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**PRINCETON UNIVERSITY
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**THEORY DIVISION
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I. Transport in a Stochastic Magnetic Field

R. B. White, J. M. Rax¹, and Yanlin Wu

Collisional heat transport in a stochastic magnetic field configuration¹⁻³ is investigated. Well above stochastic threshold, a numerical solution of a Chirikov-Taylor model shows a short time nonlocal regime, but at large time the Rechester-Rosenbluth effective diffusion is confirmed.⁴ Near stochastic threshold, in addition to the short time nonlocal regime, subdiffusive behavior is observed for an extended period, but the very long time behavior is diffusive. The nature of this subdiffusive behavior is understood in terms of orbits experiencing long time trapping near islands. This trapping, and the spectrum of islands in the stochastic sea determine both the subdiffusive behavior and the regular diffusive regime.

A three dimensional toroidal magnetic field is a Hamiltonian system, and the existence of magnetic surfaces in an axisymmetric configuration is a consequence of the K.A.M stability theorem. The occurrence of small resonant magnetic field perturbations can lead to the onset of chaotic field line diffusion, provided that the Chirikov criterion is fulfilled.¹ This deconfinement mechanism is a major candidate to explain the anomalous confinement properties of Tokamak discharges.^{2,3}

Recently a large number of physical problems have displayed anomalous mean-squared displacement^{5,6}: $\langle r^2(t) \rangle \sim t^\alpha$ or $\langle r^2(t) \rangle \sim \log^\beta(t)$. The exponent α , characterizing the fractional Brownian motion, can be larger or smaller than one, with trapping or long ballistic flights often the cause of this subdiffusive or hyperdiffusive transport. On the other hand the occurrence of logarithmic behavior is often due to trapping.

Because of its potential to explain anomalous confinement, heat transport in a stochastic magnetic field has been intensively investigated. Besides the thermal Larmor radii four length scales are relevant: the collisional mean free path along the magnetic field λ_c , the longitudinal and transverse autocorrelation lengths of the perturbing magnetic field, $\lambda_{||}$ and $\lambda_{\perp}$, and the Lyapunov length λ_k associated with the Kolmogorov entropy.⁷

The existence of a finite λ_k allows description of the dynamics of a heat pulse in terms of combined collisional diffusion and exponential Lyapunov stretching, resulting in an effective diffusion $\langle r^2(t) \rangle = 2 D_{RR} t$ first obtained

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by Rechester and Rosenbluth² and Stix,³ and recently numerically confirmed by Rax and White.⁴

To set up a numerical simulation we consider the Chirikov-Taylor model. A Lagrangian representation of an Eulerian anisotropic heat flow along and across this magnetic configuration is achieved by adding a random reversal of the velocity v , along z correlated with a cross field displacement of gyroradius ρ . The Poincare section of such a dynamics for $v_t = 1$ is :

$$z_{t+1} = z_t + v_t \quad (1)$$

$$y_{t+1} = y_t + x_{t+1} \quad (2)$$

$$x_{t+1} = x_t + \varepsilon \sin(y_t) + \rho_t \quad (3)$$

and for $v_t = -1$ the map must be inverted so that for $\rho_t = 0$ a particle retraces its path back along the field line. The sign of v_t for each particle is changed each time step with probability P producing diffusive motion in z .

A collisional displacement ρ_t of magnitude ρ and random sign is given to x on those time steps that v_t changes sign. To achieve statistical accuracy typically 10^5 particles are used. To calculate the diffusion in z , consider N_0 particles initially at $z = 0$. After t steps, the number of particles which have not yet suffered a collision is $N_t = N_0(1 - P)^t$. The parallel mean free path is then $\lambda_c = \Sigma t(1 - P)^t / q(1 - P)^t = (1 - P)/P$, and the parallel diffusion is $\chi_{||} = (1 - P)/2P$. The cross field, or classical diffusion has step size ρ and occurs each time step with probability P , giving $\chi_{\perp} = .5 \rho^2 P$. The field line diffusion χ_M , autocorrelation length $\lambda_{||}$, and the Lyapunov length λ_k are determined numerically. For large ε , the magnetic diffusion and Lyapunov length can be determined using random phase approximation giving $\chi_M = \varepsilon^2/4$ and $\lambda_k = (\ln(\varepsilon/2))^{-1}$, which are commonly referred to as the quasilinear values.

The results of our simulations can be summarized as follows. The long time behavior is found to be diffusive, $\langle x^2(t) \rangle = 2 D_{eff} t$, with an effective diffusion coefficient D_{eff} in complete agreement with D_{RR} .

Excellent agreement is obtained with the single constant $k = .5$ for very large ranges of P, ρ , and ε . Some results are shown in Fig. 1.

Besides this effective diffusion regime we have also observed subdiffusive behavior at short time. Since the motion along the field line is diffusive, $\langle z^2(t) \rangle = 2 \chi_{||} t$, and the field lines diffuse in x , the combination gives

Figure 1: (a) $D(\epsilon)$ for $\rho = 10^{-8}$, $P = .1$; Numerical +, RR o, Quasilinear Δ . (b) island spectrum near threshold.

$\langle x^2(t) \rangle \simeq 2 \chi_M \sqrt{2 \chi_{||} t}$. For short times this subdiffusive behavior dominates over the collisional diffusive motion, and can be important over short distance scales.

Of particular interest for magnetic confinement is the behavior near stochastic threshold, a probable state of magnetic fields in tokamak devices.⁸⁻¹⁰ In addition to the early nonlocal $\langle x^2 \rangle \sim \sqrt{t}$ behavior we observe for an extended period of time subdiffusive behavior of logarithmic type, $\langle x^2(t) \rangle \simeq \log(t)$.

A random walk can always be decomposed as a set step/pause/step/pause and so on. To calculate the mean square displacement as a function of time we have to know two basic quantities, namely the distribution function of step size and the waiting time distribution at the pause. Extensive numerical analysis reveals that near stochastic threshold wandering closely around an island corresponds to the pause and the island size the step.

The spectrum of island size is found to have two regimes. For small islands the distribution of islands is a fat fractal, and our results confirm those of Umberger and Farmer.¹¹ For larger islands the scaling is quite different. Shown in Fig. 1 is the total area $A(s)$ of all islands with size greater than s near threshold, $\epsilon = 1.1$.¹²

The island size spectrum in the large island domain and the trapping time determine the value of the near-threshold diffusion constant, which can be orders of magnitude smaller than the quasilinear value both in the collisional

and collisionless case.

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II. Numerical Simulation of Bootstrap Current

Yanlin Wu and R. B. White

Many authors have investigated the bootstrap current, including analytical studies of the dependence on aspect ratio¹⁻³ and collision frequency.⁴ A clear confirmation of the bootstrap current has also been found in several different experiments.^{5,6} In this paper, numerical simulations as well as analytic estimates are used to investigate the neoclassical bootstrap current theory. The effects of toroidal field ripple, and magnetic and electrostatic perturbations in low and high β equilibria are investigated.

Consider an axisymmetric equilibrium of arbitrary aspect ratio, shape, and plasma pressure. By solving the Collisional-Drift-Kinetic equation, we get the bootstrap current density:

$$j_b = -f_t R_0 T_e \frac{dn(\psi_p)}{d\psi_p} \quad (1)$$

where f_t , the trapped particle fraction, is

$$f_t = \frac{\langle R \rangle}{R_0} - \frac{3}{4} \frac{\langle B^2 R \rangle}{B_{\max}^2 R_0} \int_0^1 \frac{u du}{\langle \sqrt{1 - \frac{B}{B_{\max}}} u \rangle} \quad (2)$$

where ψ_p is poloidal flux and $\langle \dots \rangle$ means flux surface average.

The analytic calculation of bootstrap current j_b thus requires the calculation of the trapped particle fraction f_t . In the ideal (i.e. low β , circular profile) case, the expression for bootstrap current is:

$$j_b = -(1.6 \sqrt{r} - .6 r) \frac{T_e}{B_\theta} \frac{dn(r)}{dr} \quad (3)$$

In the presence of significant plasma pressure or elongation of the equilibrium, the flux surfaces are more complex, and the calculation of f_t is not tractable analytically. In these cases, we numerically calculate f_t from the given numerical equilibrium.

If toroidal symmetry is broken due to magnetic or electrostatic field perturbations, banana orbits do not close, and the gap can be calculated directly from the equations of motion. If the perturbation is sufficiently large so that the gap is comparable to the banana width W_b , the co- and counter-moving

Figure 1: (a) Comparison of f_t by Hazeltine (Dashed), by Hirshman (Solid) and by Wu and White (Dotted). (b) j_b from theory and simulations for low and high β equilibria.

banana orbits are no longer correlated with a density differential given by a banana width, and the bootstrap current is destroyed. We discuss primarily the effect of static perturbations. Fluctuating perturbations will have even larger effects if frequencies exceed the bounce frequency.

Consider the effect of the magnetic perturbations on the particle orbits. After a straightforward calculation, we find that a banana orbit fails to close in one bounce time by an amount $\Delta_m \simeq \sum_{m=nq(r)} \pi m q r \alpha_{mn} / r$. By requiring $\Delta_m \geq W_b$, we get

$$\frac{\delta B_r}{B_0} \geq \sqrt{\frac{M}{2}} b_{mn} = \sqrt{\frac{2M}{r}} \frac{\rho}{\pi} \quad (4)$$

Here M is the total number of Fourier components. This gives a value of $\delta B_r / B_0$ for typical tokamak parameters of about 10^{-4} . Note that these results are for mode spectra with the modes of equal amplitude. Slightly different values would be obtained with other choices.

Note that this criterion is more stringent than that required for significant modification of neoclassical transport (A diffusion rate 10 times the neoclassical rate). Numerical simulations show that the later case has a lower threshold.^{7,8} That is why we can have both bootstrap current and anomalous transport simultaneously in tokamak discharges. We also find the critical $\delta\Phi/T_e$ to be a few percent for electrostatic perturbation.

Numerical simulations are carried out using a Hamiltonian guiding center

code which has been previously described.⁹ A Monte Carlo pitch-angle collision operator developed by Boozer and Kuo-Petravic¹⁰ is used. Thus we directly simulate only the electron contribution to the bootstrap current caused by collisions with cold background ions. The effects of electron-electron collisions are ignored and the electron temperature T_e is taken as constant for simplicity. A direct comparison with experiment requires the inclusion of the ion contribution. Nevertheless, the study of the electron contribution alone permits examination of dependence on aspect ratio, plasma shape, and collisionality and is thus of considerable interest. The bootstrap current is measured locally. An initial Monte Carlo particle distribution is produced with a triangular density profile, extending from ψ_1 to ψ_2 , centered at $\psi = \psi_0$ with $\psi_1 < \psi_0 < \psi_2$ and $|\psi_2 - \psi_1| \ll \psi_0$, uniformly distributed in pitch λ , and in θ , and ζ . Each particle is advanced in time using the guiding center equations. Once a particle exits from the domain, it is reinserted at ψ_0 with λ, θ, ζ random. The particles are advanced in time to produce a steady state density distribution. The velocity distribution is Maxwellian generated using Monte-Carlo techniques. The run time, and the time for a particle to diffuse through the domain of interest, are chosen to be at least a few collision times so that there is enough time for equilibration between trapped and passing populations. Typically 10^4 particles are used and the domain ψ_1, ψ_2 extends over 20 banana widths. After collisional equilibration steady state is achieved with approximately constant density gradient, positive for $\psi < \psi_0$ and negative for $\psi > \psi_0$. Associated bootstrap currents are produced in each domain opposite in sign, allowing the independent determination of both bootstrap current and Ohmic current in the case of an applied toroidal electric field.

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III. Theory Publication List for April – June 1993

Abe, H., and H. Okuda, *Computer Simulation on the Linear and Nonlinear Propagation of the Electromagnetic Waves in the Dielectric Media*, to appear in Optics Letts., January 1, 1994 issue and PPPL Report 2928 (August, 1993).

Artun, M., J.W. Reynders, and W.M. Tang, *Integral Eigenmode Analysis of Shear Flow Effects on the Ion Temperature Gradient Mode*, Phys. Fluids B **5**, 4072 (1993) and PPPL Report 2926 (July 1993).

Bernabei, S., R. Bell, M. Chance, et al., *Experimental Exploration of Profile Control in the Princeton Beta Experiment – Modified (PBX-M) Tokamak*, Phys. Fluids B **5**, 2562 (1993) and PPPL Report 2905 (May 1993).

Biglari, H., and P.H. Diamond, *A Mean Field Ohm's Law for Collisionless Plasmas*, Phys. Fluids B **5**, 3838 (1993) and PPPL Report 2919 (June 93).

Bowman, J.C., J.A. Krommes, and J. Ottaviani, *The Realizable Markovian Closure. 1. General Theory with Application to Three-wave Dynamics*, Phys. Fluids B **5**, 3558 (1993).

Bussac, M.N., R.B. White, and L. Zuppiroli, *Particle and Heat Transport in a Partially Stochastic Magnetic Field*, **Proceedings of the 20th European Conference on Controlled Fusion and Plasma Physics**, Lisbon, Portugal, July 26-30, 1993.

Chan, A., M. Xia, and L. Chen, *Anisotropic Alfvén Ballooning Modes in the Earth's Magnetosphere*, accepted in J. Geophys. Res. Space Phys. and PPPL Report 2911 (May, 1993).

Chen, L., and A. Hasegawa, *Kinetic Theory of Geomagnetic Pulsations 2. Ion Flux Modulations by Transverse Waves*, J. of Geophys. Res. Space Phys. (in press) and PPPL Report 2927 (July 1993).

Fisch, N., and J.-M. Rax, *Free Energy in Plasmas Under Wave-induced Diffusion*, Physics of Fluids B **5**, 1754 (1993) and PPPL Report 2901 (May, 1993).

Hammett, G., M.A. Beer, W. Dorland, S.C. Cowley, and S.A. Smith, *Development in Gyrofluid Approach to Tokamak Turbulence Simulations*, PPPL Report 2918 (June 1993).

Krommes, J.A., and G. Hu, *General Theory of Onsager Symmetries for Perturbations of Equilibrium and Nonequilibrium Steady States*, Phys. Fluids B **5**, 3908 (1993).

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Taylor, G., M.G. Bell, and H. Biglari, *Ion Cyclotron Range of Frequency Heating on the Tokamak Fusion Test Reactor*, Phys. Fluids B **5**, 2437 (1993) and PPPL Report 2917 (June, 1993).

Tsai, S.-T., and L. Chen, *Theory of Kinetic Ballooning Modes Excited by Energetic Particles in Tokamaks*, Phys. Fluids B **5**, 3284 1993 and PPPL Report 2907 (May, 1993).

White, R.B., J.-M. Rax, M.N. Bussac, and L. Zuppiroli, *Transport Near Stochastic Threshold*, **Proceedings of Transport, Chaos, and Plasma Physics** Marseille, France, July 5-9, 1993 (to be published).

Wu, Yanlin, *Numerical Simulation of Bootstrap Current*, Phys. Fluids B **5**, 3291 (1993) and PPPL Report 2906 (May, 1993).

Zonca, F., and L. Chen, *Theory of Continuum Damping of Toroidal Alfvén Eigenmodes in Finite- β Tokamaks*, Phys. Fluids B **5**, 3668 (1993) and PPPL Report 2908 (May, 1993).

IV. Theory Visitors for April 1993 – June 1993

Braams, Bastiaan, Courant Institute, New York University, 1 day per week visitor in 1993.

Hellberg, Manfred, University of Natal, Durban, South Africa, June 28, 1993.

Kasuya, Koichi, Tokyo Institute of Technology, Yokohama, Japan, June 25–26, 1993.

Maschke, Eric, Department of Recherches sur la Fusion Controlée, Centre D'Etudes Nucleaires de Cadarache, Cedex, France, April 5–6, 1993.

Rath, Sharadini, Jet Propulsion Laboratory, Pasadena, CA, May 28–June 12, 1993.

Rayevski, Dimitri, NYU, Courant, May 3,10,17,25 and June 3,10, 1993.

Salas, Angel, CIEMAT, Madrid, Spain, June 17–August 13, 1993.

Song, Hao, Columbia University, New York, June 15, 1993.

Wang, Caiyi, Columbia University, February 1992–May 1993.

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