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# Peaked-Density Profile Mode and Improved Confinement in Helical Systems

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The difference in the effect of the peaked density profile on the improved transport between tokamaks and toroidal-helical systems is discussed. Based on the theory that the rotational shear causes the inward pinch in tokamaks, the magnitude of the possible inward pinch is estimated. Owing to the strong damping of the rotation due to the helical ripple, the anomalous inward pinch would be small. This may be consistent with recent observation in Heliotron E device that the density peakedness of $n(0)/\langle n\rangle=5$ does not correspond to the improved confinement.

Keywords: Improved Confinement, Peaked Density Profile
Anomalous Transport, Helical Systems,
Tokamaks

The anomalous transport has recently been widely known for toroidal helical systems[1-3]. The global energy confinement time $\tau_E$ has been studied and the empirical scaling law was proposed. This scaling law, similar to the L-mode in tokamaks, the strong deterioration of $\tau_E$ with respect to the heating power appears[1]. Extension of the scaling law to the parameters of the reactor-grade plasma was studied, and it was found that the present scaling law will be an obstacle in achieving the break-even condition[2]. The reduction of the anomalous loss is the most urgent issue for the programme of toroidal helical systems.

The improved confinement modes have been investigated in tokamaks. One of the most successful achievement is the H-mode[4]. The other class of the improved mode has recently been also found by proper control of particle sources; the Pellet-mode[5], the Supershots[6], the IOC mode[7], the IL-mode[8] and the counter NBI mode[9]. These modes are characterized by the inward pinch of particles and peaking of the density profile. The peaking of the density has been known to correspond to the improvement of $\tau_E$ in tokamaks. The mechanism has not been clarified yet; it is the phase of research where the working hypothesis is proposed[10] and will be tested in experiments.

The questions whether the density peaking can be realized and whether the density peaking causes the improved confinement in helical systems are issues to deserve investigations. On one hand, this is an experimental method to look for the improved confinement mode. On the other hand, an answer to the questions provides a touchstone to test the model of inward pinch in tokamaks.

Recent experiment on Heliotron E device (toroidal helical device with the pitch number m=19 and the multipolarity $\ell$=2, the aspect ratio R/a=11) has shown that the peaked density profile can be realized by NBI or pellet up to the level of n(0)/<n>=5 (n is the electron density). Although this peaked value is realized, $\tau_E$ is almost on the same scaling as the flatter density profiles[11]. At present, the peaked density profile does not cause the reduction of the anomalous loss.

We in this article discuss this phenomena applying the theory of inward pinch due to the velocity shear[10]. The anomalous inward pinch is found to be weak compared to that in tokamaks. The rate of confinement improvement will be small. The strong peaking of the density profile is not predicted to be the result of the anomalous inward pinch. The localization of the source or the neoclassical effect are the candidates. This is consistent with the experimental observation that the peakedness of the density is not associated with the improvement of $\tau_E$.

An model of the inward pinch in tokamaks is based on the viscous transport of the toroidal flow. The improved confinement modes quoted above are associated with the net-inward particle flux against the density profile. Unless the other dissipation compensates this reduction of the entropy production rate, this would be in contradiction with thermodynamic law. The relation is more clearly seen by studying the equation of the entropy production rate, which is given as[12-14)

$$H = \frac{d}{dt}\int \rho S \, dV = -\int \frac{\vec{\Gamma}\cdot\nabla n}{T}\, dV - \int \frac{\vec{q}\cdot\nabla T}{T^2}\, dV$$

$$+ \int \left( \frac{\eta}{2T}\sum_{ik}\left\{\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\nabla\cdot\vec{v}\right\}^2 + \frac{\zeta}{T}(\nabla\cdot\vec{v})^2\right) dV, \qquad (1)$$

where $\rho$ is the mass density, s is the entropy per unit volume, $\Gamma$ is the particle flux, q is the heat flux, T is the temperature, $\eta$ and $\zeta$ are viscous coefficient,

$$\sigma'_{ik} = \eta\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\nabla\cdot\vec{v}\right) + \zeta\delta_{ik}\nabla\cdot\vec{v}, \qquad (2)$$

where $\sigma'$ is the viscous stress tensor, and the integral is taken over the plasma column. In the following, we consider the contribution to the RHS (right hand side) of Eq.(1) from the anomalous terms and separates from collisional terms. We assume that terms $\Gamma$, q, $\eta$ and $\zeta$ have the same origin.

The first term in the RHS of Eq.(1) is the entropy production rate due to the particle flux, the second is that due to the heat flux and the third is the contribution from the viscous momentum flow. The particle flux in the direction of the density gradient, $-\nabla n$, can be represented as

$$\Gamma = -D\nabla n + nV_{in}, \qquad (3)$$

where the observed "pinch term" $nV_{in}$ is smaller than or at most equal to the diffusion term $D\nabla n$ in usual situations. The first term in RHS of Eq.(1) is not negative, showing that the particle diffusion increases the quantity H. On the contrary, , $\Gamma$ is opposite to $\nabla n$ direction so that $-\Gamma\cdot\nabla n$ is negative in many cases of the improved mode with peaked-density profile. The term due to the heat flux also reduces or stays constant. This would be possible if the reduction of the first and second terms is compensated by the increment of the third term. Reference[10] studies the inward pinch caused by the transport of momentum across the magnetic field by the anomalous viscosity, and found that the inward pinch is possible when the rotational shear penetrates into the core plasma, being not localized near the edge.

From the thermodynamical consideration, one may evaluate the upper bound of the spontaneous inward pinch from Eq.(1). In order to keep H positive definite, the change of inward flux, $\Delta\Gamma$, must satisfy the inequality

$$\int \frac{\Delta\Gamma\cdot\nabla n}{T}\, dV \lesssim \int \left( \frac{\eta}{2T} \sum_{ik} \left\{ \frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\nabla\cdot\vec{v} \right\}^2 + \frac{\zeta}{T}(\nabla\cdot\vec{v})^2 \right) dV, \quad (4)$$

In deriving eq.(4), we assume that the energy outflux stays constant. If $-q\cdot\nabla T$ increases, the reduction of $\Gamma$ can be larger than Eq.(4). However, such a state is associated with larger energy loss, i.e., deteriorated confinement and we discard such a situation.

Without performing the variational optimization, we estimate the 0th order evaluation. Taking the typical flow velocity v (either toroidal or poloidal component) and scale length of a (minor radius), we have

$$|\Delta\Gamma|\cdot|\nabla n| \lesssim \frac{n}{2}\left(\frac{v}{a}\right)^2 \tag{5}$$

from Eq.(4). The flow is assumed to be incompressible. This result shows that the rotation (with the shear length of the order of a) must be piled up over the plasma column. In the limit that the particle source is negligible, we have $\nabla\cdot\Gamma=0$, and $\nabla n = -\Delta\Gamma/D$, where D is the diffusivity. Equation (5) reduces to

$$|\Delta\Gamma| \lesssim \sqrt{\frac{n}{D}}\,\frac{|v|}{a}, \tag{5'}$$

where a is the minor radius of the torus. Typical velocities are estimated for tokamak and toroidal helical systems as follows.

In tokamaks, the toroidal coordinate is ignorable and the poloidal rotation $U_p$ damps off. The E×B toroidal drift velocity is roughly given from the ion momentum balance equation as

$$v_t \simeq \frac{E_r}{B_p}, \tag{6}$$

and the typical electric potential difference reaches to the level of 1-2 times of $T_i(0)$.

On the contrary, the toroidal rotation damps off in the toroidal helical devices (except in the vicinity of the magnetic axis) due to the helical ripples[15]. In this case, v is evaluated as

$$v_p \approx \frac{E_r}{B_t} . \tag{7}$$

The actual value of the radial electric field, normalized to T/ea, is reported to be in the same order of magnitude in both tokamaks and helical systems[15]. The comparison of Eqs.(5')-(7) yields the upper bound of inward pinch in helical systems, which satisfies the relation

$$\Delta\Gamma(\text{hel}) \sim \frac{\mu(\text{hel})}{\mu(\text{tok})} \frac{B_p}{B_t} \Delta\Gamma(\text{tok}) \tag{8}$$

for the similar values of minor radius a and density n, where $\mu=\sqrt{\eta/D}$. The parameter dependence of $\mu$ can be different in tokamaks and helical systems depending on the origin of the anomalous viscosity. At present there is an experimental data showing that anomalous viscosity $\eta$ in helical systems is similar to that in tokamaks[15]. For the diffusivity, similar value has been reported experimentally. We therefore assume that the value $\mu$ takes the similar values in tokamaks and toroidal helical systems. We obtain

$$V_{in}(\text{hel}) \sim \frac{B_p}{B_t} \cdot V_{in}(\text{tok}) \tag{9}$$

for the same values of minor radius and density. This ratio, $B_p/B_t$, is order of 1/10 for typical plasma parameters. We expect smaller pinch effect in helical systems.

In summary we have applied the model of inward velocity of tokamaks to toroidal helical systems. In tokamaks, the poloidal flow damps heavily, but the toroidal flow can remain. The damping of toroidal rotation in tokamaks occurs owing to the real space diffusion, making the compensation of the radial particle flux. However, this process does not give large inward pinch in helical systems. In helical systems, the toroidal and poloidal flows are strongly damped by the helical and toroidal ripples. The decrease of flows reduces the possible inward pinch.

The gradient of the density may be sustained by the inward pinch and the central particle source. We take the limit that the source is negligibly small to show the role of the inward pinch clearly. In actual experiments, the density peaking is possible either by the localization of the particle source or classical flux driven by such as $\nabla T$. The peaking caused by these processes is not related to the anomalous inward pinch and hence is not associated with the improvement of the anomalous loss.

This kind of modelling suggests the importance of the measurements of the distribution of the rotational velocity. A preliminary observation in toroidal helical systems has been made in CHS torsatron device[15), awaiting the further thorough analysis.

This model predicts the way to search the improved confinement mode. If one intends to look for the peaked density modes, the retention of the rotation is essential. One way is to keep the helical symmetry instead of the toroidal symmetry. This concept has recently been studied in heliac/helias studies[16-17]. It has not been clear, whether the helical flow does not decay or not. The method to develop the configuration with the minimum rotational damping would be necessary to search the improved confinement with peaked density profile.

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