INSTITUTE OF PLASMA PHYSICS
NAGOYA UNIVERSITY

RESEARCH REPORT

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Trapping of Charged Particles by a Travelling Wave with Increasing Phase Velocity

Yukio Midzuno

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The number of charged particles which are trapped by an accelerated wave in a plasma is calculated on the basis of a simple model. It is assumed that particles move adiabatically in travelling mirrors of the form $B(z) = B_0\{1 + \varepsilon \cos k(z - v_{ph}(1 + \frac{1}{2}\eta t)t)\}$ and that the initial velocity distribution is an isotropic Maxwellian. The ratio of the number of trapped particles to the total particle number is found to be

$$R = (\sqrt{8}/\pi)\ \varepsilon^{1/2} e^{-A}\ f(y) \qquad \text{for} \quad \varepsilon \ll 1\ ,$$

where $A = mv_{ph}^2/2T$, $y = 2\eta A/\varepsilon k v_{ph}$ and $f(y)$ is a monotonically decreasing function of y ($f(0) = 1$). The function $f(y)$ is presented in a graph as well as a table. As an application of the formula, an estimation is made on the required RF power for sustaining the plasma current in Golovin's model of the Tokamak fusion reactor.

§1. Introduction

In a previous papaer[1], we discussed the induction of electron current by a train of travelling magnetic mirrors of the form $B(z) = B_0 + B_w \cos k(z - v_{ph}t)$ and its application to the current sustaining in a Tokamak[2∿6]. It was shown there that the current is induced mainly through a deformation of velocity distribution due to trapping of electrons. Since the induced current is of the order $\varepsilon^{3/2}$ ($\varepsilon = B_w/B_0 \ll 1$), while the number of trapped electrons is of the order $\varepsilon^{1/2}$, it is expected that the increasing of the phase velocity is very effective for the induction of current, provided that a significant fraction of trapped electrons remains trapped. It is also suggested[7] that a similar idea may be applied to the production of an ion beam, which may be used in place of the injected ion beam in a fusion reactor proposed by Dawson et al[8].

In order to estimate the effectiveness of this method for these applications, it is essential to investigate how many particles remain trapped, when the phase velocity of the travelling wave increases gradually. In this paper, we derive an expression for the ratio of the number of trapped particles to the total number. When $\varepsilon \ll 1$, this expression can be reduced to a simple formula, in which the effect of the increasing phase velocity is represented by a multiplying factor.

We present a simple model in §2. The essential assumptions are that the motion of the charged particles is adiabatic and one-dimensional, and that the initial velocity distribution is an isotropic Maxwellian. In §3 we derive the condition for a particle to be trapped. In §4 the ratio of the number of trapped particles to the total number is calculated and an asymptotic expression in the limit of small ε is obtained. Some remarks are given in §5. A tentative estimation is made in §6 on the required RF power for sustaining the plasma current in Golovin's model of the Tokamak fusion reactor.[9]

§2. The Basic Model

As in a previous paper[1], a plasma in cylindrical vessel is considered. The plasma is immersed in a steady, strong magnetic field B_0 in the axial direction. The magnetic field is so strong that each charged particle is frozen to a certain magnetic line of force.

A coil is wound on the wall of the vessel and a current starts to flow at $t = 0$. The current density in the coil is assumed to be

$$j(r, t) = I_W \sin[kz - \omega(1 + \tfrac{1}{2}\eta t)t]\,\delta(r - R)\,e_\theta \qquad (2.1)$$

in the laboratory system, where the cylindrical coordinates are used and e_θ is the unit vector in the θ direction. This surface current induces an electromagnetic field in the plasma. The z component of the magnetic field on a magnetic line of force is approximately expressed in the form

$$B_z(z,\ t) = B_0 + B_w \sin[kz - \omega(1 + \tfrac{1}{2}\eta t)t]. \tag{2.2}$$

Equation (2.2) implies a train of magnetic mirrors, which travels in the z direction with the velocity

$$v = (\omega/k)(1 + \eta t) \equiv v_{ph}(1 + \eta t)\ , \tag{2.3}$$

that is, with an acceleration ηv_{ph}, where v_{ph} is the initial phase velocity.

Let us move to the "wave frame", in which the surface current (2.1) looks as a steady current and the magnetic field (2.2) is a train of standing mirrors:

$$B_z(z) = B_0 + B_w \cos(kz)\ . \tag{2.4}$$

Since the wave frame is accelerated by ηv_{ph}, a particle in this frame will find itself in an additional force field $-m\eta v_{ph}$, where m is the mass of the particle. Accordingly, the equation of motion for the particle in the wave frame will be

$$m\,\frac{dv_z}{dt} = -\,m\eta v_{ph} - \mu\frac{\partial}{\partial z}\,B_z(z) \tag{2.5}$$

where we have assumed the adiabatic behaviour of the particle so that the magnetic moment

$$\mu = \frac{mv_\perp{}^2}{2B_z(z)} \tag{2.6}$$

is a constant of motion.

Finally, the initial velocity distribution of particles is assumed to be Maxwellian in the laboratory system. Accordingly, that is a shifted Maxwellian distribution in the wave frame at t = 0:

$$f_0(v) = n\left(\frac{m}{2\pi T}\right)^{3/2}\exp\left\{-\frac{m}{2T}[v_\perp{}^2 + (v_z + v_{ph})^2]\right\} . \qquad (2.7)$$

Collisions among the particles are neglected.

§3. The Condition for a Particle to Be Trapped

We consider the motion of charged particle, which is governed by eq.(2.5). Let us specify the initial state of the particle as

$$z = z_0 , \quad v_\perp = v_{\perp 0} , \; v_s = v_{z0} \qquad \text{at } t = 0 , \qquad (3.1)$$

and assume that

$$0 \leqq z_0 < 2\pi/k \quad . \qquad (3.2)$$

The equation of motion (2.5) has the energy integral

$$\frac{1}{2} v_z{}^2 + \Phi(z) = C , \qquad (3.3)$$

where the effective potential $\Phi(z)$ is given by

$$\Phi(z) = \eta v_{ph} z + (\mu B_w/m) \cos kz . \tag{3.4}$$

The constants C and μ are expressed in terms of the initial values of variables as

$$C = \frac{1}{2} v_{z0}^{2} + \Phi(z_0) , \tag{3.5}$$

and

$$\mu = \frac{\frac{1}{2} m v_{\perp 0}^{2}}{B_0 + B_w \cos kz_0} . \tag{3.6}$$

For the particle to be trapped, the potential $\Phi(z)$ must have a trough. The condition for the existence of a potential trough is easily found to be

$$\eta v_{ph} < \mu B_w k/m . \tag{3.7}$$

When this condition is satisfied, the potential $\Phi(z)$ has a maximum at z_M and a minimum at z_m, for which relations $z_M < z_m$ and $kz_M + kz_m = \pi$ hold. The second condition for this particle to be trapped is that the "energy" C must be smaller than the potential maximum:

$$C < \Phi(z_M) . \tag{3.8}$$

The final condition is that the particle must lie initially in the trough of the potential:

$$z_0 > z_M . \tag{3.9}$$

The conditions (3.7), (3.8) and (3.9) are seen as well sufficient as necessary for a particle to be trapped.

Now, we will express these conditions explicitly in terms of the initial values of variables (3.1). Introducing dimensionless parameters

$$\varepsilon = B_w/B_0 \quad \text{and} \quad \zeta = \eta/\omega\varepsilon, \tag{3.10}$$

we transform the condition (3.7) into

$$v_{\perp 0}^2 > 2\zeta(1 + \varepsilon \cos kz_0)v_{ph}^2 . \tag{3.11}$$

When this condition is satisfied, we can define z_M as a root of the equation

$$\sin k z_M = 2\zeta(1 + \varepsilon \cos kz_0)(v_{ph}/v_{\perp 0})^2 \tag{3.12}$$

under the condition $0 < kz_M < \pi/2$. Then the condition (3.8) is rewritten as

$$v_{z0}^2 < \varepsilon\{\frac{v_{\perp 0}^2}{1 + \varepsilon \cos kz_0} (\cos kz_M - \cos kz_0) - 2\zeta v_{ph}^2 (kz_0 - kz_M)\} \tag{3.13}$$

Finally, if we define z_ℓ as the root of the equation

$$\Phi(z_\ell) = \Phi(z_M) , \quad \frac{1}{2}\pi < kz_\ell < 2\pi , \tag{3.14}$$

the condition for z_0 is more explicitly written as

$$z_M < z_0 < z_\ell \tag{3.15}$$

(see Fig.1)

§4. The Ratio of Number of Trapped Particles

Let us consider a group of particles, whose velocity distribution function is given by eq.(2.7) at $t = 0$ in the wave frame. Then the ratio of the number of particles, which are trapped by the wave (2.4), to the total number is given by

$$R = \frac{k}{2\pi}\,\frac{1}{n}\int dz_0 \int f_0(v_0)\,dv_0$$

where the limits of integrations are to be determined from the conditions (3.11), (3.13) and (3.15). Analysing these conditions, we get an explicit expression for the limits of integrations (see Appendix):

$$R = k\left(\frac{m}{2\pi T}\right)^{3/2} \int_0^{2\pi/k} dz_0 \int_{v_{\perp 0c}}^{\infty} v_{\perp 0}\,dv_{\perp 0} \int_{-v_{z0c}}^{v_{z0c}} dv_{z0}$$

$$\times \exp\left\{-\frac{m}{2T}\left[(v_{z0} + v_{ph})^2 + v_{\perp 0}^2\right]\right\}, \tag{4.2}$$

where

$$v_{\perp 0c}^2 = 2\zeta\,\frac{1 + \varepsilon \cos kz_0}{\sin kz_{Mc}}\,v_{ph}^2 \tag{4.3}$$

and

$$v_{z0c}^2 = \varepsilon\{\frac{v_{\perp 0}^2}{1 + \varepsilon \cos kz_0}(\cos kz_{Mc} - \cos kz_0) - 2\zeta v_{ph}^2 (kz_0 - kz_{Mc})\}, \tag{4.4}$$

kz_{Mc} being a root of the equation

$$\cos kz_{Mc} - \cos kz_0 = (kz_0 - kz_{Mc}) \sin kz_{Mc} \tag{4.5}$$

subject to the condition $0 < kz_{Mc} \leqq \pi/2$.

We are interested in the behavior of R in the limit $\varepsilon << 1$. We assume that ζ is a quantity of the order 1. Then we can derive the following, asymptotic expression for R:

$$R = (\sqrt{8}/\pi)\varepsilon^{1/2} e^{-A} f(y) \tag{4.6}$$

where

$$A = (m/2T) v_{ph}^{\ 2} \equiv v_{ph}^2 / v_{th}^2 , \tag{4.7}$$

$$y = 2\zeta A , \tag{4.8}$$

and f(y) is a monotonically decreasing function of y. Explicitly, the function f(y) is given by

$$f(y) = \frac{y^{3/2}}{\sqrt{8\pi}} \int_0^{2\pi} d\theta \int_0^{\phi_c(\theta)} d\phi \left[\frac{\cos\phi - \cos\theta}{\sin\phi} - \theta + \phi\right]^{1/2} \times \frac{\cos\phi}{\sin^2\phi} \exp\left(-\frac{y}{\sin\phi}\right) , \tag{4.9}$$

where $\phi_c(\theta)$ is a value of ϕ, which makes the square root in the integrand to vanish and satisfies the condition $0<\phi_c(\theta) \leqq \pi/2$.

It is not difficult to show that

$$\lim_{y\to 0} f(y) = 1 \tag{4.10}$$

and

$$f(y) \simeq 0.9351\, y^{-3/4} e^{-y} \quad \text{for } y >> 1, \tag{4.11}$$

where

$$\text{"}0.9351\text{"} = \frac{1}{2^{7/4}} \{ \frac{1}{2\sqrt{\pi}} \Gamma(\frac{1}{4}) + \sqrt{3}\, \Gamma(\frac{3}{4}) \} , \tag{4.12}$$

$\Gamma(x)$ being the gamma function. The equation (4.10) implies that $f(y)$ represents the rate of reduction of R when the acceleration of the phase velocity presents. Since we are interested in the case where y is of the order 1, $f(y)$ is computed numerically and the result is presented in Fig.2 and Table 1. The reduction seems to be tolerable if $y \lesssim 1$, but to be formidable if $y >> 1$.

§5. Remarks

1. The argument of the reduction factor $f(y)$ in eq.(4.6) can be rewritten as follows

$$y \equiv 2\zeta A = \frac{1}{\pi\varepsilon} \cdot \frac{2\pi}{k\, v_{th}} \cdot \frac{\eta\, v_{ph}}{v_{th}} \quad . \tag{5.1}$$

This expression can be interpreted as

$$y = \frac{1}{\pi\varepsilon} \frac{\text{increase of phase velocity in } \delta t}{v_{th}} \tag{5.2}$$

where $\delta t = 2\pi/(kv_{th})$ is the time interval in which a particle with the thermal velocity traverses one wavelength. Consequently, the acceleration of the wave must be so slow that the velocity increase (in the unit of v_{th}) in δt is at most of the order of ε in order that the reduction of R is tolerable.

2. In a toroidal configuration, there are usually static mirrors along a magnetic line of force, whose mirror ratio R_M satisfies the inequality $\varepsilon \ll R_M - 1 \ll 1$. These static mirrors can hinder the traveling wave from trapping particles. It can be shown, however, that this hindrance is not serious. The reason is as follows. While the velocity component ratio $(v_{\parallel}/v_{\perp})$ of a trapped particle is very small in the wave frame $(\lesssim 0\,(\varepsilon^{1/2}))$, the corresponding value in the laboratory system is of the order 1 in general, because the particle travels with almost the same velocity as the phase velocity of the wave. Consequently, a weak mirror $(R_M - 1 \ll 1)$ gives only a small disturbance on the motion of the particle.

A preliminary computer experiment was made to show that this hindrance is in fact not serious. A result is shown in Fig.3. In this experiment we followed the motion of particles in the magnetic field of the form

$$B_z(z,t) = B_0\{1 + \varepsilon\sin[kz-\omega(1+\tfrac{1}{2}\eta t)t] + \varepsilon_s\sin(k_s z + \theta)\}, \quad (5.3)$$

$\varepsilon_s = (R_M - 1)/(R_M + 1)$ being the relative amplitude of the static mirror to the uniform field, and counted the number of trapped particles. Initial distribution is assumed to be uniform along the z axis and isotropic Maxwellian in the velocity space. In this figure we see that the effect of the static mirror is only to bring the reduction of R by a factor 3 even if $\varepsilon_s/\varepsilon$ is so large as 15.

3. A small change of $v_\parallel$ can make a particle to slip out of trapping, because ε is very small. Accordingly, the effective loss frequency for a trapped particle is probably much larger than the conventional collision frequency for momentum transfer. Cautious treatments will be required, especially for the application to the ion beam production.

§6. Current Sustaining of Tokamak

As an example of the application, an estimation is made on the required RF power for sustaining the plasma current in a Tokamak.

Electrons constituting the current in a Tokamak lose their momentum through collisions with ions. The amount of loss of momentum is given by

$$\Delta = n_e m_e \bar{v} \quad \nu_{ei} \quad (6.1)$$

per unit volume and unit time, where n_e is the number density, m_e is the electron mass, $\bar{v}$ is the mean velocity of electrons ($\bar{v} = - j/n_e e$, j being the current density) and ν_{ei} is the collision frequency of an electron with ions.

We shall supply the same amount of momentum by accelerating a number of electrons. Then we have

$$n_t m_e \; \delta v_t/\delta t \;=\; \Delta \tag{6.2}$$

where n_t is the number of accelerated electrons and $\delta v_t/\delta t$ is the increase of velocity in unit time.

The acceleration of electrons is achieved by trapping them in the troughs of travelling magnetic mirrors with increasing phase velocity. Using the travelling mirrors specified by eq.(2.2), we have

$$\delta v_t/\delta t = \eta v_{th} \; . \tag{6.3}$$

The ratio of the number of trapped particles is given by eq. (4.6). Substituting these expressions into eq.(6.2), we have

$$\frac{\bar{v}}{v_{th}} \; \frac{\nu_{ei}}{\omega} = \frac{\sqrt{8}}{\pi} \varepsilon^{3/2} A^{1/2} e^{-A} \; \zeta \; f(2A\zeta) \tag{6.4}$$

This equation gives a relation among the parameters of the RF wave, which we need to supply.

In Golovin's Tokamak[9], $n_e = 3 \times 10^{14}$ cm^{-3}, $T_e = 15$ keV, a (plasma radius) $= 1.5 \times 10^2$ cm, I (plasma current) $= 8.55 \times 10^6$ A, plasma volume $V = 2.3 \times 10^8$ cm^3 and $B_0 = 50$ kG. Then Spitzer's formula gives $\nu_{ei} = 8.9 \times 10^3$ sec^{-1}, and the mean velocity $\bar{v}$ is estimated to be 2.5×10^6 cm/s.

We shall give an example of the required RF wave. We choose $k = 1.0 \times 10^{-2}$cm^{-1}, $A = 0.01$ (i.e. $v_{ph} = 0.1\ v_{th}$), and $\zeta = 1.0$. Then we have $\omega = 7.3 \times 10^6$ s^{-1}, $\varepsilon = 3 \times 10^{-4}$ (i.e. $\varepsilon B_0 = 15$ G), $\eta = 2.2 \times 10^3$ s^{-1} and the required power:

$$P \equiv \frac{(\varepsilon B_0)^2 V\omega}{8\pi Q} = \frac{1.5 \times 10^9}{Q}\ \text{W} \tag{6.5}$$

where Q is the Q-value of the coil system. This value of the input power seems reasonably small in comparison with the output power of Golovin's Tokamak (5GW).

The increasing of the frequency in this method implies the need of repeated application of RF wave. It was suggested[7)] that we should have the same effect as the increasing of the frequency by changing the wavelength (i.e. the spacings between the coils).

§7. Summary

We have considered the motion of particles in a train of an accelerated magnetic mirror (eq.(2.2)) and evaluated the ratio of the number of trapped particles to the total number. When $\varepsilon = B_W/B_0$ is small, the expression for the ratio is reduced to a simple one (eq.(4.6)) and the effect of the acceleration is represented by a multiplying factor f(y). The functional form of f(y) is presented in Fig.2 and the physical meaning of the parameter y is given by eq.(5.2). If this parameter is much larger than 1, the reduction of trapping ratio due to the acceleration is formidable. As an application, an estimation is made on the required RF power for sustaining the plasma current in Golovin's model of the Tokamak fusion reactor. The result (eq.(6.5)) gives a reasonably samll value in comparison with the output power of the reactor.

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Appendix Derivation of Eqs.(4.2) and (4.5)

The limits of integration in eq.(4.2) are obtained from the following considerations. If we fix z_0, the quantity kz_M defined by eq.(3.12) approaches to 0 as $v_{\perp 0} \to \infty$, and increases monotonically up to $\pi/2$ as $v_{\perp 0}$ decreases. Accordingly, when $0 < kz_0 < \pi/2$, there is a critical value of $v_{\perp 0}$, at which kz_M is equal to kz_0. The critical value $v_{\perp 0C}$ is easily found to be

$$v_{\perp 0C}^2 = 2\zeta \frac{1 + \varepsilon \cos kz_0}{\sin kz_0} v_{ph}^2 \tag{A.1}$$

which is a special case of eq.(4.3) for $kz_0 < \pi/2$. The condition $z_M < z_0$ in eq.(3.15) is equivalent to the condition $v_{\perp 0} > v_{\perp 0C}$.

In a similar way, we can show that kz_ℓ defined by eq.(3.14) approaches to 2π as $v_{\perp 0} \to \infty$ and decreases monotonically down to $\pi/2$ as $v_{\perp 0}$ decreases. Accordingly, when $\pi/2 < kz_0 < 2\pi$, there is a critical value of $v_{\perp 0}$, at which kz_ℓ is equal to kz_0. The lower limit $v_{\perp 0C}$ is given by a root of the following system of simultaneous equations, in which $kz_{Mc} < \pi/2$:

$$\sin kz_{Mc} = 2\zeta(1 + \varepsilon \cos kz_0)(v_{ph}/v_{\perp 0C})^2 , \tag{A.2}$$

$$\frac{v_{\perp 0C}^2}{1 + \varepsilon \cos kz_0}(\cos kz_{Mc} - \cos kz_0) - \zeta v_{ph}^2 (kz_0 - kz_{Mc}) = 0 . \tag{A.3}$$

This system of equations is easily reduced to eqs.(4.3) and (4.5). Then the condition $z_0 < z_\ell$ in eq.(3.15) is replaced by the condition $v_{\perp 0} > v_{\perp 0C}$.

The upper limit of v_{z0}^2 is easily found to be given by eq.(4.4).

The asymptotic expression (4.6) is obtained as follows. When $\varepsilon << 1$ and $\zeta \sim O(1)$, the integration with respect to v_{z0} is eq.(4.2) can be replaced by $2v_{z0C}$ × (integrand at $v_{z0} = 0$) in the lowest order in ε. Then, introducing dimensionless variables $w = v_{\perp 0}/v_{ph}$, $w_C = v_{\perp 0C}/v_{ph}$, $\theta = kz_0$, $\theta_M = kz_M$, $\theta_{Mc} = kz_{Mc}$ and $A = mv_{ph}^2/2T$, we have

$$R = 2\left(\frac{A}{\pi}\right)^{3/2} \int_0^{2\pi} d\theta \int_{w_C}^{\infty} wdw[w^2(\cos\theta_M - \cos\theta) - 2\zeta(\theta-\theta_M)]^{1/2}$$

$$\times \exp[-A(1 + w^2)]\varepsilon^{1/2} \tag{A.4}$$

where

$$\sin\theta_M = 2\zeta/w^2 ,$$

$$w_C^2 = \begin{cases} 2\zeta/\sin\theta & \text{for } \theta < \pi/2 \\ 2\zeta/\sin\theta_{Mc} & \text{for } \pi/2 \leq \theta < 2\pi \end{cases} \tag{A.5}$$

If in eq.(A.4) we take θ_M as the variable of integration in place of w, we arrive at eq.(4.6).

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Figure Captions

Fig.1. The effective potential $\Phi(z)$, which a particle feels in the wave frame.

Fig.2. The function f(y) which represents the rate of reduction of the trapping efficiency R caused by the acceleration of the phase velocity.

Fig.3. A result of a computer experiment showing the effect of a periodic static mirror on the trapping efficiency R. The abscissa ε_s represents the ratio of the amplitude of the static mirror to the uniform magnetic field.

Table 1

y	f(y)	y	f(y)
0.00	1.000	1.1	0.156
0.01	0.958	1.2	0.136
0.02	0.927	1.3	0.120
0.03	0.900	1.4	0.105
0.04	0.875	1.5	0.923×10^{-1}
0.05	0.852	1.6	0.812×10^{-1}
0.06	0.831	1.7	0.715×10^{-1}
0.07	0.811	1.8	0.631×10^{-1}
0.08	0.792	1.9	0.556×10^{-1}
0.09	0.774	2.0	0.492×10^{-1}
0.1	0.757	3.0	0.148×10^{-1}
0.2	0.618	4.0	0.464×10^{-2}
0.3	0.516	5.0	0.150×10^{-2}
0.4	0.436	6.0	0.496×10^{-3}
0.5	0.371	7.0	0.166×10^{-3}
0.6	0.318	8.0	0.561×10^{-4}
0.7	0.274	9.0	0.191×10^{-4}
0.8	0.237	10.0	0.658×10^{-5}
0.9	0.206	11.0	0.228×10^{-5}
1.0	0.179	12.0	0.790×10^{-6}

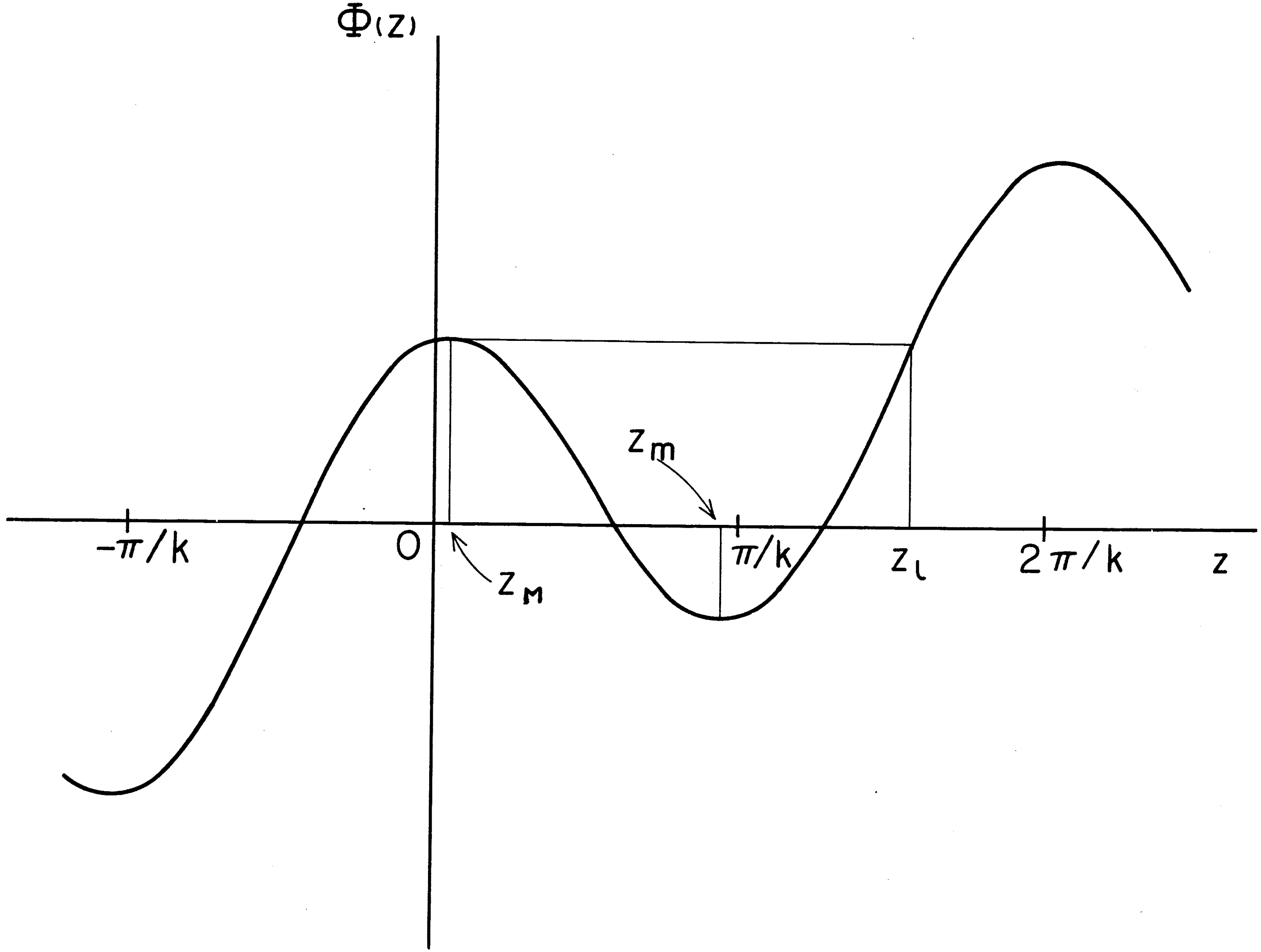

Fig 1

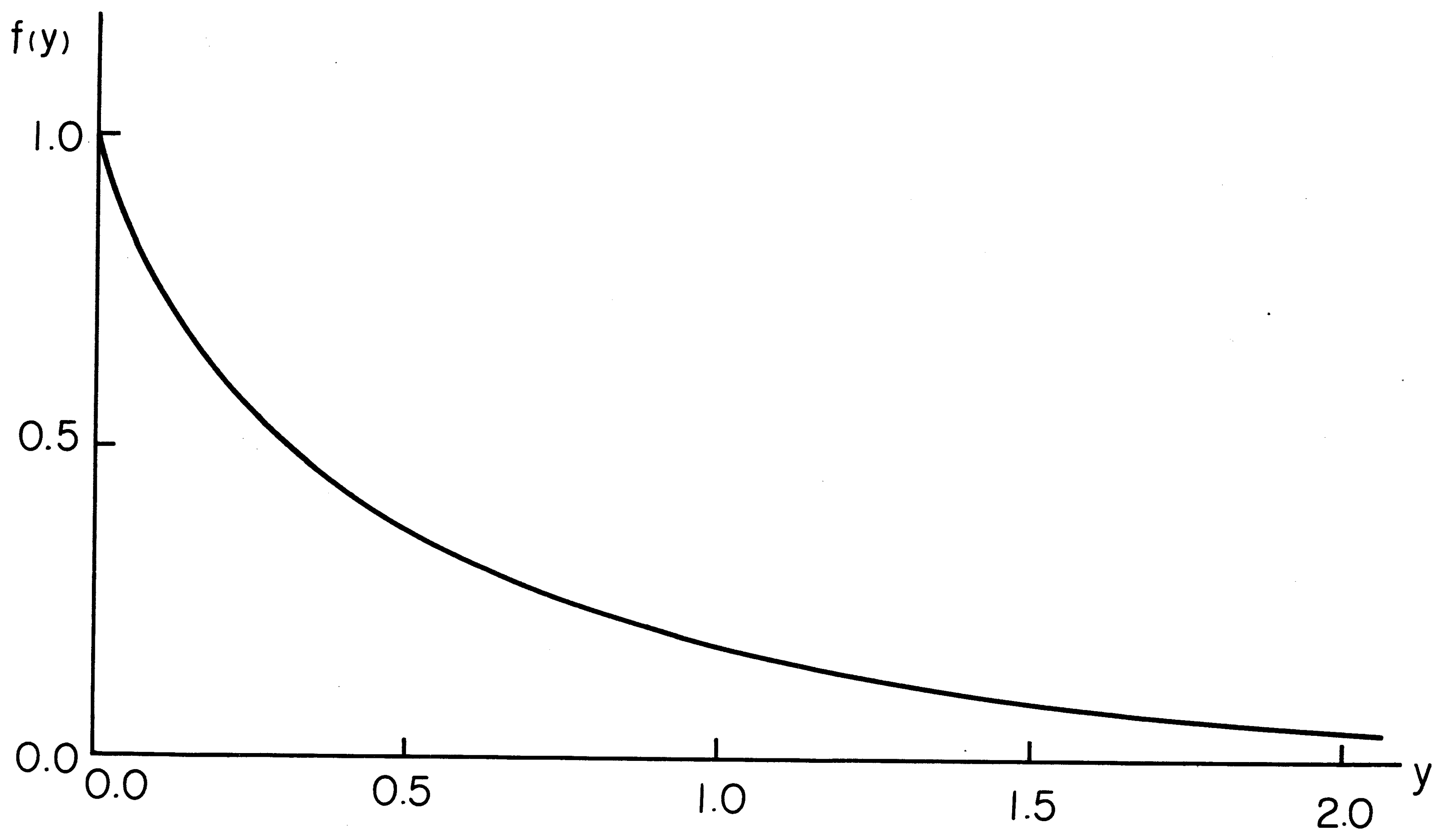

Fig. 2

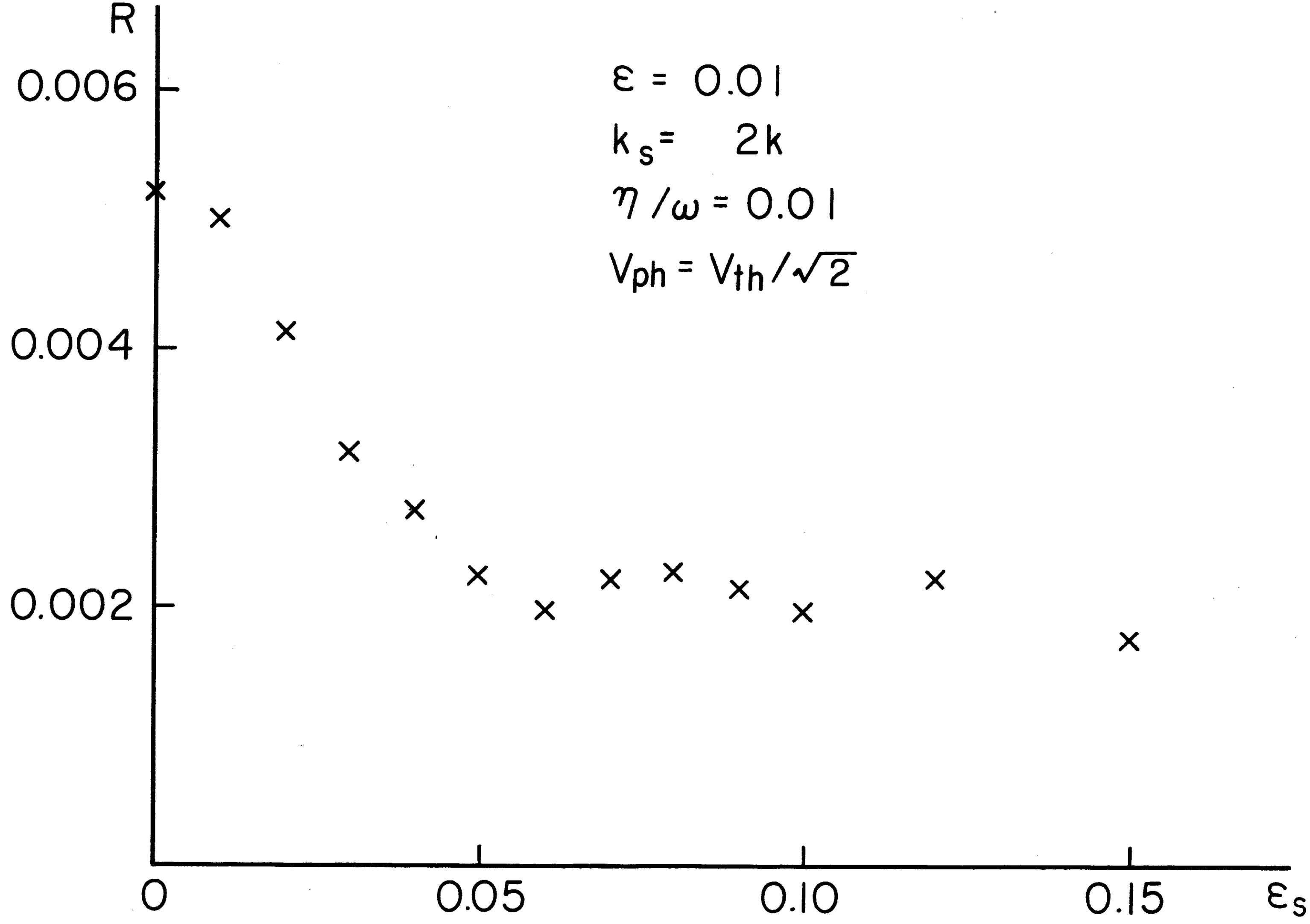

Fig. 3