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Magnetic mirror effect as a trigger of collisionless magnetic reconnection

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Abstract

A new mechanism of collisionless magnetic reconnection is proposed. It is based on the current density redistribution along the magnetic field lines caused by the reflection of meandering particles due to the magnetic mirror effect from the would-be reconnection region.

Keywords: magnetic reconnection, collisionless plasma, magnetic mirror effect, meandering particles.

Collisionless magnetic reconnection in a Harris-type equilibrium configuration [1] is not well understood as yet. Two questions remain not answered satisfactorily: i) How is the reconnection electric field generated along the neutral line and ii) what kind of particle dynamics does control the reconnection rate, at least at the initial phase? In this Letter we try to answer these questions.

We consider a 2D magnetic reconnection process in the plane perpendicular to the neutral sheet current (let it be the x,y-plane and the current direction be the z-direction). The magnetic field is created by a thin electric current layer (see Fig.1). Such a magnetic configuration is characterized by the existence of a neutral sheet at the central part of the current layer where the magnetic field value vanishes and driven reconnection of magnetic field lines caused by a non-uniform compression would occur. The necessary condition for magnetic reconnection is a suppression (decay) and/or removal (redistribution) of the neutral sheet current from a certain place in the neutral sheet region by some mechanism. Usually, by the analogy with the case of the resistive medium, only the decay of the neutral sheet current at a certain region is thought to be an origin of reconnection. This process assumes a loss of the particle momentum in the electric current direction by any collisions, say, by particle-particle or particle-wave interactions. In the present case, however, neither particle-particle nor particle-wave collisions are possible because of a homogeneity and a collisionless assumption. In such a system the generalized momentum has to be conserved. Hence, no current decay takes place. Nevertheless, even in such a case magnetic reconnection is possible because the neutral sheet current can be redistributed by an external force. Even without invoking any direct particle momentum loss by collisions it becomes possible to make a current density redistribution in the neutral sheet. A current redistribution in the neutral sheet leads to electric field generation which is equivalent to triggering magnetic reconnection. Traditionally, escape of current carrying particles from the vicinity of a would-be reconnection point is thought to be related with a particle, mostly electron, excursion across the magnetic field lines, especially across the neutral line, based on cyclotron gyration or meandering motion. Two kinds of "transverse" (across both the magnetic field and the electric current) particle transport near the reconnection point are usually considered; namely, the regular and chaotic transports. The first one corresponds to a well-known magnetic reconnection process scaled by the collisionless skin depth, c/ω_{pe}, and determined by deceleration of unmagnetized particles during the meandering period. The second one is related with the effective irregular exchange of momentum between particles and the magnetic field during a stochastic motion (such a motion corresponds to an "anomalous" particle transport across the magnetic field lines in x,y-plane in Fig.1). In either case the transverse particle transport causes reconnection. It is not so surprising because the particle transport across the magnetic field lines could be treated as a "diffusion" of magnetic field through the plasma.

In this Letter proposed is a new mechanism of collisionless reconnection based, not on the "transverse", but on the "longitudinal" (along the magnetic field lines) particle dynamics. The important feature of this dynamics is a local magnetic mirror effect caused by an inhomogeneous compression of the magnetic field. Usually the Larmor radius or the meandering orbit width in the neutral sheet current is larger than the skin depth. It is likely therefore that the meandering particles would play a crucial role in a collisionless reconnection, if any. Because of the magnetic mirror effect the meandering particles moving along the neutral sheet are reflected and can not penetrate into the compressed part which would be a reconnection point. The mirror effect leads to a current redistribution along the neutral sheet and the corresponding generation of a reconnection electric field (along the z-direction). This mechanism is first triggered by ion motions when a characteristic width of the current layer becomes comparable with the ion excursion radius as was observed in the numerical simulation results [2-4].

We consider a 2D magnetic configuration which is typical for the initial phase of driven magnetic reconnection (see Fig.1):$\boldsymbol{B} = (\frac{\partial A}{\partial y}, -\frac{\partial A}{\partial x}, 0)$, $\boldsymbol{E} = (0, 0, -\frac{\partial A}{\partial t})$, $\boldsymbol{j} = (0, 0, j)$. We neglect the spatial charge separation effect (i.e., no E_x, E_y exist) which would be important in some cases. Let us also assume that no binary particle collisions are important and the system is homogeneous along the electric current direction, i.e.,$\frac{\partial}{\partial z} \equiv 0$ everywhere in space and time. Under such a condition the particle dynamics is described by the following equations

$$\frac{d\,V_{\alpha x}}{d\,t} = \left\{ \frac{\partial\,A}{\partial\,x} \left[\frac{e_\alpha\,V_{\alpha z}(0)}{m_\alpha} + \frac{e_\alpha^2}{m_\alpha^2} \left(A_\alpha(0) - A\right) \right] \right\}_{\boldsymbol{r}_\alpha}, \tag{1}$$

$$\frac{d\,V_{\alpha y}}{d\,t} = \left\{ \frac{\partial\,A}{\partial\,y} \left[\frac{e_\alpha\,V_{\alpha z}(0)}{m_\alpha} + \frac{e_\alpha^2}{m_\alpha^2} \left(A_\alpha(0) - A\right) \right] \right\}_{\boldsymbol{r}_\alpha}. \tag{2}$$

Here, for the α-th particle, $V_{\alpha z}(0)$ and $A_\alpha(0)$ represent the initial values; $\{\}_{\boldsymbol{r}_\alpha}$ means that the quantity is taken at the position of a particle; all other notations are conventional. In Eqs.(1) and (2), conservation of the generalized momentum along the particle trajectory,

$$\frac{d}{d\,t} \left[V_{\alpha z} + \frac{e_\alpha}{m_\alpha} A(\boldsymbol{r}_\alpha, t) \right] = 0, \tag{3}$$

is taken into account. This conservation law follows from the condition of symmetry, $\frac{\partial}{\partial z} \equiv 0$, and denotes that the change in the velocity, $V_{\alpha z}$, is closely related with the orbit shift across the magnetic flux surface. As for the particle motion along a magnetic field line, the conservation law does not allow a change in $V_{\alpha z}$ because of the constant A value along the field line. Nevertheless, the current redistribution is possible because of the current density dependence on the local density of current carrying particles. The particle density, of course, depends on the longitudinal (along the A=const lines in x,y-plane) particle dynamics.

One of the important features of the longitudinal particle motion in a non-uniform magnetic field is the well-known magnetic mirror effect. In the case of magnetized particles and slowly varying magnetic field the magnetic moment conservation is satisfied, namely,

$$\mu_\alpha = \frac{1}{B} \cdot \frac{m_\alpha\,V_{\alpha\perp}^2}{2} = const. \tag{4}$$

The existence of this adiabatic invariant along with the particle energy conservation, $\epsilon_\alpha = \frac{m_\alpha}{2} (V^2_{\alpha\perp} + V^2_{\alpha//}) = const$, in a quasi-stationary magnetic configuration leads to the reflection condition,

$$V_{\alpha//} = \sqrt{\frac{2}{m_\alpha} (\epsilon_\alpha - \mu_\alpha B)} = 0, \tag{5}$$

if the magnetic field variation along the field line, δB, exceeds some critical (for a given particle) value $\delta B \approx \epsilon_\alpha / \mu_\alpha$.

Meandering particles move along the neutral line where $B = 0$. However, the same effect takes place in this case because the meandering particles experience a finite transverse excursion and, hence, "feel" non-zero magnetic field aside the neutral line. Let us consider the vicinity of the neutral line, i.e. $y = 0$ line in Fig.1, where approximately $A \approx \frac{1}{2} y^2 A_0''$ and A_0'' is a function of the longitudinal coordinate only (it is just proportional to a current density at $y = 0$). Let the $< V^2_{\alpha y} >= \dot{y}^2_\alpha |_{y=0}$ be a measure of transverse particle energy. Then, the transverse "fast" motion under a "slow" longitudinal change of parameters can be described by the equation

$$(\dot{y}_\alpha)^2 - A_0'' \left[\frac{e_\alpha V_{\alpha z}(0)}{m_\alpha} y^2 - \frac{1}{4} (\frac{e_\alpha}{m_\alpha})^2 A_0'' y^4 \right] =< V^2_{\alpha y} > = const. \tag{6}$$

Here $A_\alpha(0) = 0$ was assumed for simplicity. The corresponding adiabatic condition in Eq.(6) is that the meandering period τ_f is much shorter than the characteristic transit time, $\tau_f \ll l_x / V_{\alpha x}$, where l_x stands for the characteristic scale length of the magnetic structure along the field lines. "Slow" motion is described by Eq.(1) after averaging over the period of "fast" motion. In obtaining this equation an approximate expression $\left(\frac{\partial A}{\partial x}\right)_{\boldsymbol{r}_\alpha} \approx \frac{a}{2} y^2_{max} \frac{\partial A_0''}{\partial x}$ should be taken into account where y_{max} is the maximal excursion of meandering particles and the numerical factor $a \approx 0.5$ comes from the averaging procedure. From this equation it follows that in a quasistationary case where $\frac{\partial A_0''}{\partial t} \approx 0$ an "adiabatic" invariant for the "slow" motion exists:

$$\frac{1}{| A_0'' |^a} \left[V_{\alpha z}(0) + sign(e_\alpha A_0'') \cdot \sqrt{\epsilon_\alpha - V^2_{\alpha x}} \right] = const. \tag{7}$$

Here $\epsilon_\alpha = V_{\alpha x}^2 + V_{\alpha z}^2 + < V_{\alpha y}^2 >$. This equation is analogous to Eq.(5) but is more complicated because of a more complicated dynamics of meandering particles. Of course, it predicts reflection ($V_{\alpha x}^2 = 0$) of a meandering particle from the region with a higher value of A_0''. The most part of meandering particles moving along the neutral line will be reflected from the would-be reconnection region when $\frac{j_0}{j_\infty} \approx 2^{1/a}$, as it follows from Eq.(7). Here j_∞ and j_0 denote the values of current density at $| x | = \infty$ (far away from the reconnection point) and at $x = 0$ (near the reconnection point) respectively. In the worst case where $V_{\alpha y}^2(0) \ll V_{\alpha z}^2(0)$ (only a small part of the total amount of particles obey this initial condition) the reflection condition is $\frac{j_0}{j_\infty} = \left[\frac{V_{\alpha y}^2(0)+V_{\alpha z}^2(0)}{V_{\alpha y}^2(0)}\right]^{1/a}$. Thus, if the inhomogeneouty of the current density along the magnetic field lines exceeds $\frac{j_0}{j_\infty} \approx 3^{1/a}$, then the most part of the meandering particles can not pass through the would-be reconnection region and can only escape from it along the magnetic field lines. Note that this conclusion does not depend on the particle mass, hence, is valid both for the ions and electrons. As the meandering particles support a considerable part of the total current, especially when the current layer width is comparable with the ion meandering radius, the described magnetic mirror effect leads to an effective current redistribution in the vicinity of the reconnection point. This current redistribution inevitably causes electric field generation and consequent magnetic reconnection.

Now let us consider the exact Maxwell equation for such an electric field:

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} + \mu_0 \frac{\partial j}{\partial t}, \tag{8}$$

where μ_0 is the magnetic permability in vacuum. Taking into account the vanishing initial conditions, $E(t=0) = \frac{\partial E}{\partial t}(t=0) = 0$, and the irradiational boundary condition (no waves come from the infinity) ,it is possible to write the following expression for the electric field:

$$E(x, y, z) = -\frac{c\,\mu_0}{2\pi}\int_0^t d\tau \left[\int\int_{\rho<c(t-\tau)} \frac{(\frac{\partial J}{\partial \tau})_{\xi,\eta,\tau}}{\sqrt{c^2(t-\tau)^2 - \rho}}\, d\xi\, d\eta \right], \tag{9}$$

where $\rho^2 \equiv (x-\xi)^2 + (y-\eta)^2$. Because of the current density dependence on the electric field history Eq.(9) should be considered as an integral equation for E. Nevertheless, it is possible to estimate the value of the generated electric field using in Eq.(9) some physically reasonable current redistribution model. Say, it is quite reasonable to assume that a current redistribution is controlled by some advection-like process with a characteristic velocity of $u \approx V_{T\alpha} \ll c$. Using approximately $\frac{\partial j}{\partial t} \approx -(\vec{u} \cdot \vec{\nabla}) j$ and integrating Eq.(9) by parts one can estimate the electric field at the x-point as $E \sim u \, \frac{\mu_0}{2\pi} \, \frac{I_0}{l}$, where l is the characteristic space scale of the region with $\frac{\partial j}{\partial t} \neq 0$ and I_0 is the total current inside this region. As $2\pi l \; B_0 \sim \mu_0 \; I_0$, where B_0 is a characteristic magnetic field, one obtains $E \sim u \; B_0$. Thus, the electric field generated by a current redistribution reaches to the magnitude of the external "driving" electric field E_0 which causes plasma compression with the drift velocity of $u_d = \frac{E_0}{B_0}$. Such a field can really trigger and maintain the reconnection process, at least at the initial phase. The characteristic rate of reconnection,γ, can be estimated in terms of an ion escaping time from the reconnection region (electrons just follow the ions keeping charge neutrality). The ion escaping time, $\tau \sim l_x/u$, can be treated in terms of corresponding "dynamical" conductivity, $\sigma \sim \tau$, which determins the reconnection rate. Thus, one has

$$\gamma \sim \frac{1}{\sigma} \sim \frac{1}{\tau} \sim \frac{u}{l_x} = \omega_{ci} \left(\frac{1}{l_x} \frac{u}{\omega_{ci}} \right) \sim \omega_{ci} \frac{\rho_i}{l_x}, \tag{10}$$

where ρ_i is the ion Larmor radius. It is in good agreement with the results of numerical simulation [2-4] where the rate of "slow" reconnection phase was equal to $\gamma \approx 0.1 \; \omega_{ci}$ at the observed characteristic longitudinal magnetic structure length $l_x \approx 10 \; \rho_i$. The existence of magnetic mirror effect for the meandering particles is also confirmed by the analysis of numerical data [2]. In Fig.2 the trajectories of 50 test meandering ions (up) and electrons (down) are presented for two magnetic configurations corresponding to the begining of "slow" ("a", $t = 0.67 \cdot t_A$) and "fast" ("b", $t = 1.5 \cdot t_A$) reconnection phases. In Fig.3

the time histories of the relative numbers of reflected particles (N_i *and* N_e, in percents) are presented. Strong correlation between the begining of reconnection process and the reflection of meandering particles moving along the neutral line is certainly observed. Thus, the key idea of the proposed triggering mechanism of a driven colissioless magnetic reconnection in a system with neutral line is well confirmed.

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Figure Captions

Fig.1. - Magnetic field geometry.

Fig.2. - Trajectories of meandering ions (up) and electrons (down) in x,y-plane for slow (a) and fast (b) reconnection phases observed by the particle simulation of Horiuchi and Sato [2].

Fig.3. - Relative number of reflected ions (N_i) and electrons (N_e) as a function of time obtained by the same simulation as in Fig.2.

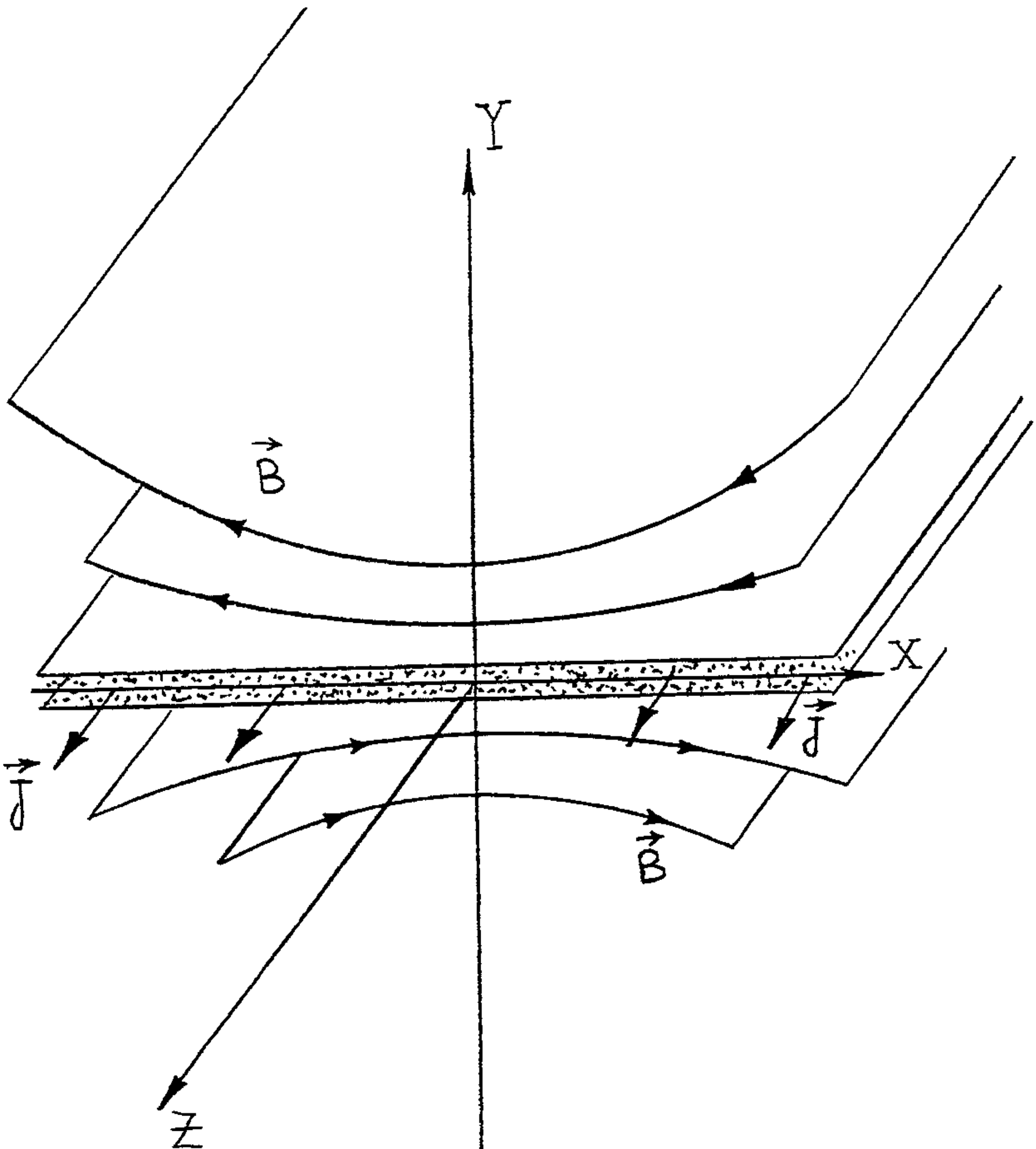

Fig. 1

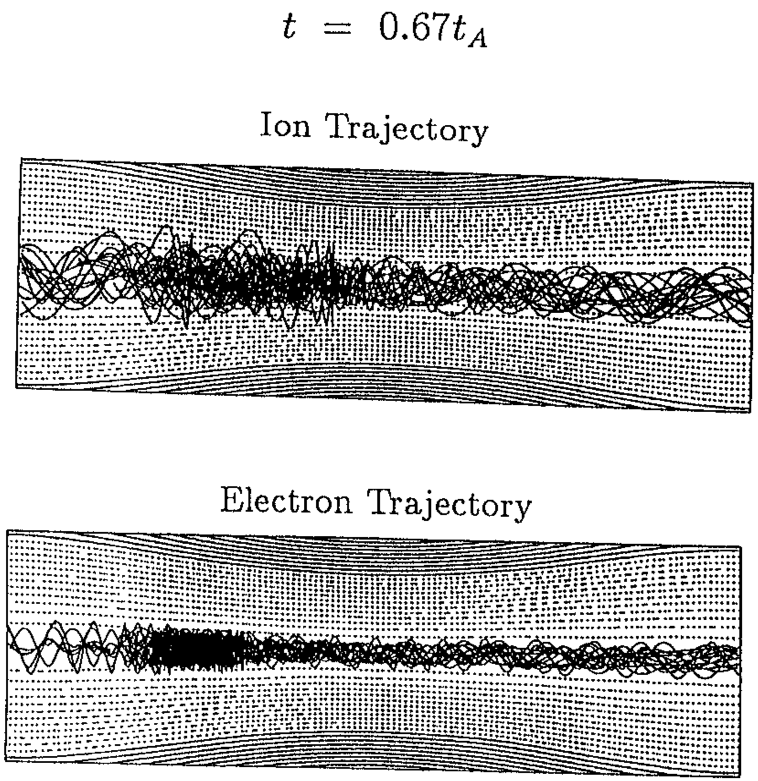
$t = 0.67t_A$
Ion Trajectory
Electron Trajectory

Fig. 2 a)

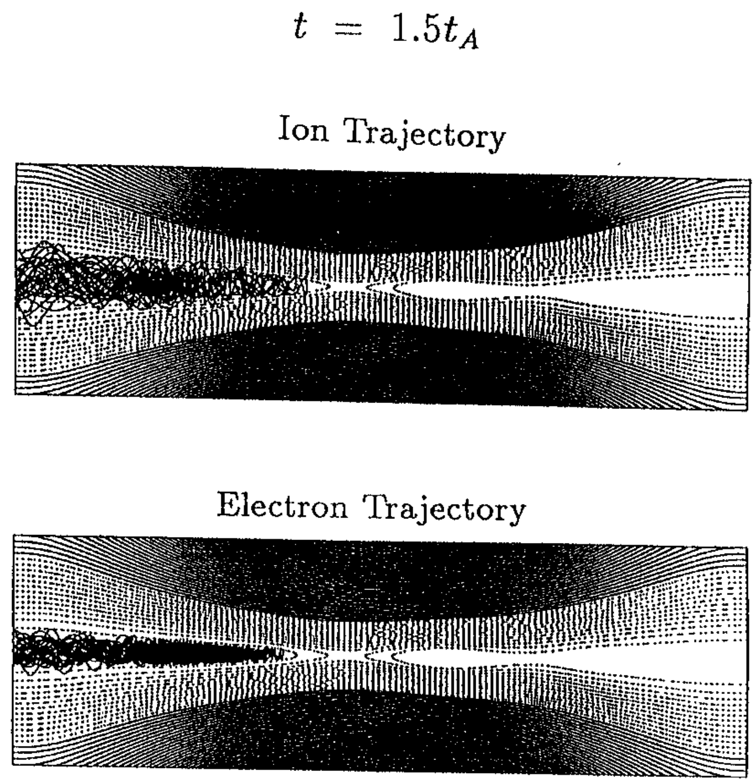
$t = 1.5t_A$
Ion Trajectory
Electron Trajectory

Fig. 2 b)

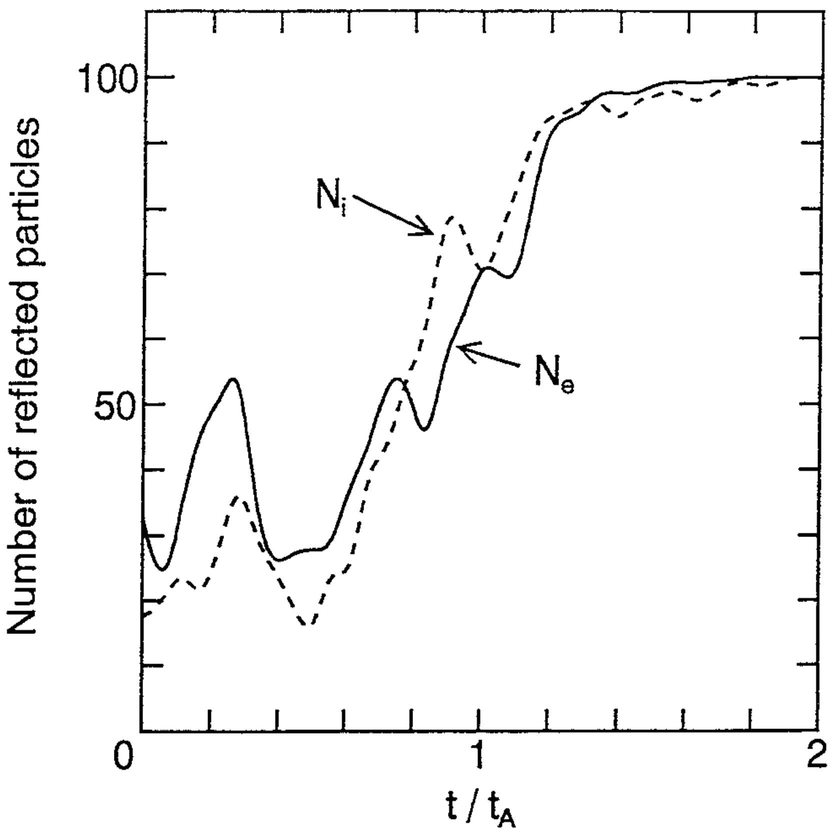

Fig. 3

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