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Bifurcation phenomena in magnetic confinement

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Various pioneer work of plasma physics in the last 30 years is reviewed in this talk. The following findings are discussed: 1) radial electric field shear in H-mode pedestal, 2) curvature of radial electric field and temperature profile, 3) intrinsic torque for plasma rotation, 4) hysteresis of flux-gradient relation in dynamic transport, 5) bifurcation of magnetic island states and 6) trigger problem for abrupt events. In several years after the finding, some of these topics already became a mainstream research and others are a state-of-the-art frontier research.

The mainstream research in plasma physics for nuclear fusion has been focused to find a scenario to produce and sustain the high density and high temperature in magnetically confined devices. Therefore, the physics connection between the magnetic field structure and performance of plasma in the steady state has been intensively studied. In contrast, the pioneer work has been done in the field of bifurcation phenomena due to a strong non-linear process in the high temperature plasma. The most epoch making finding in the plasma physics in a magnetically confined plasma was finding the transition from low performance (L-mode) to high performance (H-mode) as bifurcation phenomena. This is the bifurcation phenomena of transport at the plasma boundary and the high pressure gradient region, which is called pedestal, suddenly appears even for the constant heat flux in time. This finding provides for paradigm shift for nuclear fusion research, because the performance of the plasma in not only determined by the magnetic field structure and strongly affected by self-organization process in the plasma. The strong radial electric field shear [1,2] and curvature [3], which appears associated with the transition from L-mode to H-mode, contributes the reduction of turbulence and transport in the pedestal region.

After the finding of the H-mode, there are various bifurcation phenomena reported both in the transport and MHD instability caused by a strong non-linear and self-organized process in the plasma. In the transport, bifurcation phenomena of transport state were also found interior plasma, which is called an internal transport barrier (ITB). The bifurcation of curvature of temperature (second derivative of ion temperature) was observed in the ITB region of the plasma. These phenomena is called curvature transition between concave ITB and convex ITB [4]. Bifurcation of momentum transport was observed as reversal of spontaneous rotation [5], non-diffusive term [6] and intrinsic torque [7]. The bifurcation of the transport has been observed as hysteresis of flux-gradient relation in dynamic transport [8-10]. This bifurcation phenomena strongly suggests the existence of non-local transport (in violation of local closure) [11, 12].

The bifurcation phenomena were also found in the MHD instability. The topology of the magnetic field shows the bifurcation phenomena between nested magnetic field state and stochastic magnetic state [13-17]. It was found that the turbulence level and transport are reduced inside magnetic island [18, 19]. The bifurcation of transport inside the magnetic island was also observed [20, 21]. Therefore, the heat pulse propagates slowly inside the magnetic island. The bifurcation of transport inside the magnetic island was observed as the bifurcation of propagation speed of heat pulse inside the magnetic island. One is the state in which the heat pulse penetrates inside the magnetic island and the other is the state in which the heat pulse does not penetrate into the magnetic island due to the slower propagation speed.

More recently, the bifurcation phenomena were also found to play an important role in triggering the abrupt event [22]. This is the bifurcation from modal MHD instability to non-modal MHD instability, where the deformation of the plasma is highly localized poloidal, toroidal and radial directions [23, 24]. In this talk, pioneer work on plasma physics, which has become or will become a mainstream research, is reviewed.

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