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Transport barrier formation and bifurcation in CHS

Discoveries of internal and edge transport barriers have stimulated interest in the physics of the transition and in the bifurcation of toroidal plasma structures. A number of experiments and theories suggest that the mechanism of transport barrier formation should be related to a bifurcation in the radial electric field.

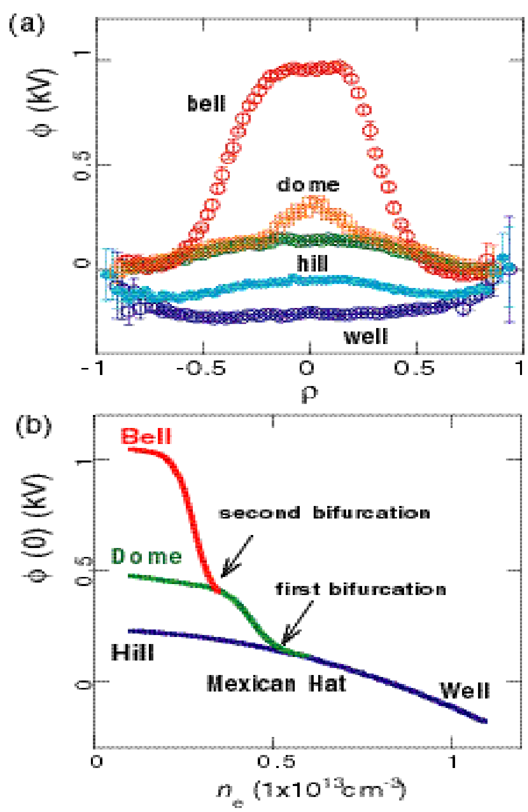

Fig. 1. (a) Potential profile patterns in CHS plasmas. All of the potential profiles are observed in ECRH plasmas, while only the *well* shape is identified in neutral beam-heated plasmas. (b) A schematic diagram of central potential as a function of line-averaged density.

In the Compact Helical System (CHS), intensive studies of the internal radial electric field, performed using a heavy ion beam probe, have led to a number of findings about the radial electric field [1]. In particular, bifurcation-related phenomena have been found in electron cyclotron resonance heated (ECRH) plasmas with on-axis resonance (gyrotron frequency: 53.2GHz; magnetic field strength: 0.88T). The most important finding for fusion applications is the first confirmation of transport barrier formation in a stellarator [2].

In CHS, the observed potential profiles are classified into five patterns, as shown in Fig. 1(a). The patterns are termed *bell*, *dome*, *hill*, *Mexican hat*, and *well*, ordered from higher to lower values of the central potential $\phi(0)$. Figure 1(b) shows how the potential patterns appear; the measured values of $\phi(0)$ are plotted as a function of line-averaged density.

Figure 1(b) shows three curves corresponding to bifurcation. Two critical densities are identified, where the shape of the potential profile changes drastically or the potential profile bifurcates. Below the first critical density, the hill potential profile can acquire a dome around the core. This change is characterized by creation of an E_r shear point at $\rho \sim 0.3$. Below the second critical density, the bell profile is observed; it can be defined as occurring when the base of the dome at $\rho \sim 0.3$ moves outward to $\rho \sim 0.5$.

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The hill, dome, and bell branches represent three distinctly different states. This is simply demonstrated by the time evolution of the central potential, which changes abruptly in a few dozen microseconds [1]. Therefore, the hill, dome, and bell are recognized as bifurcated states. On the other hand, as the density increases along the hill branch, the potential profile changes continuously from hill to well through the Mexican-hat shape.

The bell and dome profiles are quite important for fusion applications since they possess rather large E_r shear that may result in reduction of fluctuation-driven transport. Actually, for the dome state, it was confirmed that an electron thermal transport barrier was established at the radius of the maximum E_r shear, $\rho \sim 0.3$.

During the transition from the hill to the dome state, the gradient of electron temperature at the barrier position $\rho \sim 0.3$ increased from 0.12keV/cm (hill) to 0.57keV/cm (dome). The electron temperature profile is shown in Fig. 2(a). The radial electric field around the barrier ($\rho \sim 0.3$) was deduced from fine-structure measurements of potential [Fig. 2(b)], and the analysis yielded a maximum E_r shear of ~40V/cm^2 at $\rho \sim 0.3$.

A reduction in density fluctuation is also confirmed at the transport barrier or the radius at which the maximum shear in E_r occurs. Figure 3 shows the power spectrum of the density fluctuation around the barrier. The fluctuation reduction is obvious at the barrier (Δr = 0cm). The reduction of fluctuation power at the shear maximum point is ~50% (see Fig.2) if the integral fluctuation level (with noise subtracted) is used for the estimate.

The formation of this internal transport barrier is associated with the bifurcation of the radial electric field inherent in a toroidal helical plasma. In the dome profile, E_r inside the barrier bifurcates into a strongly positive branch, with E_r outside remaining in the weakly positive branch. Then an interface appears at the radial location where the two E_r-branches meet, a sufficiently large E_r-shear is produced, and the internal transport barrier is formed because of the reduction in the fluctuation-driven transport.

In toroidal helical plasmas, both the absolute value of E_r and the E_r shear are important for transport, particularly in the collisionless regime. Strongly positive E_r (electron root) should have better neoclassical transport properties than slightly positive E_r (ion root). Hence, the transition of E_r to the strongly positive branch could contribute to the formation of the internal transport barrier and the transport improvement inside the barrier.

For plasmas with the bell profile, the maximum E_r shear is evaluated as ~60V/cm^2 at $\rho \sim 0.5$, which is equivalent to that of the dome shape. It is expected, therefore, that the internal transport barrier may be established for plasmas with the bell profile. However, the bell states have not yet been maintained for a long enough time. Finding an operational condition where the bell branch is stably realized is an important future task because the branch may be associated with an internal transport barrier located at an outer radius of $\rho \sim 0.5$, which would result in improved plasma performance.

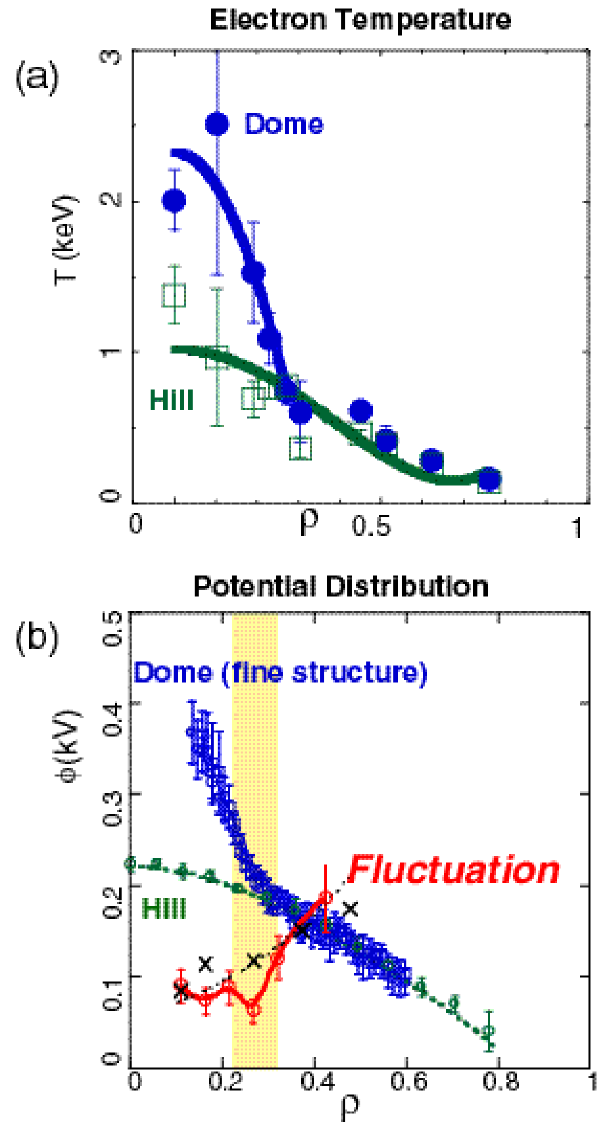

Fig. 2. (a) Electron temperature profiles of the dome and hill states. (b) Potential profiles of the dome and hill states, with total fluctuation power of the density. Density fluctuation is reduced where the E_r shear is maximum.

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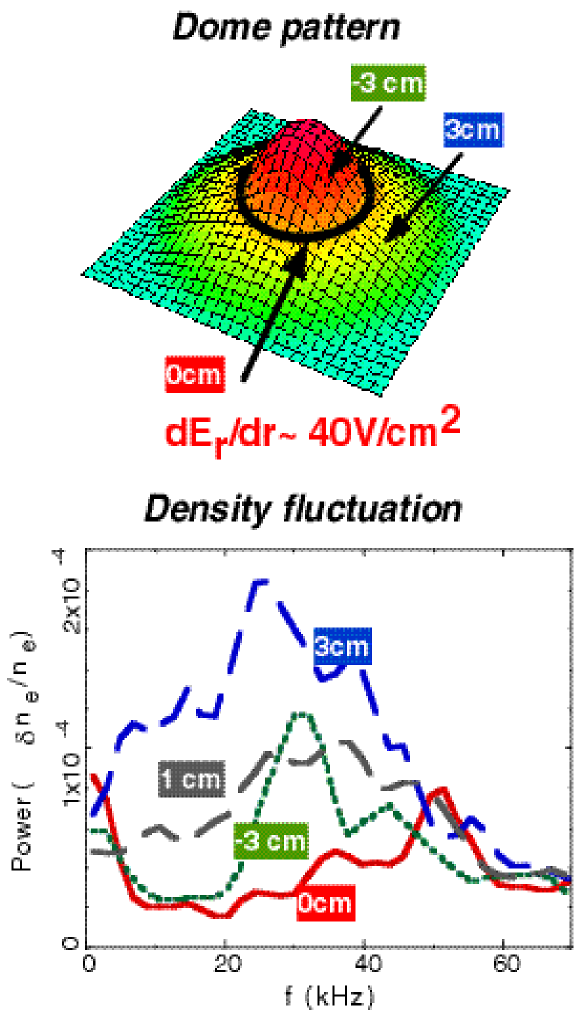

Fig. 3. Power spectrum of the density fluctuations around the barrier in the dome state. Δr = 0 cm indicates the radius at the transport barrier.

References

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[2] A. Fujisawa et al., Phys. Rev. Lett. **29**, 2669 (1999).