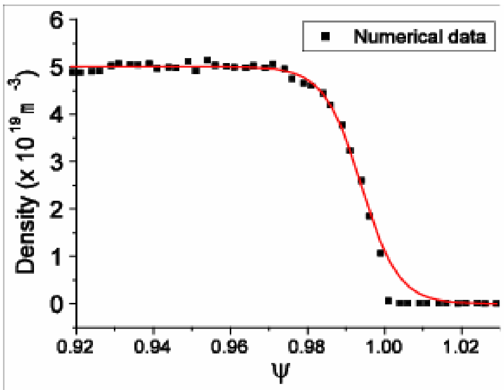

Fig. 3 Neoclassical edge density pedestal profile with a Tanh fit

Figure 3 shows a maximal neoclassical density pedestal profile obtained from XGC (dots) and a Tanh-fit (line). A DIII-D equilibrium is used with the axis-magnetic field 1 T, pedestal ion temperature 1 keV and pedestal density 5 x 10^{13} cm^{-3}. The horizontal axis is the normalized poloidal flux ψ. Agreement with the Tanh-fit is remarkably good, as was in the experimental pedestal data fittings. The pedestal width obtained here is about 1 cm, which is somewhat narrower than, but in the right ball park with the experimentally measured values. The Tanh-fit defines a consistent pedestal width for scaling studies. We note here again that the pedestal foot may extend further into the scrape off layer, making the width somewhat broader, due for the reasons stated in the previous section. However, the location and shape of the pedestal shoulder should be quite accurate if the plasma is quiescent.

Figure 4 shows scaling of the density pedestal width (in ψ) against the square root of the pedestal ion temperature, obtained from the Tanh-fit to the maximal pedestal shapes for various ion temperature values. It shows an offset linear behavior above 300 eV. As mentioned before, the ion temperature pedestal shape is not well defined. Thus, the definition of ion pedestal temperature is ambiguous. The ion pedestal temperature in the present study is measured at the inner most radial location in Fig. 2, which can be different from what is used in the experiment.

A similar scaling study has been performed in magnetic field, which shows a rather surprising result (Fig. 5).. It shows a strong $1/B_T$ dependence, not a $1/B_P$ dependence. In fact, the pedestal width shows only a weak dependence on the poloidal magnetic field. The density width dependence on the pedestal density has also been examined. The maximal pedestal scaling shows that the density width does not vary much as the pedestal density is varied. It shows a fairly weak increase with density increase, confirming the observation made from an actual buildup process in Sec. II. Thus, the neoclassical density pedestal width Δ_n does not increase with the poloidal ion gyroradius, nor it decreases with density, but scales approximately as $\Delta_n \propto T_i^{1/2} B_T^{-1}$. This scaling seems to agree with a preliminary experimental result on C-MOD [6] (but not conclusive yet).

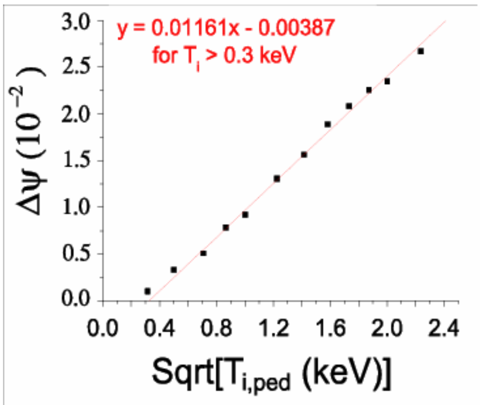

Fig. 4. Density pedestal width vs SQRT of pedestal Ti

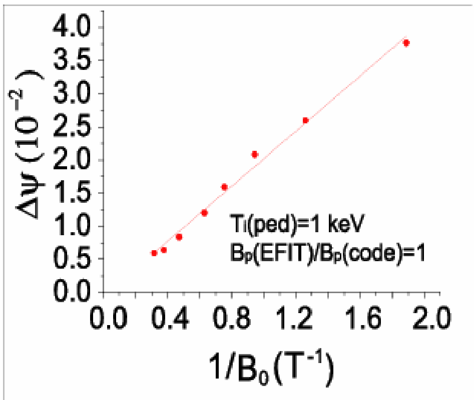

Fig. 5. Density pedestal width v.s. 1/B(axis, Tesla)

Another interesting finding from this study is that there is often a positive toroidal momentum source in a strong pedestal edge, supporting a recent observation on C-MOD [John Rice, 2003 APS-DPP, Invited Paper]. Without a toroidal momentum source, a conventional neoclassical theory and XGC predict a negative toroidal flow generation in a steep pedestal. However, a positive toroidal momentum is often observed from XGC in a strong pedestal region at a separatrix edge. It is also found that the ion distribution function at the foot of the pedestal (in the scrape-off layer) can be highly anisotropic, in agreement with a recent observation on DIII-D [Keith Burrell, 2003 APS], which suggests that an anisotropic radial force balance equation should be used to deduce an E_r profile from the experimentally observed pressure gradient and plasma flows.

IV. Conclusion and discussions

Assuming that the plasma edge is turbulence free, we have performed a 3D kinetic neoclassical simulation of plasma ions in a realistic flux surface and first wall geometry using our XGC code. For a more reliable simulation of the neutral penetration physics, an axisymmetric kinetic Monte Carlo neutral particle transport module is built into the code. In this purely neoclassical system, the plasma electron transport is too slow to evolve within the simulation time scale (about 10 ms). The electron-ion coupling is also too weak to affect evolution of electron temperature profile within simulation time. Thus, buildup of electron temperature pedestal at a similar rate as the density pedestal buildup is beyond neoclassical analysis. An independent electron transport mechanism (a residual electron turbulence) may be necessary to model an electron temperature pedestal buildup.

Pedestal scaling law has been deduced, which shows that the density pedestal width is proportional to $T_i^{1/2}/B_t$ where T_i is the ion temperature and B_t is the toroidal magnetic field. Density pedestal width does not show a strong dependence on B_p or density, in disagreement with some recent reports. Existence of a residual turbulence may modify this conclusion to an unknown degree. Comparison with experimental data is under active persuit by the authors.

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