Pis'ma v ZhETF, vol. 77, iss. 9, pp. 587 – 589 © 2003 May 10

Improvement of confinement in tokamaks by weakening of poloidal magnetic field near boundary

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Submitted 2 April 2003

Theory of turbulent equipartition and experiment indicate that density, pressure, and temperature profiles follow to poloidal magnetic field profile. Therefore it is suggested to change magnetic geometry between core and boundary by toroidal conductors and/or plasma current. As a result density and temperature gradients will become steeper, and stored energy will be higher with low boundary plasma parameters. Suggested new mode of confinement may essentially simplify achieving of ignition.

PACS: 52.55.–s

Turbulent transport remains a major obstacle to achieving controlled nuclear fusion. Despite several decades of experimental and theoretical efforts even the nature of the transport remains unclear. This paper suggestion is based on many experimental observations [1 – 5] and theoretical arguments [6 – 10] that plasma pressure and density profiles depend on the safety factor profile. Explanation of the dependence from safety factor profile was reached during last 10 years with theory of turbulent equipartition (TEP), based on the dominant role of trapped particles [11]. TEP theory describes only a turbulent attractor (density profile, and, with lesser accuracy, pressure and temperature profiles) using a Lagrangian invariant, see [6, 7]. TEP theory explains phenomenon of canonical or resilient profiles in line with [12] and has common features with concept of marginal stability [13]. TEP theory is limited and says nothing about unstable modes or heat flux, but unstable modes and heat flux are necessary for calculating of profiles, which are given by the TEP attractor directly. TEP is sufficient to design "turbulent part" of tokamak.

In the first approximation, tokamak plasma is frozen in poloidal magnetic field only. To be more exact, theory argued that toroidal and poloidal components of the frozen-in law decay with different rate on the turbulent transport time scale, which makes turbulent convection possible and leads to TEP profiles. Since angular magnetic momentum and angle are drift Hamiltonian canonical variables, TEP density profile is a plateau

$$dN/dM = \text{const} \tag{1}$$

on the distribution function of the angular magnetic momentum $M = eAr$, where e is a particle charge, A is the toroidal component of vector potential of poloidal magnetic field, r is radius measured from main axis of tokamak, and N is a number of particles inside a magnetic surface $M =$ const. Since particle density is by definition $n = dN/dV$, where V is volume inside a magnetic surface, the density can be rewritten as

$$n \sim dM/dV. \tag{2}$$

In small aspect ratio tokamaks the TEP density profile may be expressed as a function of the well known safety factor $n \sim 1/q$.

TEP had resolved an impressive paradox of particle pinch, long ago observed in all tokamaks. Correlation of the pinching and boundary safety factor was found in [1, 2]. The pinch paradox is that density profiles has strong maximum at the center while the source of the particles is at the periphery.

In tokamaks plasma temperature could be estimated with empirical 1D adiabatic law

$$T \sim n^2 \sim (dM/dV)^2, \tag{3}$$

perhaps, because electrostatic drift changes mostly longitudinal energy of the trapped particles. Thus TEP gives density, temperature, and pressure plasma profiles, while real profiles should be flatter than the ideal TEP profiles. There are many experimental indications that pressure attractor is more stiff than density and temperature attractors. It is a natural property of the marginal stability, since instabilities are driven by pressure gradients [13]. Stronger stiffness of the pressure attractor explains flattening of the density profile during strong central heating in T-10 [14], since density flatness compensates for increased temperature peakedness. It explains also paradoxical growth of the central temperature during plasma injection at the boundary [15, 16] by compensation of density flatness with temperature peakedness.

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Experiments indeed have demonstrated, that L-mode density and temperature profiles follow to profile of poloidal magnetic flux in every compared tokamak with a consistency almost excluding coincidence [7, 3, 5, 4] . Recent comparison of several hundred profiles in TCV tokamak with variable magnetic geometry is especially impressive [5, 4]. While no serious contradictions with theory were found, more massive comparison of other tokamaks is highly desirable. Basic features of H-mode and Reversed Shear mode (aka Internal Transport Barriers) are also in line with expectations of the TEP theory, since the transport barriers appear where suppression of trapped particles instabilities was predicted, [11, 17, 18, 7].

In this paper we suggest a change in the magnetic geometry, which do not suppress turbulence and do not introduce transport barriers. Instead, turbulence is used to create desirable profiles, to provide heat and impurities sink, and to tune confinement time. Plasma convection is analogues to L-mode, but particle and temperature pinch should be stronger [12], providing better isolation of the core plasma. Plasma energy should be higher with the same boundary parameters and energy flux. In accordance with formulas (2) and (3), the ratio of central to boundary pressure is given by formula

$$\frac{p_c}{p_b} = \frac{(dM_c/dV_c)^3}{(dM_b/dV_b)^3}. \tag{4}$$

As was already mentioned, experiments do not contradict to this formula, but it would be useful to extract an empirical power in this ratio from experimental data. The reason is that TEP theories [7 – 10] differ in treating of passing particles and therefore predict slightly different powers. The above ratio grows with weakening of the average boundary poloidal magnetic field, since $B_p \sim dM/dV$. There are two possibilities to improve turbulent pinch, to change plasma current or external coils currents. Both were actually used, while without reliance on TEP physics. In TFTR Supershots [19] the ratio (4) was increased by peakedness of plasma current. Boundary poloidal magnetic field may be also weakened by reversing of the toroidal plasma current between core and boundary, but control of the current profile may be difficult. A decreasing of $B_p \sim dM/dV$ by external toroidal currents looks more promising. Poloidal bays in ideally conducting vacuum chamber decrease the average poloidal magnetic field since it is evidently weaker in the bays. The same magnetic geometry can be provided by coils instead of chamber currents. Poloidal magnetic fields of the bays may or may not include X-points. X-points lead to a logarithm divergency of dV/dM near separatrix, where the model does not valid. Divertor tokamaks have weakened poloidal magnetic field near the X-point of separatrix, and therefore JET experiments exhibit strong L-mode plasma gradients near separatrix [20] in accordance with the above formulas. Stronger effect may be achieved with a directed design of coils, but it requires a numerical code. To weaken magnetic field even stronger, the cross-section of vacuum chamber may have several bays, the number of the bays is a multiple in dV_b/dM_b.

Peakedness of the toroidal core current may be combined with bays, while excessive current peaking leads to MHD instability. Improvement of confinement by weakening of the poloidal magnetic field near boundary was observed in TFTR current ramp-down experiment [21]. While the improvement is not sustainable, it supports suggested tokamak design.

To calculate energy confinement time we have all but connection of boundary plasma parameters with the energy flux. The gain coefficient for core plasma pressure against conventional L-mode could be introduced, according to ratio (4). If boundary parameters are the same, energy confinement time is proportional to the gain coefficient. The same coefficient describes lowering pressure at the edge if central core parameters are fixed. Suggested bays may improve energy confinement several times, more reliable number requires simulation of poloidal magnetic field with a 2D code. In the presented ideal model the theoretical gain (4) is unlimited, while after some improvements TEP should be violated by sharp gradients or something else. Note, that the discussed effects were theoretically studied in a dipole trap more rigorously [13], because convection in a dipole trap can be described by MHD. Any improvements at the camera wall, like use of Lithium, [22], are complimentary to the suggested improvement.

Conclusion. Experiment and theory point to plasma pressure dependence from the safety factor. While the exact dependence is not known, TEP profiles of L-mode can be made more peaked with additional toroidal conductors and corresponding change of shape of vacuum chamber. The suggested new mode of confinement is beneficial in several ways: 1) it improves plasma isolation thus lowering the auxiliary heating and the size of facility necessary to reach ignition; 2) TEP profiles are resilient and therefore more predictive than transport barriers; 3) turbulent mixing prevents accumulation of helium and impurities in the core plasma, simultaneously delivering hydrogen to the core; 4) turbulence provides a controlled heat sink in ignited plasma; 5) this new mode of confinement does not require essentially new equipment.

While the idea of improving magnetic confinement by weakening of the magnetic field looks paradoxical, it deserves experimental testing.

The same idea may be applied to quasi-helical (quasi-symmetrical) stellarator.

I am grateful to K. A. Razumova for many fruitful discussions. I would like to acknowledge Lyudmila Fomenkova for support, love and nourishment.

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