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GLOBAL EFFECTS OF DOUBLE LAYERS

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GLOBAL EFFECTS OF DOUBLE LAYERS

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Abstract Locally the formation of an electrostatic double layer in a current carrying plasma leads to a direct acceleration of particles which may penetrate far into the surrounding medium. The potential across the double layer, giving this acceleration, must be maintained by the external system and is a basic parameter for the local to global coupling.

The double layer potential is associated with an electric field parallel to the magnetic field. In general this leads to a magnetohydrodynamic relaxation of the surrounding medium providing the influx of energy which is dissipated by the double layer. The double layer potential is limited as is the maximum possible rate of energy influx.

If the global response of the external medium can be represented by an external circuit and if an equivalent circuit element can be found to represent the double layer, for example a negative resistance for intermediate time scales, it is possible to give a description of the dynamics and stability of the whole system.

1. Introduction

Electrostatic double layers may form in current carrying plasmas and sustain a large potential difference over a local region. This leads to the conversion of energy to beams of accelerated particles. The large scale global dynamics of the plasma can be radically altered by the appearance of potential differences along magnetic field lines due to the formation of double layers.

The structure of a simple steady state double layer is indicated in Fig. 1 (taken from Raadu and Carlqvist (1981)). The potential acts as a barrier to low energy plasma electrons on the high potential side and similarly reflects low energy ions approaching from the low potential plasma region. There is incidentally a lowering of the particle density within the double layer. Plasma ions entering from the high potential side are accelerated through the double layer to form a high energy, low density beam on the low potential side. Similarly electrons are accelerated in the opposite direction to form an energetic beam on the high potential side. If the injection velocities of these free components is sufficiently large (Bohm condition) their associated charges will drop less rapidly than those of the reflected components. The net charge distribution can then be of the correct form to self consistently produce the double layer electric field.

Particular models of such steady state one dimensional double layers may be found by self consistently solving the Vlasov and Poisson equations (Knorr and Goertz, 1974). The procedure is essentially that of Bernstein, Greene and Kruskal (1957) for non-linear electrostatic waves. For a strong double layer, with a potential difference $_o$ greatly exceeding the thermal potentials of the particles, the internal structure is essentially that due to cold beams of ions and electrons. In this case Langmuir's (1929) solution is a good approximation:

$$|i_e|\, d^2 = C_o \frac{4\varepsilon_o}{9} \sqrt{\frac{2e}{m_e}}\, \phi_o^{\;3/2}$$

The constant Co ≃ 1.865 and the ion and electron currents satisfy the Langmuir condition $|i_e|/|i_i| = \sqrt{m_i/m_e}$.

2. Global Effects

The nature of a double layer determines the properties of the emerging accelerated particles. A strong double layer produces essentially monoenergetic beams with energies given by the potential across the double layer. The relative production rate of energetic ions and electrons is then in the non-relativistic case equal to $\sqrt{m_e/m_i}$, but tends to unity in the highly relativistic case (Carlqvist, 1969). Thus the parameters of the particle beams are given by the local properties. However they then propagate out into the surrounding plasma with which they may interact through collisions or collective effects. In the laboratory a beam-plasma interaction is found due to the energetic electrons leading to a peak in Langmuir wave energy well separated from the double layer (Torvén and Lindberg, 1980). The ionisation produced by interaction with the electron beam is in single ended plasma devices necessary for ion production to support the double layer as has been modeled by Andersson (1981) and Andersson and Sörensen (1983).

In addition to the effects of the injected particle beams, the energy release by the double layer must be provided externally leading to large scale modifications of the system. Mass motions are in general set up in the surrounding plasma as a result of magnetohydrodynamic relaxation and the rate of energy delivery to the double layer is limited by the velocities of the available wave modes. In these ways the double layer can trigger large scale global effects in the surrounding medium which react back on the double layer thereby imposing extra constraints on its parameters.

These global effects can provide a signature of the presence of a double layer in naturally occurring phenomena. Carlqvist and Boström (1970) have argued from observations of shearing motions in visible aurora that the implied electric fields for the drift motions are consistent with a double layer with a potential of several kilovolts.

Solar flares occurring in a localised region at the sun produce large scale effects which may even disturb the earth's ionosphere. Jacobsen and Carlqvist (1964) and Alfvén and Carlqvist (1967) have proposed tht the trigger for the energy release is provided by the formation of a double layer within a current system storing the flare energy. Here we have a very dramatic demonstration of the global effects of a double layer. In view of the complex chain of events there is not yet unambiguous evidence for their theory, but the direct production of the highest energy particles is a special feature of the theory which may prove crucial with the accumulation of observational material.

The development of the double layer theory of solar flares (Carlqvist, 1969 and 1979) has brought out the significance of the global effects of double layers. In particular the questions of how the double layer potential is provided and the nature of the magnetohydrodynamic relaxation have been raised. These will be considered in the following two sections.

3. Double Layer Potential

As already noted in the introduction, a double layer is a region of dissipation of electromagnetic energy. The energy released is transferred to the emerging accelerated beams of particles. The double layer acts as a load on the system. An external generator is required which maintains the potential and current supply to the double layer. To sustain the double layer the global response of the whole system must impose a potential difference across the double layer. Also this means that the source of energy for the double layer is external to it.

To emphasize this last point we can estimate the internal energy stored within a strong double layer. As a measure of this the electrostatic energy W_E per unit area may be evaluated:

$$W_E = \int \frac{\varepsilon_o E^2}{2}\, dx = A_1 \frac{\varepsilon_o}{2} \left\{ \frac{8 m_e i_e^2}{\varepsilon_o^2 e} \right\}^{1/4} \phi_o^{5/4}$$

The dimensionless constant $A_1 \simeq 0.571$ and is of order unity. To get a feeling for the order of magnitude of W_E we can calculate the time τ during which an equal amount of energy is transferred to electrons by acceleration in the double layer potential:

$$\tau = \frac{W_E}{i_e \phi_o} \simeq 0.40\, \omega_{peb}^{-1}$$

where ω_{peb} is the plasma frequency of the accelerated electrons in the emerging beam. This is in fact of the same order but less than the transit time τ_e of an electron through the strong double layer:

$$\tau_e \simeq 1.652\, \omega_{peb}^{-1}$$

and very much less than the ion transit time $\tau_i = \sqrt{(m_i/m_e)}\, \tau_e$. We conclude that the electrostatic energy stored in the double layer would not even be sufficient to sustain it during the transit time of an electron. The energy required for the particle acceleration by a steady state double layer must be provided by an external source.

In general the energy delivered to a double layer can be provided from the kinetic energy of mass motions or magnetic energy. As an illustration of this consider the cylindrically symmetric situation shown in Fig. 2. It is assumed that outside the double layer the plasma motion satisfies

$$\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B} = 0$$

so that we are dealing with a high conductivity plasma or with a situation where the particles move adiabatically. We suppose that the double layer is limited to a finite radius r_o. Outside the cylinder of radius r_o there is a constant axial magnetic field and no mass motions. Choosing cylindrical coordinates originating at the double layer (z=0), boundary planes are assumed to be symmetrically placed on both sides at $z = \pm L$. The angular velocity $\Omega(z,r)$ is taken to be antisymmetric about the plane of the double layer ($\Omega(-z,r) = -\Omega(z,r)$), so that the system has no net angular momentum.

The first case we consider, Fig. 2a, is a steady state in which all plasma to the left of the double layer within the cylinder of radius r_o has an angular velocity Ω_o. There is then a potential $\Phi_1(r)$ given by

$$\Phi_1(r) = \int_r^{r_o} r\,\Omega_o B_z\,dr$$

within the rotating part of the cylinder. To the right the angular velocity is $-\Omega_o$ and the potential $\Phi_2(r) = -\Phi_1(r)$. The potential across the double layer $\Phi_o(r)$ is then equal to $\Phi_1 - \Phi_2 = 2\Phi_1(r)$ and varies with the radial distance. The mass motions provide the double layer potential and if the axial current is j_z the energy released in the double layer is given by

$$\dot{W} = \int j_z \Phi_o(r)\;2\pi r\,dr$$

setting $\mu_o r\,j_z = \partial(rB_\phi)/\partial r$ and integrating by parts gives

$$\dot{W} = 2\int_0^{r_o} r\Omega_o\,\frac{B_oB_z}{\mu_o}\;2\pi r\,dr$$

On both boundaries ($z=\pm L$) there must also be a finite angular velocity, $\mp\Omega_o$ ($r<r_o$), and the total mechanical work done against the surface magnetic stresses to maintain the rotation is given exactly by this second expression for $\dot{W}$. The energy dissipated by the double layer in this steady state situation is provided by the work done on the ends of

the cylinder. As a possible solar physics situation one may think of a magnetic flux tube with foot points in regions of rotational motions in the photosphere and extending out into the low density corona. The energy source is then the turbulent photospheric motions.

The second case, Fig. 2a, arises if the rotational motions are not sustained at the ends of the cylinder. Instead a constant gradient in the rotational velocity is assumed on each side of the double layer so that the velocity is zero at the bounding surfaces ($z=\pm L$) and equal to $\mp\Omega_o$ at the double layer ($z=\pm 0$). The double layer potential and energy release are as in the first case. However due to the gradient of the rotational velocity the magnetic field is uniformly unwinding so that

$$\frac{\partial B_\theta}{\partial t} = -\frac{\Omega_o}{L} B_z$$

No work is being done on the end of the cylinder. However magnetic energy is being released by the unwinding at a rate

$$\dot{W}_B = \frac{\partial}{\partial t}\left\{2L\int\frac{B_\theta^2}{2\mu_o}\, 2\pi r\, dr\right\}$$

Substituting for $\partial B_\theta/\partial t$ this gives exactly the second previously obtained expression for $-\dot{W}$. The energy supply to the double layer is now at the expense of the stored magnetic field energy. Here we have essentially the situation considered by Alfvén and Carlqvist (1967; Carlqvist 1969) in their double layer theory for a solar flare. The energy stored by twisting of a magnetic flux tube by photospheric motions is released by the formation of a double layer. Energy may be accumulated over a comparatively long time, but the release of energy occurs so rapdily that during the flare photospheric motions are negligible and it is the stored magnetic energy that is released by the flare.

The cylindrical geometry was chosen for simplicitly and it is also of interest to consider an axisymmetric situation with a central rotating body (e.g. sun, star) surrounded by a magnetised plasma, Fig. 3. If we introduce the stream function Ψ for the magnetic field the poloidal field is given by

$$B = \frac{\underset{\sim}{\nabla}\Psi \times \underset{\sim}{1}_{\varphi}}{r \sin\theta}$$

adopting spherical coordinates. For a steady state the rotational velocity of the plasma is a constant on field lines and is a function $\Omega(\Psi)$ of the stream function. There is then an associated electrostatic potential

$$\phi(\Psi) = \int \Omega\ (\Psi)\ d\Psi$$

which is constant on field lines, again assuming that the rotational velocity is given by the adiabatic drift velocity.

If for example we now assume that there is a ring of non-rotating plasma situated on the equatorial plane and extending between field lines Ψ_1 and Ψ_2, the electric field must there be zero. The equipotential surfaces are then distorted so that the non-rotating plasma has a constant potential Φ_c. There are consequently potential differences $\phi(\Psi) - \phi_c$ along the field lines which may be supported by double layers on both sides of the plasma ring (Fig. 3). The situation is in essence the same as that discussed by Alfvén (1977) cf his Fig. 9.

The plasma outside the ring is assumed to have a low density so that force-free conditions prevail and currents are there aligned along the magnetic field lines. Outside the region intercepting the ring we assume not only that there are no currents, but also that the magnetic field is purely poloidal. Hence surface currents on the magnetic surfaces Ψ_1, Ψ_2 are implicitly assumed so that the total current is zero.

Now if the magnetic surfaces Ψ_1, Ψ_2 intercept the central body at colatitudes Θ_1, Θ_2 the mechanical work done against the surface magnetic stresses is given by

$$\dot{W} = \int_{\theta_1}^{\theta_2} \Omega r \sin\theta \, \frac{B_r B_\theta}{\mu_o} \, 2\pi r^2 \sin\theta d\theta$$

We may again integrate by parts to find an equivalent expression

$$\dot{W} = \left[(\phi-\phi_o) \, \frac{2\pi r \sin\theta B_\varphi}{\mu_o} \right]_{\theta_1}^{\theta_2} - \int_{\theta_1}^{\theta_2} (\phi-\phi_o) \, j_r 2\pi r^2 \sin\theta d\theta$$

The integral term is the energy dissipated by the distributed currents though the double layer. The first term gives the corresponding effect of the implicitly assumed surface return currents along the inner and outer limiting magnetic surfaces. This term may be made zero if for example there is no surface current on the inner surface Ψ_2 and the constant potential $\Phi_c = \Phi(\Psi_1)$. Here we have a steady state situation where the rotational energy of a central body provides the energy released in the double layers via a system of currents and potential differences.

4. Magnetohydrodynamic Relaxation

In discussing the ways in which the gobal response of the ambient plasma may provide the current and sustain the potential difference required by a double layer, it becomes clear that in general large scale mass motions may be set up as a result of double layer formation. Within a double layer there is an electric field component parallel to the magnetic field which results in a decoupling of the plasma motions on either side of the double layer. In this respect a double layer plays a similar role to a region of anomalous resistivity or to a thin current sheet undergoing magnetic diffusion and break up due to tearing mode instabilities. In an astrophysical situation the sudden onset and nature of the mass motions resulting from such a decoupling can provide an indication of the existence of such localised anomalous regions.

In the previous section we have considered situations in which there are rotational motions only. However in general the form of the mass motions requires an analysis of the global plasma dynamics. It can for example be argued tht the initial response in a low density plasma will set up mass motions perpendicular to the magnetic fields in the direction of the magnetic forces. The plasma will then have drift motions parallel to the Poynting vector (ExH). Thus since a double layer is a region of energy dissipation there should also be an initial mass flow directed towards it. This is the basis of Carlqvist's (1979) flare associated surge mechanism. Such a mass flow is suppressed if incompressibility is assumed and in a cylindrically symmetric situation only rotational motions are then allowed. The dynamics is also simplified as for example of the magnetohydrodynamic waves only the Alfvén mode is available.

As pointed out by Carlqvist (1979) the dynamics of the plasma within a current filament sets a limit on the double layer potential. Once again consider the situation where energy is provided by the untwisting of a mangetic flux rope (Fig.4). The maximum length of the flux tube which can be untwisted after the formation of a double layer must be determined by the distance Alfvén waves can propagate in both directions from the double layer. Then in the case of a uniform axial current an upper limit to the rate of energy release by untwisting of the magnetic flux rope is

$$\dot{W}_{max} = \frac{\mu_o}{8\pi} I^2 V_A$$

where I is the total axial current and V_A is the Alfvén velocity for waves propagating along the flux tube. The released energy goes both to the double layer and to the mass motions set up by the untwisting of the flux rope. To set up mass motions a part of the total current must leak out before reaching the double layer, so that only a fraction η passes through the double layer. Thus the rate of energy release by the double layer is given by

$$\dot{W}_o = 1/2\ \eta\ I\ \phi_o(o) = 1/2\ \eta\ I \Omega_o B_z r_o^2$$

where the axial field is now assumed to be uniform. If we now assume that the plasma within the partially untwisted region has only rotational motions the rate of energy imput to these is

$$\dot{W}_1 = \frac{\pi}{2}\rho\ r_o^4 \Omega_o^2 V_A$$

Clearly this must be less than the total energy release rate $\dot{W}_{max}$ and therefore

$$\phi(o) = \Omega_o B_z r_o^2 < \frac{\mu_o I}{2\pi} \frac{B_z}{\sqrt{\mu_o \rho}}$$

This is in principle the same argument and result given by Carlqvist (1979) and we may also consider a partial untwisting so that the energy release rate is

$$\dot{W} = \frac{\mu_o}{8\pi} \ (1-\eta^2) \ I^2 \ V_A$$

Equating this to the imput to the double layer $\dot{W}_o$ and the rotational motion $\dot{W}_1$ and solving the resulting quadratic equation for the double layer potential we find

$$\phi(o) = \frac{\mu_o}{2\pi} \ (1-\eta) \ I \ \frac{B_z}{\sqrt{\mu_o \rho}}$$

Noting that $V_A = B_z/\sqrt{\mu_o \rho}$, the energy release rate in the double layer is now given by

$$\dot{W}_o = \frac{1}{2} \eta \ I \ \phi_o(o) = 2\eta(1-\eta) \ \dot{W}_{max}$$

and the rate of energy imput to the rotational motions is

$$\dot{W}_1 = (1-\eta)^2 \ \dot{W}_{max}$$

This implies a maximum dissipation in the double layer when $\eta = 0.5$. In this case half as much energy goes to the mass motions. This is in agreement with Carlqvist (unpublished).

Here we have implicitly been considering an infinite flux rope. For a flux rope of length 2L as considered in the previous section this is a good approximation for a time interval less than L/V_A from the formation of the double layer. On a longer time scale boundary conditions are essential. The simple model of magnetic energy release (Fig.

2b) is then possible provided that the untwisting rate Ω_o is much smaller than V_A/L.

If we now remove the restriction of incompressibility the global response of the system to the formation of a double layer becomes much more complicated. One aspect of this is that the radial force balance of the twisted flux tube is altered by untwisting of the field resulting in expansion and compression of the plasma. In the case where magnetic forces dominate a radial force-free equilibrium may be assumed locally.

$$\frac{d}{dr}\left(\frac{B^2}{2}\right) + \frac{B_\theta^2}{r} = 0$$

To study the radial expansion or contraction consider the variation of the axial field B_z which is in the absence of axial motions proportional to the plasma density on a given magnetic surface. The mean value $\langle B_z^2 \rangle$ may be found using the force-free condition:

$$\langle B_z^2 \rangle = B_o^2$$

where B_o is the external magnetic field. It then follows that since $\langle (B_z - B_o)^2 \rangle > 0$ we have the inequality

$$\langle B_z \rangle \leqslant B_o$$

This implies that, if we start with an untwisted flux tube with magnetic field B_o, this must expand as a whole when it is twisted since the cross sectional area is by flux conservation inversely proportional to $\langle B_z \rangle$. However since we have shown that $\langle B_z^2 \rangle = B_o^2$ there must be regions where

$B_z > B_{ext}$. This shows that there are regions of compression and expansion during the twisting up of a flux rope and hence in general during untwisting. As a consequence in the case of non-uniform untwisting of a flux rope that we have considered here pressure driven axial motions as well as adiabatic heating and cooling of plasma should result from the formation of a double layer.

5. Equivalent Circuits

In a real situation one can expect a close coupling between the internal dynamics of a double layer and the global response of the external system. As energy is released at the double layer there will be a continuous magnetohydrodynamic relaxation of the surrounding region. This can lead to variations in the double-layer current and potential. The current to the double layer may even be partially diverted leading to energy release in mass motions as in the case of fast unwinding of a magnetic flux tube discussed above. The complexity of the global response has led to attempts to model this by equivalent circuits, simplifying the volume distribution of electrical currents to a limited number of currents passing through circuit elements.

For example an equivalent circuit for the geomagnetic substorm current system is discussed by Boström (1974). This models the coupling between the solar wind, magneto-tail and ionosphere, and represents the behaviour of what in fact is a complicated three-dimensional system in a relatively simple way which even reproduces the essential quantitative features. The substorm is associated with a redirection of a part of the neutral sheet current down into the ionosphere via Birkeland currents as the result of an unspecified instability which increases the neutral sheet resistivity. The formation of a double layer within the neutral sheet would also have a similar effect within the circuit (Alfvén, 1977).

So far we have discussed the double layer as a passive structure which supports the externally applied potential difference and carries the associated current. This is a useful approach as it shows that the resulting global response does imply restrictions on the double layer parameters. However the internal response of the double layer should not be overlooked. This is particularly evident if we consider the problem of double layer formation. In plasma simulation studies only the plasma regions near the double layer are normally modeled. The large scale response is only included implicitly through the assumed boundary conditions, constant current or externally applied voltage being frequently assumed.

Smith (1982) has emphasised the need to take more careful notice of the large scale plasma response during double layer formation. In his simulations of double layer formation an external circuit is explicitly included. The current through the simulated region is assumed to be closed through this circuit which includes inductance, resistivity and a voltage source. The circuit current is then given by an integral equation and depends on the past history of the potential across the simulated plasma region. In this way he is able through the assumption of an external circuit to include the global response of the external plasma to the local processes leading to the formation of a double layer.

In order to survey the mutual interaction of a double layer and the external plasma it is also possible to represent the double layer itself as a suitably chosen circuit element connected to an external circuit. Due to the complexities of the internal plasma dynamics this representation must be a considerable simplification and for example apply only over a restricted frequency range. Silevitch (1981) has studied the response of a double layer on an intermediate time scale such that the ions may be regarded as providing a fixed charge distribution whereas the electrons respond to parameter changes by modifying their steady state motion. He finds that the double layer can then behave as a negative resistance. In particular he shows that this is the case for Kan and Lee's (1980) double layer model which is treated in a more complete analysis in a later paper (Raadu and Silevitch, 1983). If the double layer negative resistance excedes the external resistance the system becomes unstable to perturbations in the double layer current and voltage. The development will eventually be effected by the ion response which may lead to relaxations oscillations of the type found for diodes (Burger, 1965).

6. Conclusion

The aim of this paper has been to highlight the importance of the global response of the plasma to the presence of a double layer. The double layer provides a means of localised energy conversion accelerating particles at the expense of energy sources present in the whole system. The global effects of the double layer include large scale motions set up by the magnetohydrodynamic relaxation initiated by the double layer and the injection of energetic particle beams produced by the double layer. These effects can provide a possible diagnostic of the presence of a double layer in space plasmas and astrophysical objects where the double layer itself may not be directly observed. Further studies of the global coupling of double layers are desirable and the field is as yet only partially explored.

Acknowledgements

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Figure Captions

Fig. 1 The potential distribution (a), ion and electron phase space distributions (b,c) for a double layer. Both the ions and electrons may be separated into a free component which can cross the double layer and a component reflected by the potential.

Fig. 2 (a) Steady state situation. Plasma on either side of the double layer has a constant angular velocity in opposite senses (heavy arrows). The magnetic field (in the direction of the light arrows) is unchanged. Mechanical work is performed agains the magnetic stresses at both end surfaces.

(b) Slowly unwinding flux tube. There is a gradient in the angular velocities which are zero on the end surfaces. The magnetic field is uniform but decreasing in time. Magnetic energy is released at the double layer.

Fig. 3 Plasma rotates about the axis of a central body. The field lines are also equipotential surfaces except at the non-rotating ring (shaded). The electric fields along the magnetic field resulting from the distortion of the potential surfaces may be supported by double layers with potentials of order $\Delta\phi$.

Fig. 4 Rapidly unwinding flux tube. Formation of the double layer produces magnetic disturbances moving away at the Alfvén velocity V_A. A part of the axial current I is diverted setting the plasma into rotation (heavy arrows). A reduced current ηI crosses the double layer. The released energy is shared by the double layer and the mass motions.

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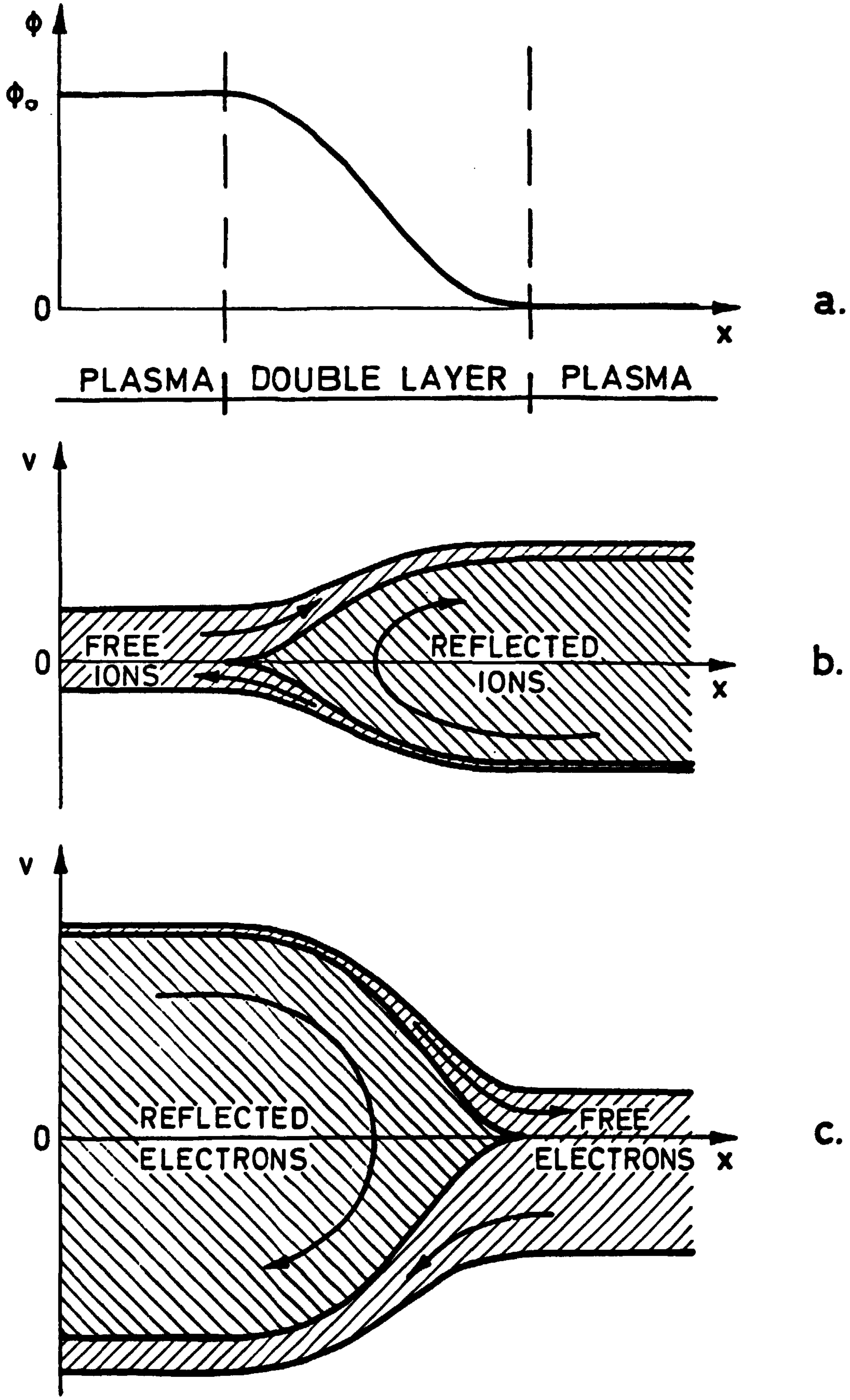
Φ
Φ₀
0
x
a.
PLASMA
DOUBLE LAYER
PLASMA
v
0
FREE IONS
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x
b.
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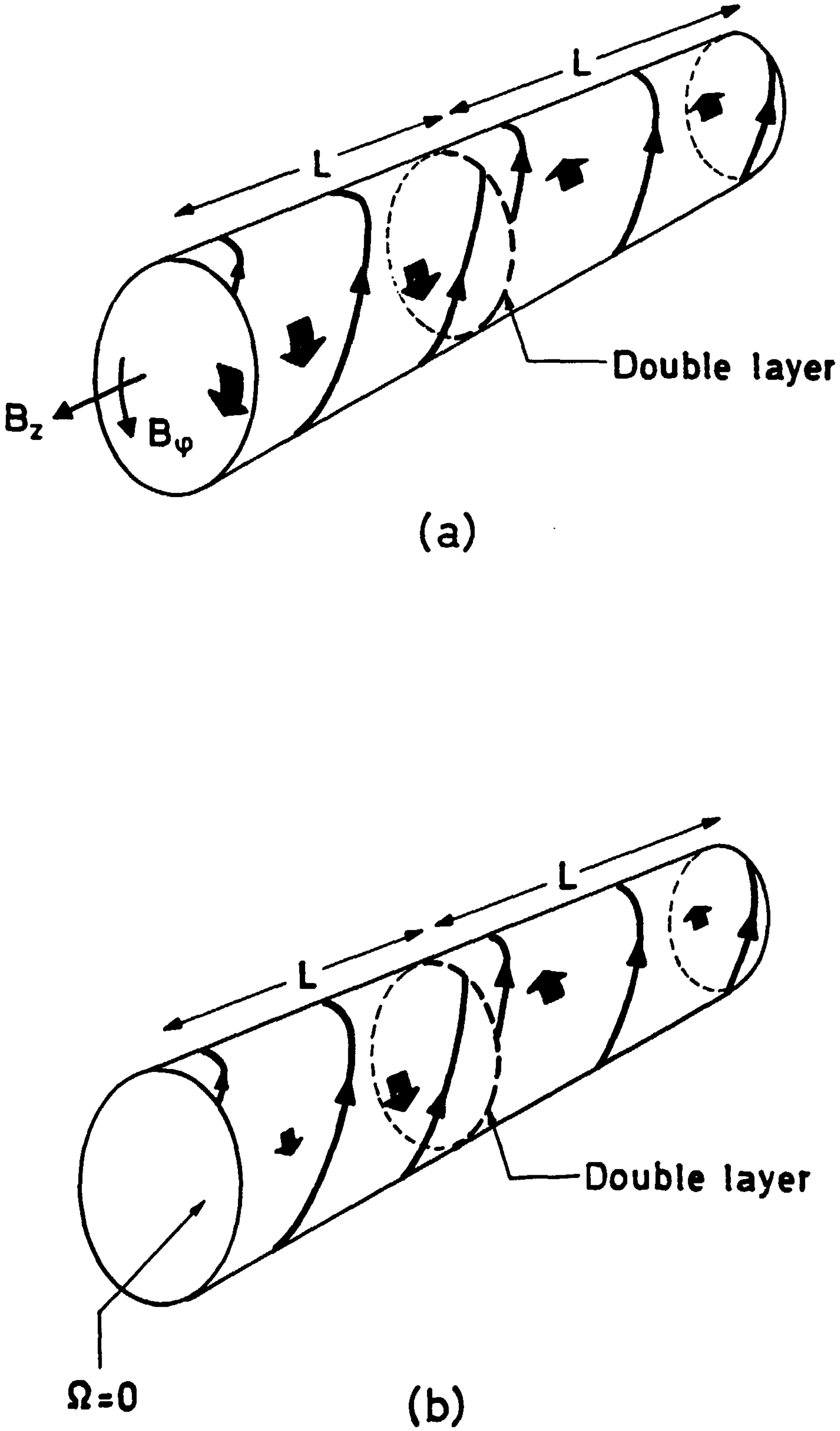
0
REFLECTED ELECTRONS
FREE ELECTRONS
x
c.

Fig. 1



(a)

(b)

Fig. 2

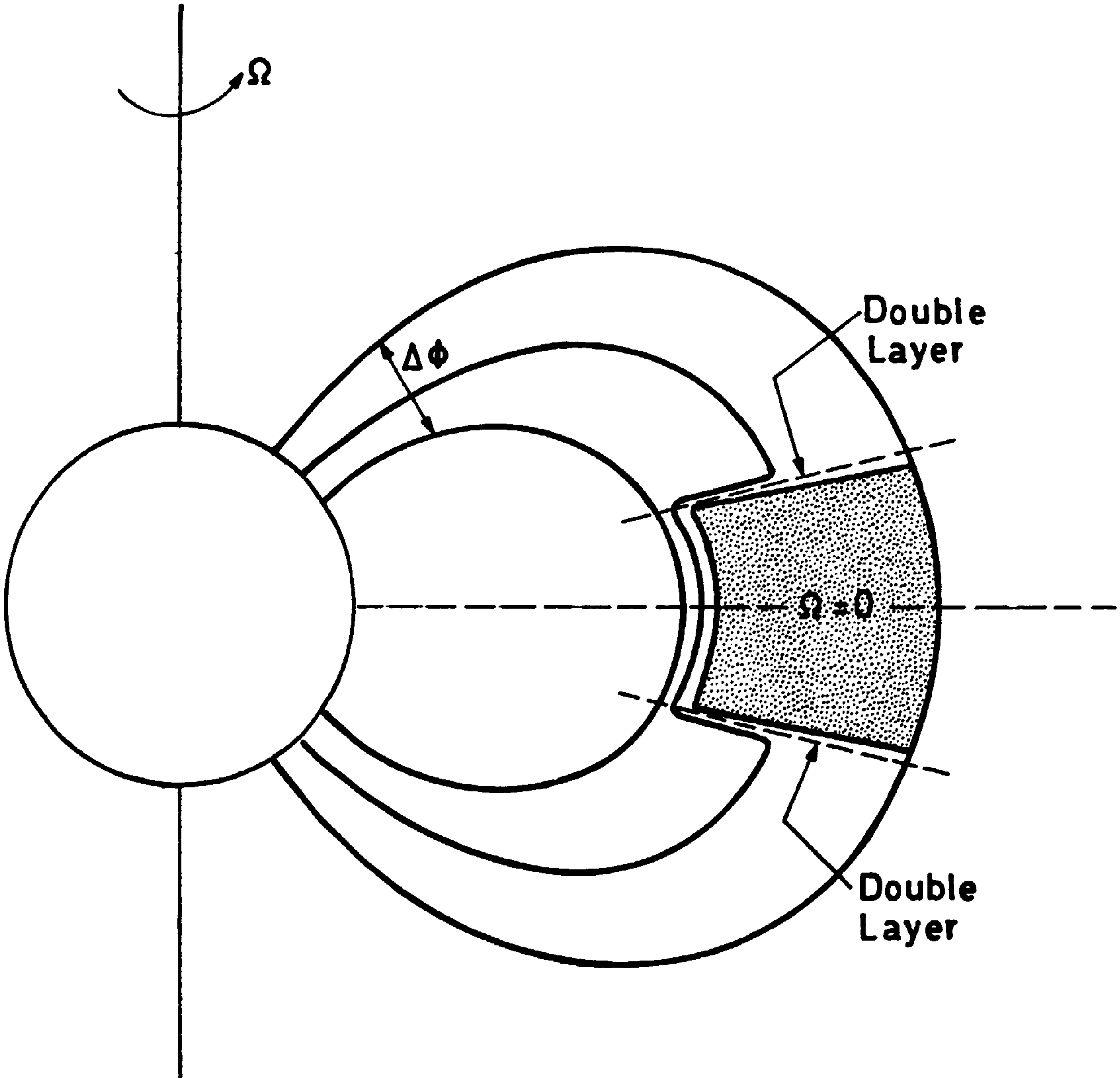


Fig. 3

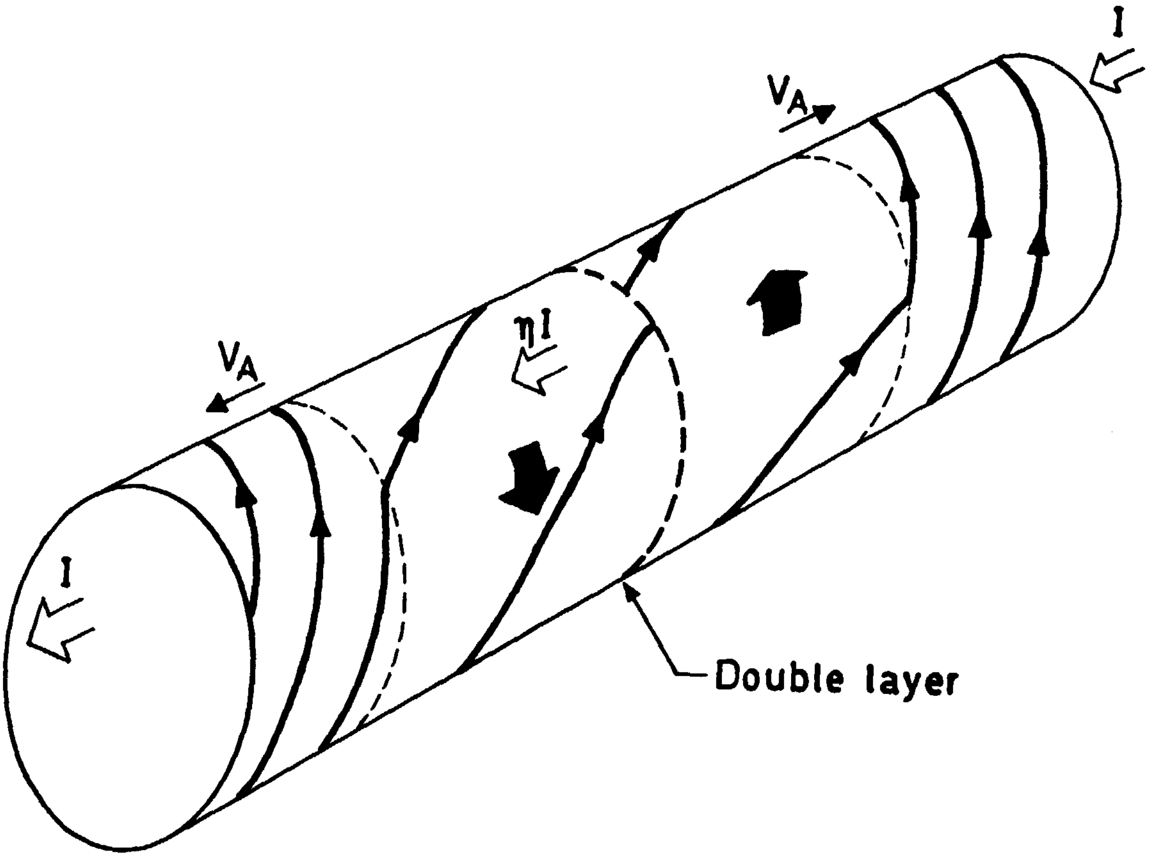


Fig. 4

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Key words: Double layer, Particle acceleration, Energy release, Magnetohydrodynamic relaxation, Circuits