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Edge Pedestal and Er-Layer Formation by X-Transport in a Diverted Tokamak[1]

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Whether the H-mode bifurcation into a turbulence-suppressed state is from a turbulence generated zonal flow or from a neoclassical mechanism, it is important to establish a solid foundation for the transport phenomena in the plasma edge. Recently, it has been introduced by the authors that there is a robust non-ambipolar neoclassical transport mechanism in a diverted tokamak edge, which yields strong edge pedestal and sheared E×B rotation (X-transport, [1,2]). The X-transport is an intrinsically non-ambipolar transport localized to the X-region, caused by a lack of poloidal magnetic field. It is stronger than the usual neoclassical transport. The X-transport is in natural harmony with various (unexplained) phenomena observed in the H-mode and edge pedestal experiments [2].

Following the preliminary conceptual report in Refs. [1] and [2], a Monte Carlo guiding center code has been developed to study the X-transport physics in detail. Typically, over a million ions are distributed between the normalized flux surfaces 0.9 and 1.02, using a massively parallel platform at NERSC. A Monte Carlo Coulomb collisions are included, and neutral ionization and charge exchange are modeled into the simulation. Poisson equation is solved as function of flux surfaces to obtain time evolution of radial electric field. Evolution of ion density and temperature is calculated self-consistently with the radial electric field evolution. Many new results and deeper understandings have emerged, which include the collisional X-transport process, density and temperature pedestal formation, edge torque generation, and so on. Comparison between a normal tokamak (DIII-D) and a spherical tokamak (NSTX) has also been pursued.

Origin of the X-transport is the existence of unconfined collisionless orbits in the X-region. Near the X-point, poloidal magnetic field becomes vanishingly small. Ions with low parallel flow speed will have little poloidal flow out of the X-region and get poloidally "X-trapped." The vertical ∇B-drift motion then moves the X-trapped ions across the last closed flux surface into the divertor chamber (see Fig. 1).

The collisionless loss-orbits constitute a velocity space hole. Without a strong (negative) ambipolar radial electric field, the loss hole extends all the way down to or below the thermal energy level at the edge. The plasma cannot tolerate such a large non-ambipolar loss hole and generates a strong negative radial E_r to push the loss hole

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to a higher energy and to ensure an ambipolar transport in balance with the inward return current of cooler ions. Under the Coulomb collisions, in reality, the ions undergo a collisional X-transport by scattering into and out of the loss hole. An electron loss hole is absent since their parallel motion even in the X-region is much faster than their ∇B-drift motions.

Loss of ions by X-transport gives rise to edge pedestal formation and becomes a source of a strong negative radial electric field E_r. Edge E_r will increase until the $E \times B$ poloidal rotation reduces the ion velocity space hole to a steady state level, where the ion return current balances the ion X-transport current. Figure 2 shows an edge density pedestal formation without neutral effect in a DIII-D equilibrium. The horizontal axis is the poloidal flux normalized to unity at separatrix. An initial distribution of ions are allowed to relax for 50 toroidal transit periods. We observe a transient, rapid pedestal formation process up to about 20 toroidal transit periods, and afterwards a steadier collisional X-transport process begins to set in. We find that temperature pedestal is usually broader than the density pedestal and anisotropic between parallel and perpendicular directions (Figs. 3 & 4). At $\psi < 1$ the temperature anisotropy is moderate, however, at $\psi > 1$ the temperature anisotropy can be large due to the banana broadening of perpendicular energy from the pedestal region into the open field line region. Figure 5 shows the radial electric field formation in the edge, where it is assumed that the electrostatic potential is a flux function.

A simple neutral model is added to the code to study the effect of neutral ionization and charge exchange on pedestal and E_r-layer formation. It is found that the neutral particle effect does not change the essential nature of the pedestal and E_r-layer formation. The X-transport effect is so dominant that the neutral effect is only a perturbation.

What is more striking is the difference between a normal tokamak (DIII-D) and a spherical tokamak (NSTX) in the pedestal and E_r-layer formation. Figure 6 is the E×B flow generation in NSTX. For the same edge condition ($T_{ped} = 200eV$, $n_{ped} = 3 \times 10^{13}\ cm^{-3}$), NSTX in Fig. 6 shows greater V_{EXB} magnitude and much greater width than DIII-D in Fig. 5 (notice the different vertical scales). It may be more than coincidental that the plasma parameters used here yields an H-mode in NSTX (Shot 104316), but the same plasma parameters in DIII-D should yield L-mode (anticipated from Shot 96333). The rest of the NSTX figures, corresponding to those of DIII-D are shown in Figs. 7-9. It can be seen that all the pedestal widths are wider in NSTX. Edge toroidal rotation generation by X-transport is shown in Fig. 10 for NSTX.

Fundamental driving mechanisms in the X-transport are in natural agreement with various (previously unanswered) questions raised in the experiments. For example, why is a temperature pedestal usually broader than the density pedestal, why is an H-mode power threshold lower if ∇B-drift is into the divertor, why does a double null configuration require a higher power threshold, why does the edge pedestal formation prefer a diverted plasma, why does a pedestal layer have such a radial thickness, and why does an L-H transition power scaling is dependent on mass, B, density, and surface area? We refer the readers to Ref. [2] for a discussion in this matter.

[1] C.S. Chang, et al, 18th IAEA Fusion energy Conference, Italy, 2000.
[2] C.S. Chang, S.H. Ku, et al, Phys. Plasmas **9**, 3884 (2002).

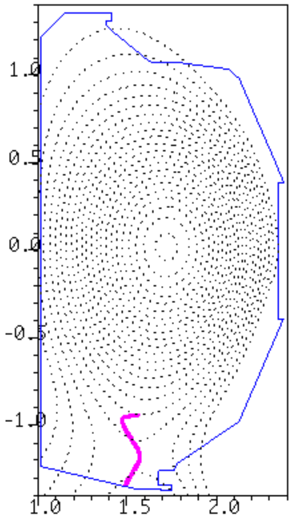

Fig. 1. X-trapping in DIII-D

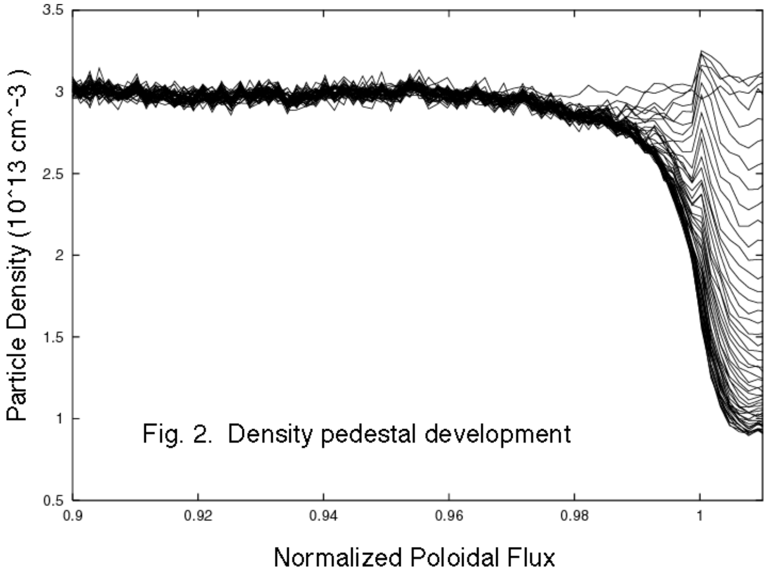

Fig. 2. Density pedestal development

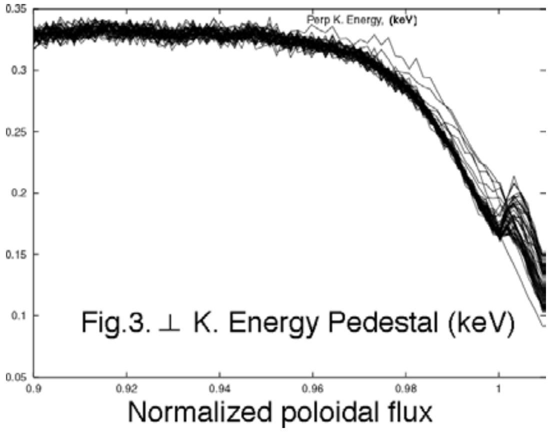

Fig.3. ⊥ K. Energy Pedestal (keV)

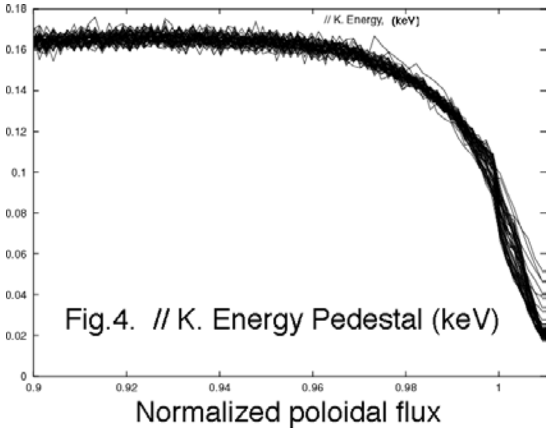

Fig.4. // K. Energy Pedestal (keV)

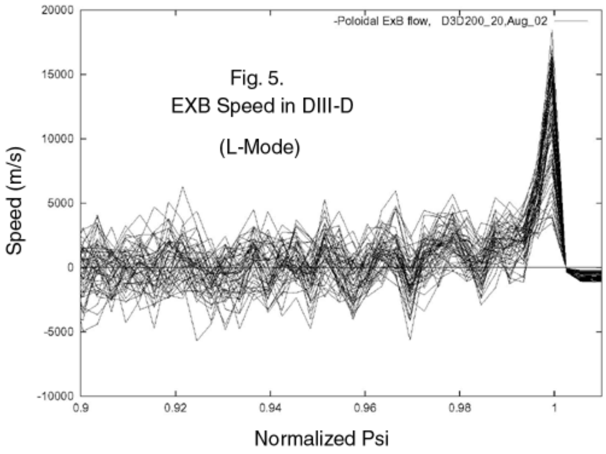

Fig. 5.
EXB Speed in DIII-D
(L-Mode)

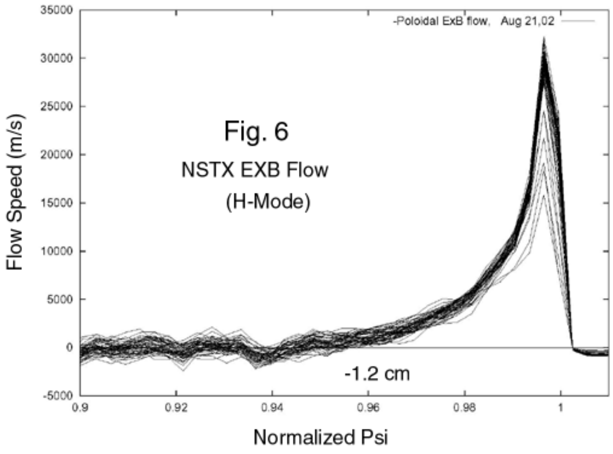

Fig. 6
NSTX EXB Flow
(H-Mode)

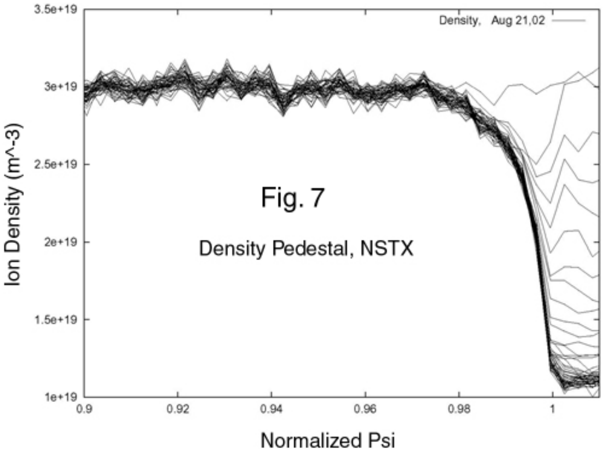

Fig. 7

Density Pedestal, NSTX

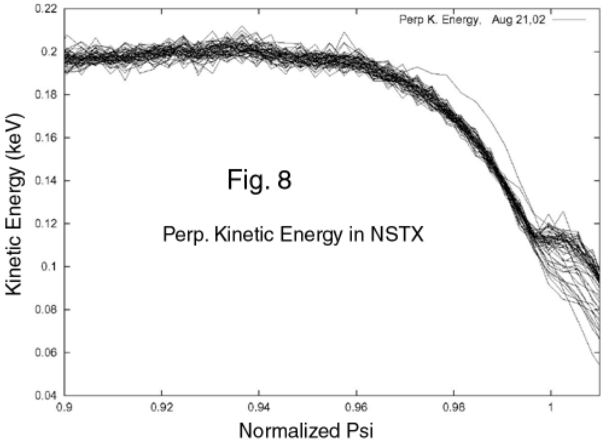

Fig. 8

Perp. Kinetic Energy in NSTX

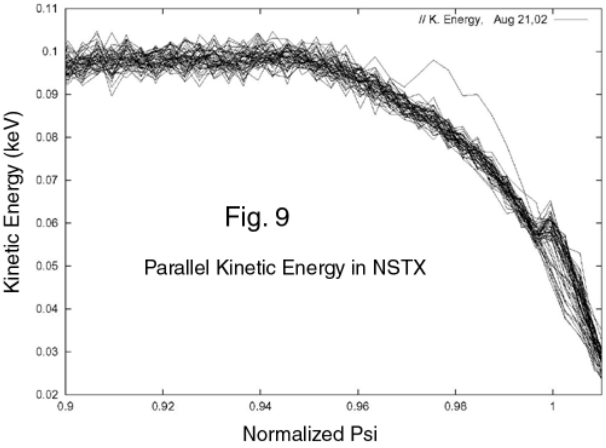

Fig. 9

Parallel Kinetic Energy in NSTX

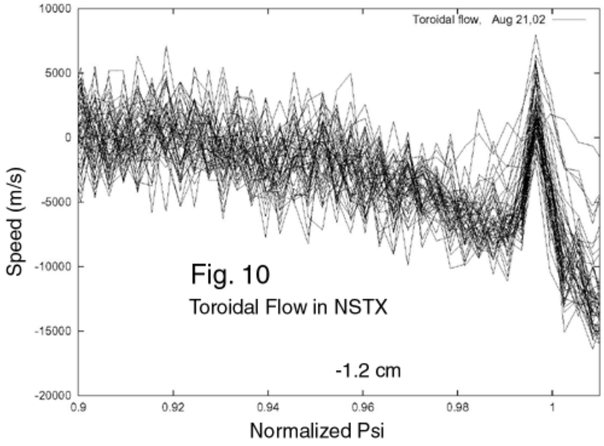

Fig. 10

Toroidal Flow in NSTX

-1.2 cm