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Self-Sustained Magnetic Braiding in Toroidal Plasmas

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Abstract

Theory for the magnetic braiding in toroidal plasmas, which is caused by microscopic pressure-gradient-driven turbulence, is developed. When the pressure gradient exceeds a threshold, the self-sustaining of the magnetic braiding and enhanced anomalous transport occur. The balance between the nonlinear destabilization and nonlinear stabilization, which determines the stationary turbulence, is solved analytically for the case of interchange mode. The enhanced thermal conductivity and magnetic perturbation amplitude as well as the threshold pressure gradient are obtained. Cusp-type catastrophe is predicted, allowing the abrupt burst of magnetic perturbations.

Keywords: magnetic braiding, anomalous transport, current diffusivity, interchange mode turbulence, magnetic well, cusp-type catastrophe.

Stochasticity of the magnetic field lines in toroidal plasma has been considered as one of the candidates to explain the anomalous transport.[1] When magnetic perturbation exceeds a certain critical level, the nested magnetic surfaces are broken and the rapid motion of the high temperature plasma along the field line can easily enhance the radial energy flux. The main theoretical task has been the determination of the fluctuation level of magnetic turbulence in toroidal plasmas. Ohkawa (and following work) investigated the role of collisionless reconnection for the anomalous transport.[2] More recently, Rebut and coworkers conjectured that the magnetic braiding exists in tokamaks, and suggested that the heat conductivity starts to increase when the pressure gradient exceeds a certain threshold.[3] Efforts were made to derive the turbulence level from the first principle (see reviews[4,5] and papers cited therein), but it is still far from satisfactory.

Recently, we have proposed a new approach for the turbulence and transport in toroidal plasmas, i.e., the picture of the self-sustained turbulence.[6] The nonlinear interaction on electron dynamics can lead to the nonlinear instability, through enhancing the anomalous electron viscosity μ_e. The balance between the stabilization effects of χ and μ determines the stationary turbulence and anomalous transport (χ and μ are thermal diffusivity and ion viscosity, respectively). The analyses has been done for the $E \times B$ nonlinearity, and have shown some success in explaining experimental observations.[7] This result was confirmed by the scale invariance technique by Connor.[8] Connor has also suggested the enhancement factor of the thermal conductivity when the magnetic braiding occurs.

In this paper, we apply the method of self-sustained turbulence to the magnetic braiding. It is found that, if the pressure gradient exceeds a certain threshold value, the self-sustainment of the magnetic braiding occur, causing higher thermal conductivity. Taking the interchange mode turbulence as an example, which is relevant to the systems of magnetic hill, the formula of χ and the amplitude of the magnetic perturbation are analytically obtained. The dependence of χ on the pressure gradient and the magnetic structure (such as shear, hill, aspect ratio) is clarified. Even the ion thermal conductivity is enhanced. The magnetic fluctuations are found to have the nature of the cusp-type catastrophe. The explosive burst is expected at the critical point, suggesting a path for the high-β disruption (beta: ratio of plasma pressure to magnetic pressure).

We study the high-aspect-ratio, toroidal helical plasma with magnetic hill and strong magnetic shear. The minor and major radii of the torus are given by a and R, respectively, We use the cylindrical coordinate (r, θ,z). The reduced set of equations for the electrostatic potential ϕ, pressure p and current J are employed.[9] The equation of motion:

$$\frac{\partial \nabla_\perp^2 \phi}{\partial t} - \nabla_\parallel J - \left(\Omega' \times \hat{\zeta}\right) \cdot \nabla\left(p_e + p_i\right) = \mu_\perp \nabla_\perp^4 \phi \tag{1}$$

the Ohm's law:

$$\frac{\partial \Psi}{\partial t} + \nabla_\parallel \phi + \eta J = \lambda \nabla_\perp^2 J \tag{2}$$

the energy balance equation for electrons and ions:

$$\frac{\partial p_{e,i}}{\partial t} + \left[\varphi, p_{0e,i}\right] = \chi_{e,i} \nabla_\perp^2 p_{e,i} \tag{3}$$

constitute the set of basic equations. In these equations, the bracket [f,g] denotes the Poisson bracket, $[f, g] = (\nabla f \times \nabla g) \cdot \vec{b}$, ($\vec{b}$ is the unit vector along the field line), Ω' is the average curvature of the magnetic field, Ψ is the vector potential, $-\nabla_\perp^2 \Psi = J$, and η is the classical resistivity. The transport coefficients μ, λ, χ_e, χ_i are caused by fluctuations, and is obtained by renormalizing the nonlinear interaction with background turbulence. The contribution of the electric perturbation was discussed in Ref.[6], and that for the magnetic turbulence was discussed in [10,11]. We here neglect the off-diagonal elements in the transport matrix for the clarity of the analytic treatment. (Note that the Ohm's law in Ref.[11] includes the term of anomalous resistivity. This term is small and neglected for the present problem.) In writing Eqs.(1)-(3), the normalization for resistive magnetohydrodynamic (MHD) modes is employed: $(\varepsilon v_A/a)t \to t$, $r/a \to r$, $z/R \to z$, $\phi/(\varepsilon a v_A B_0) \to \phi$, $\Psi/(\varepsilon a B_0) \to \Psi$, $J(a\mu_0/\varepsilon B_0) \to J$, $p(2\mu_0/\varepsilon B_0^2) \to p$, $\eta(\tau_{Ap}/\mu_0 a^2) \to \eta$, $\mu(\tau_{Ap}/a^2) \to \mu$,

$\lambda(\tau_{Ap}/\mu_0 a^4) \to \lambda$, $\chi(\tau_{Ap}/a^2) \to \chi$, where ε is the inverse aspect ratio, a/R, v_A is the Alfven velocity, B_0 is the main magnetic field, and $\tau_{Ap} = R/v_A$. It is noted that the finite electron mass and convective nonlinearlity on the current are kept in the Ohm's law, in order to discuss properly the electron dynamics. When the magnetic braiding is considered, the difference in the electron dynamics and the ion dynamics is essential, and we calculate the electron pressure p_e and ion pressure p_i separately. If one neglects the anomalous transport coefficient, Eqs.(1)-(3) reduce to that for the resistive ballooning mode, and the ideal MHD mode equation is obtained by taking η=0.

The transport coefficients μ, λ, χ_e and χ_i are given by the E×B nonlinearlity or by the v×B nonlinearlity. In both cases, we have the relations $\mu \cong \chi_i$, and $\lambda \cong (c/a\omega_p)^2 \chi_e$ (ω_p being the electron plasma frequency). (Ratios μ/χ_i and $(c/a\omega_p)^2\chi_e/\lambda$ are not exactly unity, but this does not change the result much.) The case of E×B nonlinearlity was discussed in ref.[6,7] and has given $\chi_e \simeq \chi_i$. The case of magnetic braiding was discussed (e.g., in ref.[10,11]). In this case, the relation

$$\chi_e \simeq \sqrt{\frac{m_i T_e}{m_e T_i}}\, \chi_i \tag{4}$$

holds for the strong stochasticity limit.

The marginal stability condition for the least-stable dressed-test mode, for which turbulence effect is renormalized, determines the anomalous transport coefficient.[6,7] The renormalized equation is solved by the help of the Fourier transformation to the k coordinate. The mode is microscopic, and the (m,n) component is localized near the relevant rational surface $r = r_s$ (x denotes the distance from the rational surface, $x = r - r_s$). The (m,n) modes are treated separately in Eqs.(1)-(3), because it is linearlized for the dressed test wave. We solve each (m,n) component and suppress the suffix (m,n) unless necessary. In the following, the argument k is the radial mode number. Eliminating J, p_e and p_i from Eqs.(1)-(3), we have the dispersion relation for the dressed-test mode in terms of ϕ. In the vicinity of the rational surface, the parallel mode number is expressed as $k_\parallel = k_\theta s x$ where s is the shear parameter

$r(dq/dr)q^{-2}$ and q is the safety factor. By employing the Fourier transformation, x is replaced by the operator i(d/dk). The eigenvalue equation is then given as

$$k_\theta^2 s^2 \frac{d}{dk}\frac{1}{\lambda k_\perp^2}\frac{d}{dk}\tilde{\phi}(k) + \mu k_\perp^4 \tilde{\phi}(k) - \frac{k_\theta^2}{k_\perp^2}\left(\frac{G_{0e}}{\chi_e} + \frac{G_{0i}}{\chi_i}\right)\tilde{\phi}(k) = 0 \qquad (5)$$

where the perpendicular wave number is given as $k_\perp^2 = k_\theta^2 + k^2$ and G_0 denotes the equilibrium pressure gradient coupled to the magnetic curvature, $G_{0e,i} = -\Omega'(dp_{0e,i}/dr)$, which is the origin of interchange instability.

By use of the similar analytic method shown in the previous article,[6] the marginal stability for the least-stable dressed-test mode is written as

$$\frac{G_{0e}}{\chi_e} + \frac{G_{0i}}{\chi_i} = H^*\, s^{4/3}\lambda^{-2/3}\mu^{1/3} \qquad (6)$$

at

$$k_\theta^2(\lambda\mu/s^2)^{1/3} = b^*. \qquad (7)$$

Numerical constants H* and b* were given as $H^* \cong 1.66$ and $b^* \cong 0.43$. This is a generalization of the previous results where electron energy and ion energy were not distinguished. Noting the relation $\lambda \cong (c/a\omega_p)^2\chi_e$, we have

$$\chi_i = \chi_E\left(\frac{G_{0i} + G_{0e}\chi_i\chi_e^{-1}}{G_{0i} + G_{0e}}\right)^{3/2}\frac{\chi_e}{\chi_i} \qquad (8)$$

where χ_E is the result in the case of electric fluctuations[6]

$$\chi_E = H^{*-3/2}\,\frac{(G_{0i} + G_{0e})^{3/2}}{s^2}\,\frac{c^2}{a^2\omega_p^2} \qquad (9)$$

The critical condition for the occurrence of the magnetic braiding is derived by studying the overlapping condition for the microscopic magnetic islands. The parity of the least stable dressed test modes is the even-ϕ parity (i.e., static potential is symmetric around the mode rational surface). The magnetic perturbation is the odd-parity, and is approximately written as $\tilde{B}_r(x) = \tilde{b}(x/\Delta)\exp\left(-(x/\Delta)^2\right)$. The mode width Δ was calculated[12] in obtaining Eq.(6) from Eq.(5), and is usually wider than the separation distance of the mode rational surfaces, d=1/snq. The island width is given as $\Delta_{island} \simeq \left(\tilde{b}/\varepsilon B\right)\left(1/sk_\theta\Delta\right)$. From the Ohm's law, Eq.(2), the magnetic perturbation is expressed in terms of ϕ, as

$$\frac{\tilde{b}}{\varepsilon B} \simeq \frac{k_\theta^2 s}{k k_\perp^4 \lambda}\tilde{\phi} \tag{10}$$

The overlapping condition, $\Delta_{island} \geq d = 1/nqs$, is written in terms of the perturbation amplitude as

$$\frac{k_\theta}{k_\perp^4\lambda}\tilde{\phi} > \frac{1}{sk_\theta} \tag{11}$$

Before the stochasticity switches on, the ion viscosity is close to the one in the electrostatic limit. Taking the strong turbulence limit,[6,7] $\mu \simeq \tilde{\phi}$, Eq.(11) is rewritten as $sk_\theta^2\mu\lambda^{-1}k_\perp^{-4} > 1$. Noting Eq.(7), one has the condition for the island overlapping as $s^{1/3}\mu^{4/3}\lambda^{-2/3} > b^*\left(k_\perp/k_\theta\right)^4$. The eigenvalue equation gives $k \cong k_\theta$, i.e., $(k_\theta/k_\perp)^4 = 1/4$. Substituting the relations $\lambda \simeq \left(c/a\omega_p\right)^2\chi_e$ and $\mu \simeq \chi_i \simeq \chi_e \simeq \chi_E$, we have the condition for the island overlapping as

$$G_{0e} + G_{0i} > H^* b^* \left(\frac{k_\perp}{k_\theta}\right)^4 s \cong 2.8\,s \tag{12}$$

When Eq.(12) is satisfied, the transport coefficient is influenced by the magnetic braiding. Equation (8) gives the enhanced transport coefficient in the case of braided magnetic surfaces. Substituting Eq.(4) into Eq.(8), we have the thermal conductivity in the limit of strong magnetic stochasticity as

$$\chi_i = \chi_E \left(\frac{G_{0i} + G_{0e}\sqrt{m_e T_i / m_i T_e}}{G_{0i} + G_{0e}} \right)^{3/2} \sqrt{\frac{m_i T_e}{m_e T_i}} \tag{13}$$

and

$$\chi_e = \chi_E \left(\frac{G_{0i} + G_{0e}\sqrt{m_e T_i / m_i T_e}}{G_{0i} + G_{0e}} \right)^{3/2} \frac{m_i T_e}{m_e T_i} \tag{14}$$

Comparing to the case of electrostatic limit, we see that even the ion thermal diffusivity is enhanced much when magnetic braiding is allowed to occur. The increment is more prominent for electrons as was usually expected.

We here discuss the reason why the ion thermal conductivity is also enhanced considerably in the magnetic turbulence. The magnetic braiding increases the electron viscosity, which strengthens the destabilization effect. The enhanced electron thermal diffusion, on the other hand, suppresses the electron pressure perturbation and tends to reduce the destabilization force in Eq.(1) (i.e., ∇p term). The destabilization force by the pressure perturbation is composed of both those of the ions and electrons as is shown in Eq.(1). The suppression of electron pressure perturbation causes only the partial reduction of the total pressure perturbation. (Ion pressure perturbation remains finite until χ_i becomes enhanced much.) Therefore, the increment in the electron transport, as a whole, results in the stronger destabilization. The enhanced destabilization by large μ_e is balanced only if the ion transport is increased. The magnetic perturbations continue to grow, nonlinearly, until the ion thermal conductivity and viscosity reach the value of Eq.(13).

The level of magnetic perturbation is also derived from this result. In the limit of the strong turbulence and $\tilde{B}_r/B > (c/a\omega_p)s\varepsilon$, the relation between the perturbation amplitude and thermal conductivity holds as $\chi_e = (v_{Te}/v_{Ap})\Delta(\tilde{B}_r/B)$,[4] where Δ is the radial width of the mode component and is evaluated as $\Delta \cong 1/k$ and $k \cong k_\theta$.[4] From Eq.(14), we have the amplitude in the large pressure gradient limit as

$$\frac{\tilde{B}_r}{B} \simeq \frac{G_{0e} + G_{0e}}{H^* s} \frac{c}{a\omega_p} \frac{\varepsilon v_A}{v_{Ti}} \left(\frac{m_e T_i}{m_i T_e}\right)^{1/6} \left(\frac{G_{0i} + G_{0e}\sqrt{m_e T_i / m_i T_e}}{G_{0i} + G_{0e}}\right)^{1/2} \qquad (15)$$

The behaviour of the magnetic perturbation is summarized as a function of the pressure gradient combined with the magnetic hill. Figure 1 illustrates the normalized amplitude $\tilde{A}$, $\tilde{A} = (\tilde{B}_r/B_0)(a\omega_p/c\varepsilon)$, as a function of total pressure gradient parameter G_0, $G_0 = G_{0e} + G_{0i}$. The lower line (denoted by L) indicates the level in the L-mode confinement, Eq.(10). The upper part (denoted by M) shows the level in the magnetic stochastic turbulence, Eq.(15). The dotted line shows the boundary for the onset of the magnetic braiding. In the right hand side of this Figure-S curve, the mode is unstable. The result predicts the Riemann-Hugoniot catastrophe.[13] The cusp point is given by $s \simeq 2.8\beta_i(m_i/m_e)^{1/3}$ and $G_0 \simeq 2.8s$. The branch L is characterized by the shorter-wave-length modes and the branch M by the longer-wave-length modes. Equation (7) shows that the characteristic mode number becomes smaller when the transport coefficient increases. Comparing Eqs.(7), (8), (13) and (14), we see that the mode number on the M-branch becomes $(m_e/m_i)^{1/4}$ times smaller than that on the L-branch. (In both cases, it is proportional to s.) There are two singular points, i.e., the crossing point of the line L and dashed line, and that of the line M and dashed line. At the right transition point, (i.e., the crossing point of the line L and the dashed line), the explosive growth of the longer-wave-length modes happens and the sudden increment of the amplitude occurs. This is a path of the high-β disruption. At the left transition point, the sudden decreases of the fluctuation level and transport are predicted.

The condition for the generation of magnetic braiding implies the upper bound of the pressure gradient which is accessible with the L-mode confinement scaling. Equation (12) suggests that, in the system of the magnetic hill, the magnetic braiding occurs and the transport coefficient is enhanced much if the pressure gradient exceeds a criterion as

$$\left|\frac{dp}{dr}\right| > \frac{2.8}{\Omega'} \frac{r}{q^2} \left|\frac{dq}{dr}\right| \tag{16}$$

This criterion is near the stability boundary for the ideal MHD mode: the higher the magnetic shear, the larger the critical beta. Our analysis provides a theoretical reason why the linear stability criterion against the ideal MHD mode gives fairly good estimation for the achievable beta limit.

In this article we have developed a new theoretical framework for the self-sustained magnetic braiding. The balance between the nonlinear damping and growth rates determines the stationary fluctuations. Nonlinear interactions are renormalized in a form of the transport coefficients on the test mode. Mode stability is analyzed for the interchange mode, which is accompanied by the magnetic perturbation of the *odd-*Ψ parity, in a confinement system with magnetic hill. Explicit formula for the anomalous transport coefficient and fluctuation level are obtained for the case of magnetic stochasticity. The nonlinear destabilization effect of the braiding is stronger than the nonlinear stabilization effect, so that the transport coefficient and fluctuation level are increased. The critical pressure gradient, above which the magnetic braiding takes place and the L-mode confinement disappears, is also obtained.

The dependence of the magnetic perturbation amplitude on the pressure gradient is obtained. It has the feature of the Riemann-Hugoniot catastrophe and allows the cusp type bifurcation as was studied associated with H-mode.[14] The result provides a basis for the dynamic behaviour of the magnetic perturbation near the beta limit, such as a path to the high β disruption. The condition, whether the beta limit disruption occurs or the soft beta limit appears, needs future study.

The similarity and differences between the roles of the electric fluctuations and magnetic fluctuations in different devices would be understood in a unified manner. The dimensional part of χ, $(c/\omega_p)^2 v_A/R$, agrees with Ohkawa's formula.[2] Connor has pointed out, based on the scale invariance method, that the transport coefficient can be enhanced by a factor v_{Te}/v_{Ti} in the magnetic turbulence.[6] Apart from the dimensionless factors such as a/L_p (L_p being the pressure gradient scale length) or geometrical parameters, our theory confirms Connor's prediction about the enhancement by v_{Te}/v_{Ti}. The enhancement of the transport coefficient over the electrostatic limit is found, however, even for the ion transport. The critical pressure gradient for the self-sustained turbulence is obtained. This predicts the beta value above which thermal conductivity is enhanced much compared to the L-mode transport. The criteria depends on the geometry and is given by Eq.(16). This criteria is much larger than the critical pressure gradient which has been employed in some transport model.[3] Extension to the system with magnetic well (such as tokamaks) is possible, and will be reported in a separate article with more detailed derivation .

Although several confirmations has been made for the theory of self-sustained turbulence, (including the comparison with the scale invariance technique, and a numerical simulation,[15]) further extension based on this approach is necessary. One-point renormalization may underestimate the transport coefficient .[16] Numerical simulation must be done for the stochastic magnetic fields. Connor has extended the model in the case that the electron pressure term is more important in the Ohm's law than the parallel electric field.[8] In such a case, the real frequency of the mode ωdoes not vanish. If ω is finite, the relation between $\tilde{b}$ and $\tilde{\phi}$, Eq.(10), changes, causing quantitative differences. These are left for future analysis.

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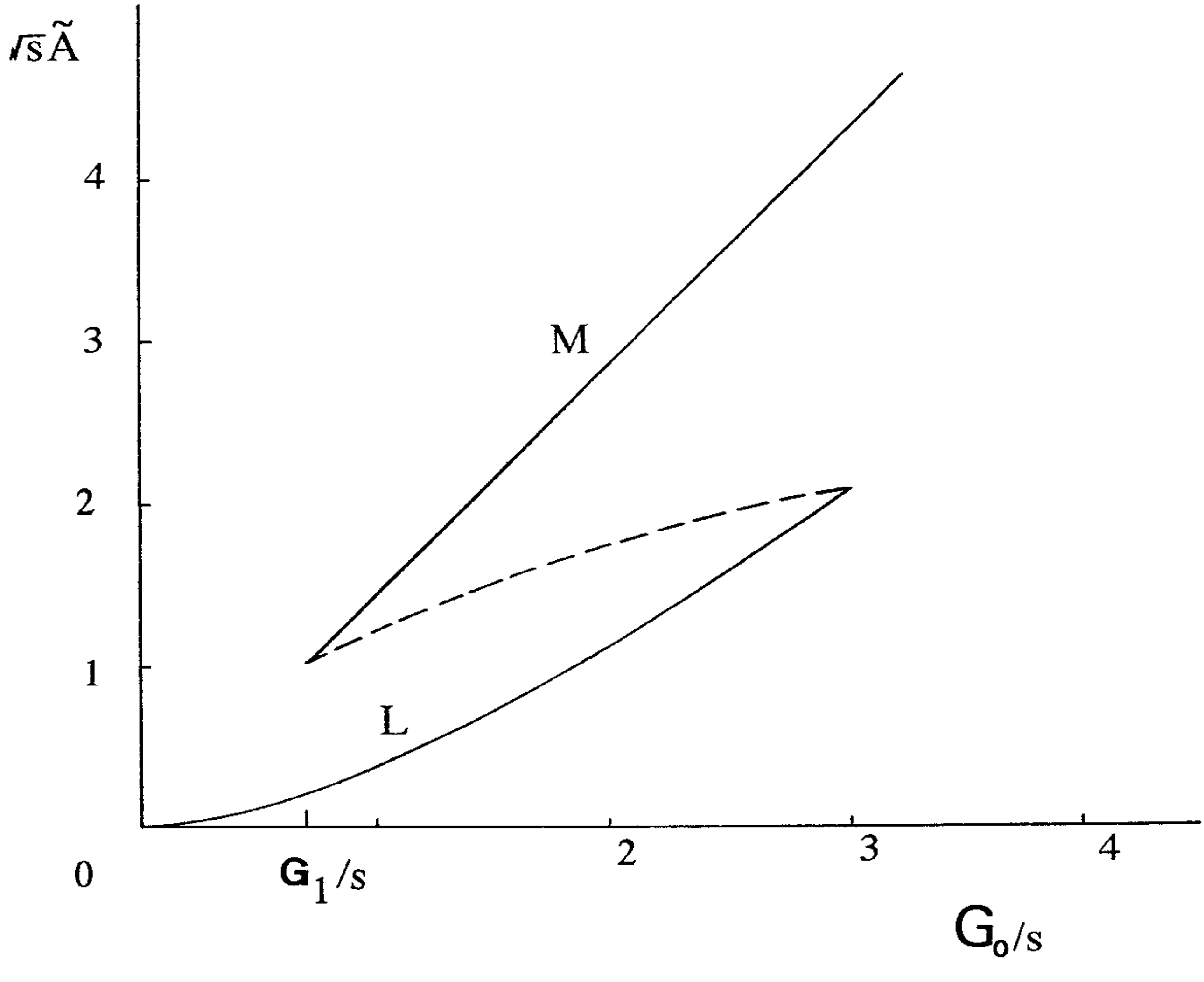
Figure Caption

Figure 1 The normalized amplitude $\tilde{A}$, $\tilde{A} = (\tilde{B}_r/B_0)(a\omega_p/c\varepsilon)$, as a function of the total pressure gradient parameter G_0. The lower line (denoted by L) indicates the level in the L-mode confinement, Eq.(10). The upper part (denoted by M) shows the level in the magnetic stochastic turbulence, Eq.(15). The dotted line shows the boundary for the onset of the magnetic braiding. The critical point G_1/s is given as $8\beta_i(m_i/m_e)^{1/3}s^{-1}$. Parameters are chosen as β_i (ion pressure divided by magnetic pressure) = s/150, and m_i/m_e = 1836.

Figure 1



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