INTRINSICALLY STEADY–STATE TOKAMAKS

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It is shown that tokamaks can be intrinsically steady state without seed currents by coupling potato bootstrap current in the region close to the magnetic axis to the banana bootstrap current away from the axis. The equilibria we find are highly elongated (e.g. $\kappa = 3$) and have naturally reversed shear profiles. The vertical instability of elongated tokamaks and theory of enhanced reversed shear mode for this class of equilibria are also developed.

Intrinsically Steady State Tokamaks

In the conventional bootstrap current theory, the width of the banana orbit is assumed to be much smaller than the radius (i.e. zero banana width assumption). The fraction of the trapped particles then depends on the square root of the inverse aspect ratio. This rules out the possibility of non-vanishing bootstrap current on the magnetic axis. Therefore one needs a seed current to maintain a steady state pressure-gradient-driven-current tokamak [1]. However, zero banana width assumption breaks down in the near axis region [2, 3]. A typical set of particle orbits in the near axis region is shown in Fig. 1.

When this assumption is removed in the kinetic theory, one finds the fraction of trapped particles and thus bootstrap current remain finite in the near axis region. This is demonstrated originally for α particles [4] and recently for electron-ion plasmas [5, 6]. The magnitude of the near-axis bootstrap current density (i.e. potato bootstrap current density because the shape of the trapped particles is similar to a potato) for an electron-ion plasma can be a significant fraction ($> 18\%$ for typical parameters) of the conventional banana bootstrap current density. Coupling the near-axis potato bootstrap current to the conventional bootstrap current away from the magnetic axis, a class of intrinsically steady state tokamak equilibria without external current drive is found [7]. This class of equilibria has naturally reversed safety

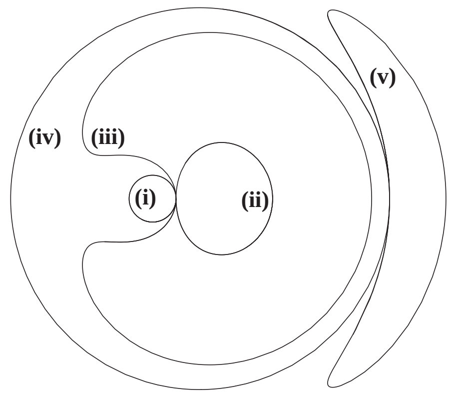

Figure 1: Standard banana orbit and particle orbits close to the magnetic axis. Class (i), (ii), and (iv) orbits are circulating particles. Class (iii) are trapped particles, i.e., potato orbits. The standard banana orbit is (v).

factor q profile and high plasma β, the ratio of plasma pressure to the magnetic field pressure. It is stable against ballooning instability. A close-fitting wall can stabilize the kink instability. Tokamaks can therefore be intrinsically steady state with the equilibrium current completely maintained by the pressure-gradient-driven current and without the need of the external current drives.

Vertical Stability and Nonlinear External Kinks

Large displacements of the plasma column during dispruptive events and the subsequent appearance of driven currents in the conducting structures around it, especially when they exhibit large poloidal and toroidal asymmetries, can pose a serious threat to the mechanical integrity of the device. In the first nonlinear, three dimensional, self-consistent studies of vertical instabilities, with our 3D MHD code CTD [8], we observe both toroidal and poloidal asymmetries in the currents generated in the wall as a result of vertical displacements coupled to external kinks. Figure 2a shows the pressure contours towards the end of such an event after the plasma has come in contact with the wall. Poloidal halo currents generated in the plasma and the wall in general show a complex pattern not expected from simpler models, as seen in Fig. 2b. Poloidal currents in the wall are not only highly localized but can locally reverse. A feature not discussed extensively in the literature is the nonuniformity of the toroidal currents generated in the wall. Depending on the relative time scales of the plasma current quench and the

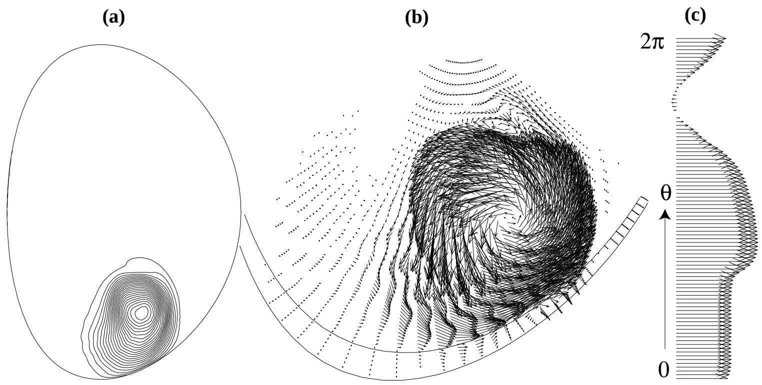

Figure 2: a) Pressure contours after the plasma comes in contact with the wall. b) Poloidal current vectors in the plasma and the resistive wall. c) Poloidal distribution of the toroidal currents induced in the wall prior to wall contact. $\theta = 0$ is at the outboard mid-plane.

plasma displacement towards the wall, a very pronounced poloidal nonuniformity in the induced toroidal wall current can be seen, since these two effects tend to produce opposing electric fields. This feature is evident in Fig. 2c, which shows the poloidal distribution of the toroidal current at a time before the plasma comes in contact with the wall. Decaying plasma current has induced large parallel currents in the wall, which slightly reverse in a narrow region opposite the approaching plasma column due to induced eddy currents by the plasma motion.

Theory of Enhanced Reversed Shear Mode

With naturally reversed shear profiles, intrinsically steady state tokamaks can be operated in enhanced reversed shear (ERS) mode. Recent experimental observation in TFTR and ASDEX-U indicates that ERS mode is triggered by a sudden increase in the magnitude of the radial electric field E_r and followed by the turbulence suppression that leads to better confinement [9, 10]. This phenomenon implies that the bifurcation mechanism is in the momentum equation just like that in the H-mode theory [11]. We present a theory of ERS mode, based on the bifurcation of poloidal $\mathbf{E} \times \mathbf{B}$ rotation over the local maximum of the nonlinear viscosity and the subsequent turbulence suppression by the radial gradient of the $\mathbf{E} \times \mathbf{B}$ and the diamagnetic angular velocity [12]. The mechanism that drives $U_{pm} = V_{\|}/\nu_{ti} - cE_r/\nu_{ti}B_p$ away from its standard neoclassical value is the viscosity associated with the additional ion ripple loss beyond the conventional neoclassical flux. Here, $V_{\|}$

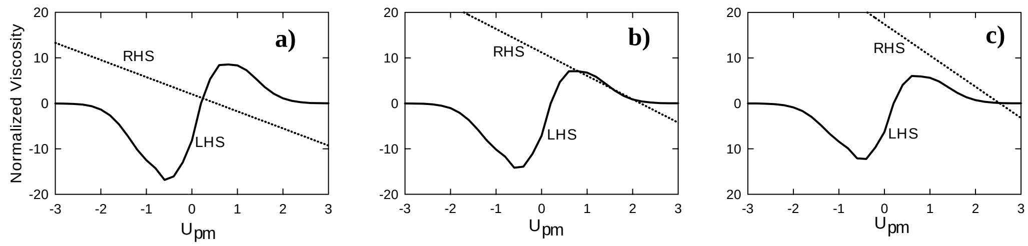

Figure 3: As ion temperature and its gradient increase, equilibrium U_{pm} increases from L–mode (a) to an intermediate state (b) and finally to ERS–mode (c)

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is the plasma parallel flow speed, ν_{ti} is the ion thermal speed, c is the speed of light, and B_p is the poloidal magnetic field strength. The theory shows that U_{pm} bifurcates from a value smaller than unity to a value larger than unity as shown in Fig. 3. The bifurcated value of U_{pm} is in good agreement with the experimental observations. This $\mathbf{E} \times \mathbf{B}$ velocity with $U_{pm} > 1$ relaxes due to profile evolution and MHD activities.

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