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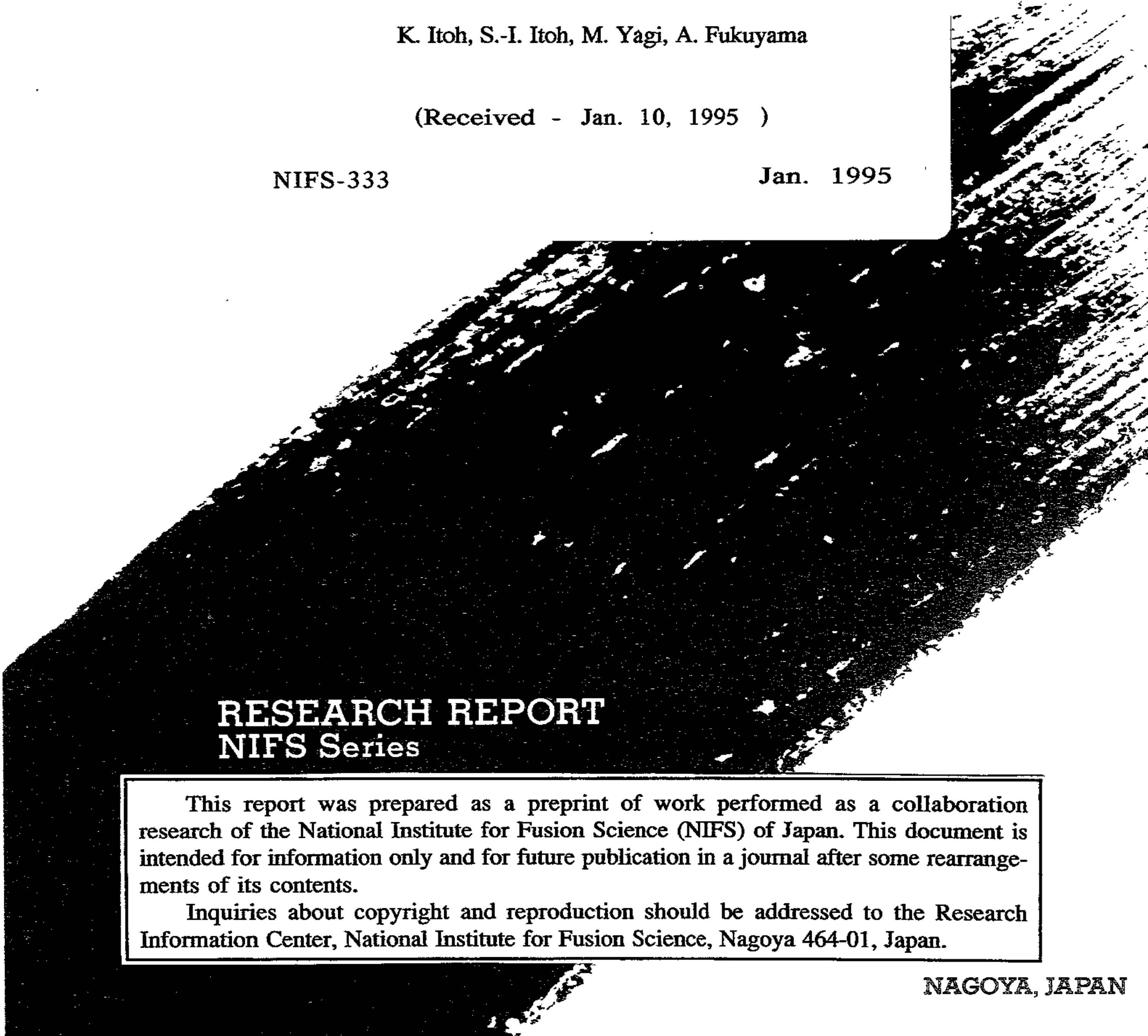

RESEARCH REPORT
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Theory of Anomalous Transport in Reverse Field Pinch

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Abstract

The transport coefficient for the magnetized plasma, which has been obtained by use of the method of self-sustained turbulence, is applied to the reverse field pinch (RFP). The dependence $\beta_p \propto n^{3/4}/I_p$ is obtained (β_p: plasma pressure divided by the poloidal magnetic pressure, n: plasma density and I_p: plasma current). This result gives an explanation of the experimental observation of the RFP scaling, $\beta_p \propto n/I_p$. The theory of anomalous transport unifies the L-mode scaling laws in the tokamaks, stellarators and Heliotron/torsatron as well as RFP.

Keywords: reverse field pinch, anomalous transport coefficient, self-sustained turbulence, magnetic braiding, L-mode

1. Introduction

Recently, efforts have been paid for understanding of the anomalous transport coefficient in toroidal plasmas [1]. It is of vital importance from the view point of the realization of the ignited plasmas. It should also be noticed that this task is one of the most challenging problem in the modern physics [2]. Experimental observation has become abundant, and various tests for the theory of the cross field transport have been performed for tokamak plasmas [3]. The study on the stellarators has been flourished as well [4]. Comparison of the anomalous transport theory with helical plasmas further improves the physics basis for the anomalous transport phenomena. New method of the plasma turbulence and anomalous transport, i.e., the self-sustained turbulence [5], seems to provide an agreement with observations in various aspects [6]. It would also be meaningful to examine the applicability of the anomalous transport theory [5] to the confinement feature of the reverse field pinch [7].

In this article, the transport coefficient, which has been obtained for the system of magnetic hill by use of the method of self-sustained turbulence, is applied to the reverse field pinch (RFP). The nonlinear theory of the pressure driven turbulence and transport is used for RFP. The dependence $\beta_p \propto n^{3/4}a^{5/4}/I_p$ is obtained (β_p, n, a, and I_p are the plasma pressure divided by the poloidal magnetic pressure, density, minor radius and plasma current, respectively). This result gives an explanation of the experimental observation of the RFP scaling, $\beta_p \propto n/I_p$.

2. Model of the RFP

We employ the model of the high aspect ratio RFP. The cylindrical coordinate (r, θ, z) is employed. The toroidicity is neglected and the magnetic field is given by the Bessel function model [8] as

$$B_t = B_0 J_0(\zeta r),\ B_p = B_0 J_1(\zeta r) \ . \qquad (1)$$

The magnetic field is characterized by parameters B_0 and ζ. The parameter ζ is in the range of $\zeta a \approx 3$. When the plasma pressure is finite, the magnetic field structure is deviated from that in Eq.(1). However, this modification does not change much the shear parameter and the magnetic hill.

This magnetic configuration is characterized by the magnetic hill. The magnetic curvature κ is calculated from the relation

$$B^2 = B_0^2\left(J_0^2(\zeta r) + J_1^2(\zeta r)\right) \simeq B_0^2\left(1 - \frac{\zeta^2 r^2}{4}\right) \qquad (2)$$

as

$$\kappa = \frac{a}{B}\frac{dB}{dr} \simeq -\frac{\zeta^2 a\, r}{4} \qquad (3)$$

The important feature of the RFP configuration is the strong magnetic shear. We use the definition of the magnetic shear parameter s as

$$s = \left| \frac{RB_t' - \iota_s R^2 (B_p / r)'}{B_p + \iota_s R B_t / r} \right| \qquad (k_{\parallel} = 0 \text{ at } \iota = \iota_s) \qquad (4)$$

where R is the major radius. It is noted that the usual expression, $s = rq'/q$ (which assumes $qR/a>>1$, q being the safety factor), is inappropriate for RFP, since q-value vanishes in the RFP plasma at the surface of $B_t = 0$. From the definition of Eq.(4), we have the estimations of the parameter s as

$$s \simeq \frac{Rr}{B_t}\frac{d}{dr}\left(\frac{B_p}{r}\right) \simeq -\frac{1}{8}\zeta^3 R r^2 \qquad (5\text{-}1)$$

near the origin. Near the field reversal surface, we have

$$s \simeq \frac{R}{B_p} B_t' \simeq -\zeta R \qquad (5\text{-}2)$$

The radial profile of s is characterized by the parameter ζ, and s remains of the order of R/a.

3. Transport Coefficient

The transport coefficient for the system of magnetic hill has been calculated based on the method of the self-sustained turbulence [5,9]. In the presence of the magnetic braiding, the thermal transport coefficient of electrons is obtained as

$$\chi = \frac{1}{s^2}(R\beta'\kappa R/a)^{3/2}\left(\frac{c}{\omega_p}\right)^2\frac{v_A}{R}\,M \tag{6}$$

where β is the ratio of the plasma pressure to the total magnetic pressure, v_A is the Alfven velocity and ω_p is the electron plasma frequency. The coefficient M denotes the enhancement factor of the magnetic braiding to evaluate χ_e. In the electrostatic limit, we have $M = 1$, and $M \approx m_i/3m_e$ for the case of magnetic stochasticity [9].

The condition for the magnetic braiding has been obtained as

$$\beta \geq \beta_c \tag{7}$$

with the critical pressure gradient [9]

$$\beta_c \simeq \left(\frac{a}{R}\right)^2\left|\frac{s}{\kappa}\right| \tag{8}$$

From Eqs.(3) and (5), we have $\kappa \approx \zeta^2 a^2/4$ and $s \approx \zeta R$. This gives an estimate

$$\beta_c \simeq \frac{4}{\zeta^2 aR} \tag{9}$$

The condition for the magnetic braiding, Eq.(7) with Eq.(9), is satisfied in the range of our interest, $\beta_p \approx 0.2$, which was given in experimental observations.

Combining Eqs.(3), (5) and (6), an explicit formula of the thermal transport coefficient is obtained. Substituting this formula into the transport code, one may perform the simulation study as has been done for tokamaks [6]. In this article, however, we perform the study on the parameter dependence, rather than on a concrete number of the confinement time. For this purpose, we perform the zero-dimensional analysis.

Noting that shear and curvature are order unity parameter, we have the zero-dimensional dependence of $<\chi>$, by employing the estimation $\beta' \approx \beta/a$. (The brackets < > indicate the space average.) In the parameter domain of reverse field configuration, $2.4 < a\zeta < 3.5$, the ratio of the average poloidal field energy $<B_p^2/2\mu_0>$ to the total magnetic field energy, $<B^2/2\mu_0>$, takes the value in the range from 0.5 to 0.6, and is a weak function of $a\zeta$. We therefore use the approximation as $\beta \sim \beta_p/2$. By use of these simplifications we have the zero-dimensional dependence as

$$\langle\chi\rangle = g\frac{\langle T\rangle^{3/2}}{\langle B_p\rangle^2 a} M \tag{10}$$

where

$$g = \frac{3^{3/2} m_e}{m_i^{1/2} e^2} \frac{\kappa^{3/2} R^2}{s^2 a^2} \tag{11}$$

and $T_i \approx T_e$ is assumed. The coefficient g includes the parameter ζ and is expressed by universal constants. The estimation of the shear parameter s and the magnetic curvature was given as $s = \zeta R$ and $\kappa = \zeta^2 a^2/4$. With this estimation the parameter g is evaluated as

$$g \simeq \sqrt{\frac{3}{m_i}} \frac{3m_e}{8e^2} \zeta a \tag{12}$$

4. Energy Balance and Confinement

The energy balance equation for the Ohmic heating plasma is given as

$$\langle\chi\rangle a^{-2}\langle n\rangle\langle T\rangle \simeq \langle\eta\rangle\langle J\rangle^{2} \qquad (11)$$

where η is the resistivity and J is the current density. We write the resistivity as

$$\eta = \eta_{0} Z_{eff} T^{-3/2} \qquad (12)$$

where η_0 is the universal constant and Z_{eff} includes both the effects of impurity collision and possible anomalous resistivity due to plasma turbulence.

From the energy balance equation (11) and resistivity coefficient (12), we have

$$\langle\chi\rangle\langle n\rangle\langle T\rangle^{5/2} = \frac{\eta_{0}}{\mu_{0}^{2}} Z_{eff}\langle B_{p}\rangle^{2} \qquad (13)$$

Combining Eqs.(10) and (13), we have

$$T^{4} = \hat{g}\, Z_{eff}\frac{aB_{p}^{4}}{n}\frac{1}{M} \qquad (14)$$

where $\hat{g} = \eta_0/g\mu_0^2$, and the bracket < > is suppressed for the simplicity.

From Eq.(14), we have the scaling of the temperature

$$T = \hat{g}^{1/4} M^{-1/4} Z_{eff}^{1/4} a^{1/4} B_{p} n^{-1/4} \qquad (15)$$

or

$$T \propto Z_{eff}^{1/4} a^{-3/4} I_{p} n^{-1/4} \qquad (16)$$

The poloidal beta value has the dependence $\beta_p \propto nTB_p^{-2}$. The scaling of the temperature (16) provides that for the poloidal beta as

$$\beta_p \propto M^{-1/4} Z_{eff}^{1/4} a^{-1/4} N^{3/4} I_p^{-1} \tag{17}$$

where N is the number per unit length, $N = na^2$.

The energy confinement time is estimated as $\tau \approx a^2/\chi$. From the estimates of Eqs.(10) and (16), we have the scaling of the energy confinement time as

$$\tau \propto M^{-5/8} N^{3/8} I_p^{1/2} a^{11/8} \tag{18}$$

The fusion triple product $n\tau T$ scales as

$$n\tau T \propto M^{-7/8} n^{9/8} I_p^{3/2} a^{11/8} \tag{19}$$

5. Comparison with Experiments

These results are compared with experimental observations.

(i) β_p scaling

It has been widely discussed that the experimental observation is summarized in a form as [7]

$$\beta_p \propto N / I_p \tag{20}$$

There is some dispersion in experimental reports. Some variation has been reported in [10] as

$$\beta_p \propto N^{0.6} I_p^{-0.6} \qquad (21)$$

(TPE-1M20) or

$$\beta_p \propto N^{0.5} I_p^{-1.2} \qquad (22)$$

(MST, HBTX-1B). The result, which is in the range of Eqs.(20) to (22), seems to agree with theoretical result Eq.(17) even if one considers the experimental variations.

(ii) T_e scaling

The dependence of the electron temperature has been studied, and a summary was proposed as [11]

$$T \propto I_p^{0.8} n^{-0.2} \qquad (23)$$

(REPUTE). This agrees well with theoretical prediction Eq.(16).

6. Summary

The theory of anomalous transport, based on the method of the self-sustained turbulence, is applied to the RFP plasma. The RFP configuration is characterized by the magnetic hill, so that the formula of the interchange turbulence is used. Owing to the high beta value, the magnetic braiding is possible in the self-sustained turbulence. This effect appears as the enhancement factor M. The theory provides the dependencies as $T \propto Z_{eff}^{1/4} a^{-3/4} I_p n^{-1/4}$ and $\beta_p \propto Z_{eff}^{1/4} a^{-1/4} N^{3/4} I_p^{-1}$. The experimental observation supports this prediction. The theory of self-sustained turbulence and anomalous transport unifies the L-mode scaling laws in the tokamaks, stellarators and Heliotron/torsatron as well as the experimental scaling law in

RFP. This result provides a prospect of the RFP confinement based on the first-principle study of the anomalous transport coefficient.

The theory of anomalous transport has also provided the level of magnetic turbulence [9]. The measurements on the fluctuations as well as the fluctuation-driven transport have made progress recently [12,13]. It would be fruitful, in future, to compare the prediction of the fluctuation level to the experiments.

The anomalous resistivity is often referred to in the RFP plasmas. Our theory predicts that β_p depends weakly on Z_{eff}. Therefore the possible role of the non-classical resistivity in the Ohmic heating term does not influence our conclusion much.

The magnetic braiding in the RFP reduces the absolute values of the energy confinement time and beta value. However this does not alter the dependence on n and I_p. It is also noted that the thermal conductivity for the ions is $1/\sqrt{M}$ times smaller than that of electrons [9]. This theory naturally provides the explanation that the ion energy confinement is much better than that of electrons. The quantitative evaluation of the energy confinement time is possible by performing the transport simulation. More realistic form of the magnetic field would be necessary for the detailed comparison with experiments. These are left for future study.

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