Pis'ma v ZhETF, vol.63, iss.6, pp.427 - 430

H-MODE IN TOKAMAKS CAUSED BY ABSENCE OF TRAPPED IONS IN POLOIDALLY ROTATING PLASMA

J.Nycander, V.V.Yankov[1]

Department of Technology, Euratom-NFR Fusion Association, Uppsala University
Box 534, 751 21 Uppsala, Sweden

Submitted 5 February 1996

It is proposed that the transport suppression in H-mode in tokamaks is caused by the absence of trapped ions in the transport barrier. If the poloidal Mach number $M = v_\theta B/(v_{Ti}B_\rho)$ is large there are exponentially few trapped ions. This criterion agrees with experimental observations of H-mode plasmas. The recently observed transport suppression by reversed shear also points to the dominating role of trapped particles in turbulent transport.

PACS 52.25.Fi, 52.55.Fa

In the high-confinement regime (H-mode) in tokamaks a narrow transport barrier is created just inside the last closed flux surface [1]. In this barrier the turbulent fluctuations and the anomalous transport are suppressed, and a strong radial electric field E_r appears. According to a widely accepted explanation, the turbulence is suppressed by the the shear in the $\mathbf{E}\times\mathbf{B}$-drift, which decorrelates the turbulent fluctuations [2, 3]. In this letter we suggest an alternative explanation, which depends on the magnitude, rather than the shear, of the poloidal plasma rotation.

It is observed in experiments that the poloidal Mach number $M = v_\theta B/(v_{Ti}B_\theta)$ is a critical parameter of the L-H transition, with a threshold value of order unity. If this parameter is much larger than unity, there are exponentially few trapped ions. Hence, we propose that the transport barrier is a region almost without trapped ions. The transport suppression is then a natural consequence of the hypothesis that the transport in tokamaks is normally dominated by trapped particles, as was assumed in the first review of turbulent transport in tokamaks [4]. The recently observed transport suppression by reversed magnetic shear also gives strong support for this hypothesis, as will be discussed below.

The mechanism we propose was predicted already in 1967 by Berk and Galeev [5] and Galeev et al. [6]. In these papers both the origin of the radial electric field and the suppression of the trapped particle instability [4] by this field were considered. However, as far as we are aware, this mechanism has not been discussed in connection with the L-H transition, which was discovered in 1982 [7].

We will now show that the fraction of trapped ions is determined by the poloidal plasma rotation. The radial force balance equation is

$$E_r = (nZe)^{-1}\frac{dp}{dr} - v_\theta B_\phi + v_\phi B_\theta, \tag{1}$$

where θ is the poloidal angle, ϕ the toroidal angle, and all fluid quantities refer to the ions. If we make a Galilean transformation to a system rotating in the toroidal direction with the velocity c (we neglect the centrifugal force

---

[1] Permanent address: RRC Kurchatov Institute, 123182 Moscow.

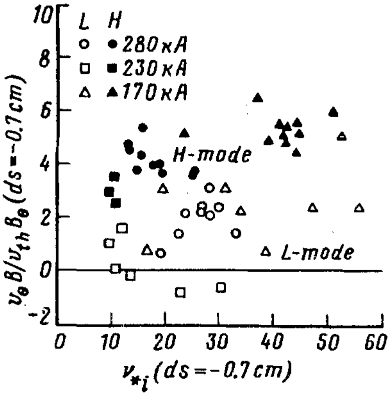
associated with the toroidal rotation), then the toriodal velocity and the electric field transform according to $v'_\phi = v_\phi - c$ and $E'_r = E_r - cB_\theta$, while the other quantities in eq. (1) are invariant.

We consider the case when the pressure gradient term can be neglected. This is justified if the characteristic length scale is larger than the ion banana width. (In the opposite case the fluid model implied by eq. (1) must be modified [8]). The fraction of trapped ions is then easily determined in the reference frame where $E_r = 0$ and $v_\theta B_\phi = v_\phi B_\theta$, i.e. v and B are parallel. If this parallel velocity is much larger than the ion thermal velocity v_{Ti}, only exponentially few ions in the Maxwell tail are trapped. The condition $v > v_{Ti}$ can be written

$$M = \frac{v_\theta B}{v_{Ti} B_\theta} > 1. \tag{2}$$

Since v_θ is invariant under Galilean transformations, this criterion can be used in any reference frame to decide whether there are only few trapped ions. From the point of view of the frame where the toroidal rotation vanishes, the effect is caused by the toroidal drift E_r/B_θ of the trapped particles, which pushes the trapped region in phase space to the tail of the Maxwellian distribution [5, 6].

The condition (2) leads to a small number of trapped ions and, consequently, to the suppression of trapped particle instabilities [4–6]. This condition agrees qualitatively with observations of H-mode plasmas. In fig (1) data from JFT-2M [9] are reproduced, where H-mode shots consistently have $M > 3$. In this experiment, however, only the rotation of impurity ions could be measured. In experiments with helium plasmas on DIII-D the rotation of the main ions was measured, and the data in fig. (4) of ref. [10] are just as clear as those in figure, with $M < 1$ in L-mode and $M > 1$ in H-mode.



Data from JFT-2M [9]. Poloidal ion Mach number M as a function of normalized ion collisionality. Open symbols stand for the L mode and closed symbols for the H-mode

Another common observation on many machines is that the turbulence and the transport in L-mode are much stronger on the outside of the torus than on the inside, and that the turbulence suppression at the L-H transition mainly affects the outside [11]. This is explained naturally by the hypothesis that the transport in L-mode is mainly caused by the trapped particles.

We do not here discuss the problem of the origin of the plasma rotation. Some authors have suggested that it is caused by particle loss at the plasma boundary [2, 8], see also the recent review [12] and references therein. This effect was predicted already in ref. [5]. Another mechanism of poloidal spin-up was considered in [13, 14]. We note that in many theories $M \sim 1$ is a critical threshold for the problem of poloidal flow generation, since the viscous force has a maximium around $M \sim 1$. For larger M the number of trapped particles, and therefore the viscosity, decrease [12].

Since the transport barrier in H-mode is very narrow, the poloidal rotation is strongly sheared. This makes it difficult to distinguish between theories that rely on the magnitude of the rotation for turbulence suppression, and those that rely on the shear. It would be easier to do this if the transport barrier was wider. Perhaps this is the case in the VH-mode observed on DIII-D and JET, which seems also to be associated with plasma rotation [15]. However, we have not been able to find published data on the poloidal rotation in VH-mode.

There are also other striking features of tokamak transport that can be explained naturally by the hypothesis that it is dominated by the trapped particles. Two such features are the particle pinch (the fact that density profiles are peaked in the center where there are no particle sources), and the correlation between q-profiles and density profiles (the peaking of the density profile increases with increasing magnetic shear). The behaviour of trapped particles is particularly sensitive to the q-profile since the safety factor $q(r) = (rB_\varphi)/(RB_\theta)$ determines the distance between the reflection points of these particles. This distance can be estimated as qR. Here r and R are the minor and major radii, respectively. Hence, if the shear is positive, $dq/dr > 0$, as in a conventional tokamak, trapped particles that drift outward while conserving the two first adiabatic invariants μ and J will expand adiabatically along the magnetic lines. The bounce frequency and the longitudinal energy therefore decrease. The released energy can drive an instability. Parcels of trapped particles that are displaced inward by the resulting turbulence are compressed, which explains the inward pinch flux.

It can be shown that nr/B_θ is a Lagrangian invariant of the bounce averaged drift motion of trapped particles [16]. Here n is the density of trapped particles. (This conservation law means that the trapped particles are frozen inlto the poloidal field.) The turbulence drives the plasma toward a uniform distribution of this invariant, which gives the canonical profile $n(r) \sim q(r)^{-1}$ [16, 17]. This simple result fits experimental data reasonably well in the case of conventional positive shear [18–20].

A more direct indicaton of the crucial role of trapped particles for turbulent transport is the strong suppression of transport by reversed shear that has been observed in several recent experiments [21–24] and simulations [25]. This is easily understood from the fact that the energy of the trapped particles decreases inward instead of outward if the shear is reversed [26]. Hence, if the pressure profile is peaked in the center the trapped particles are in a minimum energy state, which is leads to stability. (In TFTR the particle and ion thermal diffusivities dropped by as much as a factor 40 in the central region with reversed shear, down to below the neoclassical level [24]. This could perhaps be explained by the elimination of trapped particles; however, rotation was not measured in this experiment.)

We conclude that the hypothesis that the turbulent transport (like the collisional transport) is dominated by trapped particles gives simple and natural explanations of several observed features: the H-mode is explained by the absence of trapped ions in the transport barrier, the particle pinch and the canonical profiles are explained by the compression of trapped particles as they drift inward when the shear is positive, and the transport suppression by reversed shear is a result of the trapped particles being in a minimum energy state.

The difference between the conventional theory of turbulence suppression (by sheared rotation) and the one suggested here (relying on the magnitude of the rotation) is important for the future prospects for a fusion reactor. If the width of the transport barrier increases, the conventional mechanism requires a larger velocity, while the present one does not. It makes it feasible to get wider transport barriers, like the V-H-mode and the transport barrier at the $q = 3$ surface [27]. New methods of poloidal flow generation may also be developed, for example by forcing the plasma with a poloidally rotating magnetic field.

Unfortunalely, it is difficult to reverse the shear globally because of the low conductivity of the boundary plasma. Perhaps a combined regime with reversed shear in the internal zone and turbulent suppression by poloidal rotation in the zone with conventional positive shear could be globally free from turbulent transport. If this is true, break-even and, perhaps, ignition can be reached in tokamaks of the present size, with the additional advantages of a large share of bootstrap current and high beta operation.

This work has been supported by the Russian State Program "Fundamental Problems of Nonlinear Dynamics", and by the European Communities under associated contract between Euratom and the Swedish Natural Science Research Council (NFR), Grant Nos. F- AA/FU/GU 09917-311 and F- AA/FU/GU 09917-312. This work was completed while V.V.Y. was a guest at the Department of Technology in Uppsala. He is grateful to the Swedish Institute for the support that made this possible.

---

1. R.J.Groebner, Phys. Fluids B **5**, 2343 (1993).
2. K.C.Shaing and E.C.Crume, Phys. Rev. Lett. **63**, 2369 (1989).
3. H.Biglari, P.H.Diamond, and P.W.Terry, Phys. Fluids B **2**, 1 (1990).
4. B.B.Kadomtsev and O.P.Pogutse, In: *Reviews of Plasma Physics*, Ed. M.A.Leontovich, Consultants Bureau, New York, 1970 **5**, p. 249.
5. H.L.Berk and A.A.Galeev, Phys. Fluids **10**, 441 (1967).
6. A.A.Galeev, R.Z.Sagdeev and H.V. Wong, Phys. Fluids **10**, 1535 (1967).
7. F.W.Wagner, G.Becker, K.Behringer et al., Phys. Rev. Lett. **49**, 1408 (1982).
8. F.L.Hinton and Y.-B.Kim, Phys. Plasmas **2**, 159 (1995).
9. K.Ida, S.Hidekuma, M.Kojima et al., Phys. Fluids B **4**, 2552 (1992).
10. K.H.Burrell, T.N.Carlstrom, E.J.Doyle et al., Plasma Phys. Control. Fusion **34**, 13 (1992).
11. T.L.Rhodes, R.J.Taylor et al., Nucl. Fusion **33**, 1787 (1993).
12. K.Itoh and S-I Itoh, Plasma Phys. Control. Fusion **38**, 1 (1996).
13. T.E.Stringer, Phys. Rev. Lett. **22**, 1770 (1969).
14. A.B.Hassam and T.M.Antonsen, Phys. Plasmas **1**, 337 (1994).
15. K.H.Burrell, E.J.Doyle, P.Gohil et al., Phys. Plasmas **1**, 1536 (1994).
16. V.V.Yankov, JETP Lett. **60**, 171 (1994).
17. J.Nycander and V.V.Yankov, Phys. Plasmas **2**, 2874 (1995).
18. V.V.Yankov, Plasma Physics Reports **21**, 719 (1995).
19. M.B.Isichenko, A.V.Gruzinov and P.Diamond, Phys. Rev. Lett. **74**, 4436 (1995).
20. V.V.Yankov and J.Nycander, Phys. Rev. Lett. **75**, 3582 (1995).
21. M.Hugon, B.Ph. van Milligen, P.Smeulders et al., Nucl. Fusion **32**, 33 (1992).
22. E.A.Lazarus, L.L.Lao, T.H.Osborne et al., Phys. Fluids B **4**, 3644 (1992).
23. E.J.Strait, L.L.Lao, M.E.Mauel et al., Phys. Rev. Lett. **75**, 4421 (1995).
24. F.M.Levinton, M.C.Zarnstorff, S.H.Batha et al., Phys. Rev. Lett. **75**, 4417 (1995).
25. C.Kessel, J.Manickam, G.Rewoldt, and W.M.Tang, Phys. Rev. Lett. **72**, 1212 (1994).
26. J.Nycander and V.V.Yankov (to be published).
27. Y.Koide, M.Kikuchi, M.Mori et al., Phys. Rev. Lett. **72**, 3662 (1994).