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EXPANSION OF A PLASMA INJECTED FROM AN ELECTRODELESS GUN ALONG A MAGNETIC FIELD

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Abstract

The dynamics of a plasma injected from an electrodeless plasma gun (conical theta pinch) into a longitudinal magnetic field is studied theoretically. For the experiments referred to, conditions are collisionless for the ions and range from collision dominated to collisionless for the electrons. During the expansion of the injected plasma the electrons are trapped by an ambipolar electric field maintaining charge neutrality and a magnetic mirror at the gun. The development of the ion and electron distribution functions for the completely collisionless case is considered in detail. Assuming that the acceleration of the ions is negligible and taking the action integral over an electron oscillation to be an adiabatic invariant self similar solutions are found. The electrons lose energy adiabatically as a result of the plasma expansion and it is suggested that a re-thermalisation process must operate in experimental situations to account for the observed electron energies.

1. Introduction

An electrodeless plasma gun (conical theta pinch) may be used to inject plasma into a longitudinal magnetic field producing a suitable plasma stream for interaction experiments. This approach has been used to study the interaction with solid obstacles (Kristoferson 1969), the reverse deflection in a curved magnetic field (Lindberg and Kristoferson 1971, Lindberg 1978) and the critical ionisation velocity interaction with a neutral gas cloud (Danielsson 1970, Danielsson and Brenning 1975). Since most of the plasma is injected within a short time interval the flow which results from the expansion is not steady. The purpose of the present work is to investigate the basic features of the expanding plasma. The results are relevant to the interpretation of interaction experiments using such a plasma source.

The operation of plasma guns is described by Petshek (1957), Marshall (1958), Waelbroek et al (1962), Bieger et al (1963), Lindberg (1969), Hirano et al (1973) and Oki et al (1973). A range of plasma densities, temperatures and streaming velocities is found depending on the gun parameters and mode of operation. Lindberg and Kristoferson (1970) use probes to measure the properties of the plasma stream. The gun is operated by releasing a cloud of hydrogen from a fast gas valve, applying an ionising predischarge followed after a few microseconds by a main discharge which compresses and further heats the produced plasma. In the downstream region a low density precursor plasma with violent potential fluctuations is observed first. This is followed by the main plasma with a typical electron density $n_e \simeq 10^{19} m^{-3}$, temperature $T_e \simeq 10$ eV and a streaming velocity $u \simeq 3\times10^5$ m/s (Lindberg and Kristoferson, 1970). The magnetic field is typically $B \simeq 2\times10^{-2}$ T in the region where interaction experiments are performed, 2·85 m from the gun. An ion analyser may be used to record the arrival of ions within a narrow energy band. The results are found to be consistent with the bulk of the ions being emitted simultaneously shortly after the main discharge, their time of arrival being given by the free flight time from the gun to the ion analyser (Bieger et al 1963, Lindberg 1969). Even if, with an initial temperature of 300 eV corresponding to the observed streaming velocity, we assume an initial density $10^{21} m^{-3}$, two orders of magnitude higher than the density of the streaming plasma, the self collision time of the ions is $\tau_i \approx 5\ \mu s$ (Spitzer 1962), during which time the plasma will expand over 1.5 m significantly reducing the density and increasing the collision time. This is consistent with the observed free expansion of the ions. In the case of experiments on the interaction between a plasma and a neutral gas (Danielsson 1970, Danielsson and Brenning 1975) the plasma density in the gun region is of the order $10^{20} m^{-3}$ and in the downstream region is in the range $10^{17} - 10^{18} m^{-3}$. Typical electron temperatures are 5 - 10 eV and the protons with velocities $4 - 5 \times 10^5$ m/s have energies of 800 - 1300 eV. The ions may again be assumed to move without collisions in the guiding field which is typically $B \simeq 0.18$ T.

During the main gun discharge the magnetic field is at least an order of magnitude larger than the downstream magnetic field, 2 T being typical for a current 150 kA in a coil of length 0.1 m (Lindberg 1969). The plasma is therefore released from a magnetic mirror, conservation of the magnetic moments of the particles implying that their downstream motion is predominantly parallel to the magnetic field. Away from the immediate vicinity of the gun the motions may be treated as one dimensional and the magnetic mirror force neglected. Because of the high velocity of the electrons an ambipolar field directed downstream must be set up holding back the electrons to maintain approximate charge neutrality. This leads to an essential difference between the particle motions, the electrons being trapped between a magnetic mirror and an electrostatic potential wall and the relatively massive ions expanding freely even with a slight acceleration from the ambipolar magnetic field.

The electrons loose energy as a result of their expansion against the ambipolar field and this energy goes to the acceleration of the ions. It may be anticipated that their motion will be governed by a second adiabatic invariant leading to an effective ratio of specific heats, $\gamma = 3$ (Alfvén and Fälthammar 1963). The situation is modified if electron collisions are significant. Trapping of the electrons must still occur to maintain charge neutrality but the ratio of specific heats will instead be reduced to $\gamma = 5/3$.

To determine the significance of collisions for the electrons the deflection time t_D for collisions with ions may be used where

$$t_D = \frac{2\pi\, \varepsilon_0^2\, m_e^2\, v^3}{n_i\, e^4\, \log\Lambda} \simeq 6.205\times10^{-7} \frac{v^3}{n_i \log\Lambda} \qquad (1)$$

with conventional notation v being the velocity of the electron considered and the plasma parameter Λ being for low temperatures nine times the number of particles in a Debye sphere (Spitzer 1962). The times for electron-electron deflections and energy exchange are in general longer but comparable if we consider electrons with the root mean square thermal velocity, $\bar{v} = (3kT_e/m_e)^{1/2}$. For thermal electrons Equation (1) gives the mean time for electrons to be deflected by ions,

$$\bar{t}_D \simeq 2.378\times10^{11} \frac{T^{3/2}}{n_i \log\Lambda}$$

where the temperature T is in electron volts. For thermal electrons and a temperature 10 eV the deflection time ranges from 5.3×10^{-6} s to 6.3×10^{-8} s as the density varies from 10^{17} m^{-3} up to 10^{19} m^{-3} and the corresponding electron mean free path ranges from 12 m to 0.14 m. If it is assumed that the dominant electron energy loss is through their expansion against the ambipolar field, their initial energy cannot excede the observed ion energy and hence their initial temperature is at most typically 300 eV. For initial densities 10^{19} - 10^{21} m^{-3} the electron deflection times would then be 8×10^{-6} - 9×10^{-8} s. For lengths of 2 - 3 m (Danielsson 1970, Lindberg and Kristoferson 1970) and a plasma velocity 3 - 5×10^5 m/s the characteristic plasma expansion time is 4 - 10 μs. From an experimental point of view it is therefore interesting to consider the extreme case of a collisionless plasma as well as the collisional case.

2. Theoretical Formulation

The expansion of the collisionless components of the plasma may be described using the Vlasov equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \underset{\sim}{v} \cdot \frac{\partial f}{\partial x} + \dot{\underset{\sim}{v}} \cdot \frac{\partial f}{\partial v} = 0 \qquad (2)$$

where f is the distribution function for the component considered and $\dot{\underset{\sim}{v}}$ the particle acceleration. This equation implies that the distribution function is a constant following the particle motions and hence that any function of the constants of the particle motions is a possible solution.

Here we consider the situation where the plasma is released instantaneously from a thin layer, representing the experimentally observed release of plasma from the plasma gun. Individual particles move in the collective electric and magnetic fields of the plasma. It is assumed that the motions may be described by the guiding centre approximation with the magnetic moment μ of the gyrating particles an adiabatic constant of their motion. The electric field parallel to the magnetic field will be assumed to be the ambipolar field required to maintain approximate charge neutrality and will be determined by this condition as in the case of a static plasma in a mirror configuration treated by Alfvén and Fälthammar (1963) and Persson (1963, 1966). In principle the effects of perpendicular electric fields and inhomogeneity drifts should be included leading to a complicated three dimensional problem (c.f. Karlsson 1971). However we will assume here that these effects are negligible in the centre of the plasma beam and consider the expansion with this approximation. The particles then move with a guiding centre velocity $v_{\parallel}$ parallel to the magnetic field.

In all cases of interest here the ions may be considered to be collisionless. Let the coordinate s be the distance along a field line from the point at which the plasma is released (Figure 1). The initial ion distribution function is taken to be

$$f_i^o = G(v_{\parallel}^o , \mu)\, \delta(s)$$

where $v_{\parallel}^o$ is the initial parallel velocity of an ion and the magnetic moment μ is determined by the perpendicular velocity $v_{\perp}$

$$\mu = \frac{m_i v_{\perp}^2}{2B}$$

The appropriate solution of the Vlasov equation, Equation (2), is then

$$f_i (\underset{\sim}{v}, \underset{\sim}{x}, t) = G\left(v_{\parallel} - \int_o^t \dot{v}_{\parallel}\, dt , \frac{m_i v_{\perp}^2}{2B}\right) \delta \left(s - \int_o^t v_{\parallel}\, dt\right) \quad (3)$$

where the acceleration $\dot{v}_{\parallel}$ and velocity $v_{\parallel}$ are determined by the equation of motion of the ions. The ion density n_i is given by integrating over the components of the velocity $\underset{\sim}{v}$.

$$n_i = \int f_i \, d\underset{\sim}{v} = \frac{2\pi B}{m_i} \iint f_i \, d\mu \, dv_{\parallel} \qquad (4)$$

It will now be assumed that because of their relatively high inertia the ions are not appreciably accelerated by the ambipolar electric field and may be assumed to move with a constant parallel velocity outside the injection region. In this case Equations (3) and (4) reduce to

$$n_i = \frac{2\pi B}{m_i t} \int G\,(s/t,\ \mu)\, d\mu = \frac{N}{t} \; \frac{B}{B_o} \; h_i\ (s/t) \qquad (5)$$

where the distribution $h_i\ (v_{\parallel})$ over the parallel velocities $v_{\parallel}$ is normalised to unity, N is the total number of particles injected per unit area and B_o the magnetic field at the gun. With the approximation of constant velocity all particles at a given point have the same velocity corresponding to the time of flight, $s/v_{\parallel}$, to that point. The time of flight within the mirroring region of strong magnetic field is negligible and the motions beyond this region are predominantly parallel to the magnetic field. For an isotropic Maxwellian distribution at the gun

$$h_i^{(3)}\ (v_{\parallel}) = 2 \left(\frac{1}{2\pi}\right)^{1/2} \left(\frac{m_i}{kT_i}\right)^{3/2} v_{\parallel}^{\,2} \ \exp\left(- \frac{m_i\ v_{\parallel}^{\,2}}{2\ kT_i}\right) \qquad (6)$$

assuming all ions with negative velocity are immediately reflected and travel downstream. Similarly for a one dimensional Maxwellian distribution parallel to the magnetic field

$$h_i^{(1)}\ (v_{\parallel}) = 2 \left(\frac{1}{2\pi}\right)^{1/2} \left(\frac{m_i}{kT_i}\right)^{1/2} \exp\left(- \frac{m_i\ v_{\parallel}^{\,2}}{2\ kT_i}\right) \qquad (7)$$

The downstream ion density as a function of time is then given by substitution in Equation (5). Following a group of ions their density is reduced as the plasma flows into regions of lower magnetic field strength and as a result of the dispersion in their velocities giving an inverse dependence on the time of flight. In the case of a one dimensional Maxwellian distribution, Equation (7), the ions occupy a region of typical length $\ell = (kT_i/m_i)^{1/2}\ t$ extending downstream from the gun at which the density is a maximum.

For an isotropic distribution, Equation (6), the density close to the gun becomes small and has a maximum downstream.

When the plasma gun is operated at low densities the electrons may also be treated as collisionless. They are however trapped by the magnetic mirror region at the gun and an electrostatic potential Φ set up by the plasma to maintain approximate charge neutrality. In the guiding centre approximation the parallel motion is given by

$$m_e \frac{d v_\parallel}{dt} = e \frac{d\Phi}{ds} - \mu_e \frac{dB}{ds} \tag{8}$$

where for the electrons

$$\mu_e = \frac{m_e v_\perp^2}{2B}$$

It is assumed that the magnetic field at the gun, which is typically 2 T in experiments, is considerably larger than downstream where a typical experimental value is 2 10^{-2} T. This means that the mirror force, given by the last term in Equation (8) acts only at the gun and it will be assumed that the electrons are reflected instantaneously there, the rest of their motion being closely parallel to the magnetic field and determined by the electric field alone.

As the plasma expands the electrons oscillate along the field lines many times. Initially the oscillation length is short and it may be assumed that small irregularitites or collective interactions are sufficient to destroy any phase relationships in these oscillations, which would otherwise persist giving large scale electrostatic oscillations on the time scale of the oscillatory motion along the magnetic field. Assuming that the oscillation time is short compared to the expansion time of the plasma the electron motion is associated with a second adiabatic invariant J given by the action integral over an oscillation (c.f. Alfvén and Fälthammar 1963, Lichtenberg 1969)

$$J = \oint m_e v_\parallel \, ds \tag{9}$$

The appropriate solution of the Vlasov equation, Equation (2), for the electrons is then

$$f_e = f_e\ (J,\ \mu_e) \tag{10}$$

since both J and μ_e are adiabatic constants of the electron motion. The electron density follows as in the case of the ions by integration over the velocity components

$$n_e = \frac{2\pi B}{m_e} \iint f_e\ d\mu_e\ dv_{\parallel} \tag{11}$$

With the assumption that the mirror force only acts to produce an instaneous reflection at the injection point, s = 0, Equation (9) is independent of μ_e and Equation (11) may be integrated formally to give

$$n_e = \frac{n_o B}{B_o} \int I\ (J)\ dv_{\parallel} \tag{12}$$

where n_o is an arbitrary constant.

The plasma motion may now be found by solving self consistently the equation of electron motion (8) together with the condition of charge neutrality

$$n_e = n_i \tag{13}$$

where the densities are given by Equations (5) and (12) and the action integral by Equation (9).

3. Expansion of a collisionless plasma

The particular form that the ion density function, Equation (5), takes assuming free flight motion for the ions suggests that self similar solutions may be possible for the other quantities involved and we assume that the electrostatic potential, Φ, is given by

$$\Phi = a\ (t)\ \phi\ (s/t) \tag{14}$$

Equation (8), neglecting the mirror force, gives the energy integral $\mathcal{W}$ for the electron motions

$$\mathcal{W} = \frac{1}{2}\ m_e\ v_{\parallel}^2\ - e\Phi \tag{15}$$

and if we assume

$$\mathcal{W} = a(t)\, w\,(s/t) \tag{16}$$

the action integral J, Equation (9), becomes

$$J = (2m)^{1/2} \quad t\, a(t)^{1/2} \oint (w + e\phi)^{1/2}\, d\,(s/t) \tag{17}$$

and is a constant for similar orbits provided

$$a(t) = \left(\frac{t}{t_o}\right)^{-2} \tag{18}$$

This means that J is a time independent function of w and that the solution of the electron Vlasov equation, Equation (10), may equally well be written as a function of w. The electron density is now given by

$$n_e = \frac{n_o B}{B_o} \int g_e(\mathcal{W}\, t^2/t_o^2)\, dv_{\parallel} \tag{19}$$

where

$$g_e\,(w) \equiv I\,(J(w))$$

The condition of charge neutrality, Equation (13), and the equation for the ion density, Equation (5), now give

$$h_i\,(s/t) = \frac{n_o\, t_o}{N} \int_{-\infty}^{+\infty} g_e \left[\frac{1}{2}\, m_e\, (v_{\parallel}\, t/t_o)^2 - e\phi(s/t)\right] d(v_{\parallel} t/t_o) \tag{20}$$

In terms of the variables s/t and $v_{\parallel} t/t_o$ this equation is independent of time and its solutions give self similar solutions for the expansion of the collisionless plasma. Since w is a function of J only Equation (16) implies that for all solutions the electron energy depends inversely on the square of the time t.

As a specific example suppose that

$$g_e\,(w) = \left(\frac{m_e}{2\pi k T_o}\right)^{1/2} \exp\left(-\frac{w}{kT_o}\right) \tag{21}$$

Equation (20) may now be reduced to an expression for the potential

$$\Phi = \left(\frac{t_o}{t}\right)^2 \frac{kT_o}{e} \ln\left(\frac{N h_i (s/t)}{n_o t_o}\right) \tag{22}$$

which for an isotropic Maxwellian ion distribution at the gun, Equation (6), takes the form

$$\frac{e\Phi}{kT_o} = A_1 - \frac{m_i t_o^2}{2 kT_i} \frac{s^2}{t^4} + \frac{2 t_o^2}{t^2} \ln (s/t) \tag{23}$$

and for a one dimensional distribution, Equation (7),

$$\frac{e\Phi}{kT_o} = A_2 - \frac{m_i t_o^2}{2kT_i} \frac{s^2}{t^4} \tag{24}$$

From the definition of w and $\mathcal{W}$ the choice of $g_e(w)$ implies a Maxwellian velocity distribution parallel to the magnetic field for the electrons

$$h_e (v_\parallel) = \left(\frac{m_e}{2\pi kT_e}\right)^{1/2} \exp\left(- \frac{m_e v_\parallel^2}{2kT_e}\right) \tag{25}$$

with a uniform electron temperature T_e independent of position given by

$$T_e = \left(\frac{t}{t_o}\right)^{-2} T_o \tag{26}$$

Thus the electron distribution remains Maxwellian independently of the choice of the ion distribution However the electron distribution is not determined directly by the distribution over energy of the total number of injected electrons.

From the derivation of Equation (19) it may be seen that the electron distribution function integrated over the perpendicular velocities is

$$F (v_\parallel , s) = n_o \frac{B}{B_o} g_e (w) \tag{27}$$

and integrating over a magnetic flux tube the distribution over energy of the total number of injected electrons per unit area at the gun $D(\mathcal{W})$ is

$$D(\mathcal{W}) = \int F \frac{B_o}{B} \frac{\partial v_\parallel}{\partial \mathcal{W}} ds = \frac{n_o g_e(\mathcal{W} t^2/t_o^2)}{(2m_e)^{1/2}} \int \frac{ds}{(\mathcal{W}+e\Phi)^{1/2}} \tag{28}$$

Now it is reasonable to suppose that $D(\mathcal{W})$ is initially determined by the energy spectrum of electrons produced by the gun and Equation (28) shows that the function g_e (w) which determines the subsequent electron distribution in the expanding plasma depends on the form of the potential ϕ (s) as a function in space, given by Equation (22), and hence depends on the ion distribution function. In the special case of a one dimensional Maxwellian ion distribution with the potential given by Equation (24) we find

$$D(W) = \frac{n_o t_o}{kT_o} \left(\frac{\pi kT_i}{8 m_i}\right)^{1/2} \frac{t^2}{t_o^2} \exp\left(-\frac{W t^2}{kT_o t_o^2}\right) \tag{29}$$

For this particular case the energy spectrum does correspond to the subsequent velocity distribution, Equation (25), and is equivalent to a one dimensional Maxwellian distribution. For other ion distribution functions the resulting electron velocity distribution would not be Maxwellian.

For an isotropic Maxwellian ion distribution it is of interest to note that the potential given by Equation (6) is sufficient to trap the electrons and that the mirror force is not required to ensure electron trapping during the plasma expansion.

Not all choices of the distribution functions for the ions and electrons lead to solutions of the system of equations. As an example consider the choice of g_e (w) given by

$$g_e (w) = \left(\frac{2 m_e}{\pi kT_o}\right)^{1/2} \frac{w}{kT_o} \exp\left(-\frac{w}{kT_o}\right) \tag{30}$$

for positive w, and for negative w set g_e (w) equal to zero. For this choice the point in space at which the potential Φ is zero is accessible to all of the electrons and they there have a distribution over velocities similar to Equation (6) for the ions. At other points the electron distribution takes a different form. For regions with negative ϕ the condition of charge neutrality, Equation (20), gives

$$h_i (s/t) = \frac{n_o t_o}{N} \left(1 - \frac{2e\phi}{kT_o}\right) \exp\left(\frac{e\phi}{kT_o}\right) \tag{31}$$

The right hand side of this equation has a maximum value at $2 e\phi/kT_o = -1$. Now at large distances the potential must tend to $-\infty$ so as to reflect all electrons travelling downstream, assuming there is no net electron current.

Also the point at which the potential is zero, where the electron distribution takes the required form, should be included. Together these requirements imply that the critical potential giving a maximum must occur at some point away from the origin and that the particle density is a maximum there. Then Equation (31) cannot be satisfied with the ion distribution given by Equation (7) since this gives a maximum density at the origin only. For the ion distribution defined by Equation (6) the resulting density distribution has one maximum which must coincide with the critical potential and the potential must be a monotonic function of position. However the potential near the origin must then tend to $+\infty$ accelerating all the electrons into a low density high energy beam, which must be reflected by an extreme mirror force. Such a situation is physically unreasonable particularly as the reflected counterstreaming electron beam would drive two-stream instabilities.

These results show that not all choices of the functions $g_e(w)$ and $h_i(v_\parallel)$ lead to reasonable solutions and in some cases solutions may not even exist for the smooth expansion of the plasma. If electrons could be injected in an appropriate way this suggests that the initial conditions may lead to situations with large departures from charge neutrality leading to violent fluctuations in potential such as observed for some experiments in the precursor plasma (Lindberg and Kristoferson 1970).

4. Discussion

From the results derived above for a completely collisionless plasma expansion it may be seen that the electron energy $\mathcal{W}$ has the time dependence

$$\mathcal{W} \sim t^{-2} \tag{32}$$

where t is the expansion time (c.f. Equation (16) and the condition that J is a function of w only). Since the length over which the plasma has expanded is proportional to t this corresponds to the standard result that for a one dimensional expansion the effective ratio of specific heats $\gamma = 3$. For the case of collision dominated electrons the appropriate value is instead $\gamma = 5/3$ and following the ion motion, Equation (5) implies that the local electron temperature is

$$T_e \sim n_e^{2/3} \sim \left(\frac{B}{t}\right)^{2/3} \qquad (33)$$

The electrons are cooled both by the downstream expansion and the radial expansion implied by the changing magnetic field.
The ion acceleration will be small if the energy lost by the electrons is less than the ion energy. The analysis presented above applies when this condition is met. If during the initial part of the expansion the electrons have large energies the ions will be significantly accelerated and the present analysis applies once the energy transfer has been sufficient to reduce the electron energy well below that of the ions.

From the assumption that the energy of the electrons is taken up by the ions during the expansion of the plasma, as argued above the initial electron energy cannot excede $\simeq 300$ eV. Taking a low estimate of the downstream electron temperature, 5 eV, the change in energy can be accounted for by the expansion occuring over 1.3 - 10 μs or over a length 0.39 - 3 m with a typical streaming velocity 3×10^5 m/s (Lindberg and Kristoferson 1970) assuming collisionless electrons. For collisional electrons the same change in energy would result from a change in density from 4.6×10^{21} m^{-3} to 10^{19} m^{-3} which is smaller than expected since the drop in magnetic field strength from 2 T to 2×10^{-2} T already gives a change in density by two orders of magnitude (c.f. Equation (5)) quite apart from a further reduction due to downstream expansion.

In the collisionless case, since the initial length occupied by the plasma is less than 0.39 m and the energy reduction is an over estimate, a re-thermalisation process may be required to transfer energy from the ions to the electrons (c.f. Sudo _et al_ 1978). If the electrons are collision dominated however the effect of adiabatic cooling in the downstream region due to the change in the magnetic field strength can be reduced by thermal conduction from regions nearer the gun where the temperature is higher due to the greater field strength (c.f. Equation (33)). In the collisional case the plasma expansion leads to temperature gradients.

The electron distribution function in the collisionless case has been derived assuming that all of the electrons are reflected by the electrostatic potential. This is necessary for the assumed unbounded expansion since at large distances the ion density and situation the expanding plasma must eventually reach the walls of the apparatus at which the appropriate condition is that the total current is zero in the case of a non-conducting wall. This zero current condition is maintained through the presence of a wall sheath reflecting some of the electrons back upstream. The electrons which having reached the walls are reflected and become trapped between the magnetic mirror at the gun and the wall sheath do not loose energy in the reflection process and remain more energetic than in the case of free expansion. The electron current to the wall, which matches the ion current there, is carried by the more energetic electrons which are not reflected there. The low energy electron population must therefore expand less rapidly than the ions to compensate for the non-return of the high energy electrons absorbed at the wall. In this way a situation can be set up in which the ions have a relative velocity with respect to the low energy electrons which may for example drive ion-acoustic instabilities heating the electrons and hence provide a re-thermalisation process maintaining the electron temperature.

From the discussion in the introdution it is clear that intermediate situations where the electrons are neither completely collisionless nor collision dominated are relevant to the interpretation of experiments. Deflection times were evaluated for electrons with a mean thermal velocity, but if instead the whole range of velocities is considered Equation (1) indicates a strong dependence on the velocity so that a considerable proportion of the electrons may have quite different deflection rates and in particular those with higher velocities will be more nearly collisionless. With this in mind the basic features of the collisionless electron expansion are a guide to the behaviour of the high velocity component in the intermediate cases. The situation is such that a population of runaway electrons may often be produced in response to electric fields set up in interaction experiments. (Lindberg and Kristoferson 1971, Lindberg 1978).

5. Conclusions

The properties of an expanding plasma injected from an electrodeless plasma gun and flowing in the presence of a longitudinal magnetic field are studied. Typical experimental parameters are such that the ions are collisionless but the situation for the electrons ranges from collisionless to collision dominated. The ion expansion is free but the electrons must be trapped by an ambipolar electric field. The electrons loose energy adiabatically as a result of the expansion against the containing electric field and the ions are consequently accelerated. Re-thermalisation processes must be considered to account for the observed downstream electron temperatures. It is argued that modifications to the electron distribution function in the collisionless case due to the downstream interaction with the walls of the apparatus can lead to micro-instabilities heating the electrons.

The properties of the undisturbed plasma flow should be carefully considered when interpreting the results of interaction experiments.

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Figure Captions

Figure 1. Plasma is injected into the region of strong magnetic field $\mathbf{B}$, on the extreme left and expands into the downstream region. Electrons e^- are reflected by the ambipolar electric field $\mathbf{E}$ and are consequently trapped. The ions X^+ move freely downstream. The coordinate s is the distance along a field line from the injection region.

References

Alfvén, H. and Fälthammar, C.-G., 1963, Cosmical Electrodynamics, Fundamental Principles, (Oxford: Clarendon Press).

Bieger, W., Gresser, H., Noll, P. and Tuczek, H., 1963, Beschleuningung von Plasma, Z. Naturforschung, 18a, 453.

Danielsson, L., 1970, Experiment on the Interaction between a Plasma and a Neutral Gas, Phys. Fluids, 13, 2288.

Danielsson, L. and Brenning, N., 1975, Experiment on the Interaction between a Plasma and a Neutral Gas II, Phys. Fluids, 18, 661.

Hirano, K., Kondo, Y. and Shimoda, K., 1973, Experimental Study of a Conical Theta-pinch Plasma Gun, Japan. J. Appl Phys., 12, 270.

Karlsson, E.T., 1971, Plasma Flow in the Magnetosphere, Cosmic Electrodynamics, 1, 474.

Kristoferson, L., 1969, Laboratory Simulation Experiment on Solar Wind Interaction with the Moon, J. Geophys. Res., 74, 906.

Lichtenberg, A.J., 1969, Phase Space Dynamics of Particles, (New York: J. Wiley).

Lindberg, L., 1969, Experiments with an Electrodeless Plasma Accelerator, Royal Institute of Technology, Stockholm, TRITA-EPP, 69-15.

Lindberg, L. and Kristoferson, L., 1970, Electric Probe Measurements in a Moving and Magnetised Plasma, Plasma Phys., 12, 831.

Lindberg, L. and Kristoferson, L., 1971, Reverse Deflection and Contraction of a Plasma Beam Moving Along Curved Magnetic Field Lines, Cosmic Electrodynamics, 2, 305.

Lindberg, L., 1978, Plasma Flow in a Curved Magnetic Field, Astrophys. Space Sci., to be published.

Marshall, G., 1958. Acceleration of Plasma into a Vacuum, Proc. 2nd Int. Conf. on Peaceful Uses of Atomic Energy, 31, (Geneva: United Nations) p. 341.

Oki, T., Kondoh, Y. and Hirano, K., 1973, Effects of Multipole Field on the Plasma Production with a Conical Theta-pinch Gun, Japan. J. Appl. Phys., 12, 1050.

Persson, H., 1963, Electric Field Along a Magnetic Line of Force in a Low-density Plasma, Phys. Fluids, 6, 1756.

Persson, H., 1966, Electric Field Parallel to the Magnetic Field in a Low-density Plasma, Phys. Fluids, 9, 1090.

Petschek, H.E., 1957, Experiments at AVCO, Magnetohydrodymics, ed. Landshoff, R., (Stanford: Stanford University Press).

Spitzer, L., 1962, Physics of Fully Ionized Gases, (New York: J. Wiley).

Sudo, S., Sato, K. N. and Sekiguchi, T., 1978, Re-thermalisation and Flow of Laser-produced Plasmas in a Uniform Magnetic Field, J. Phys. D.: Appl. Phys., 11, 389.

Waelbroeck, F., Leloup, C., Poffé, J.P., Evrard, P., Der Agobian, R. and Véron, D., 1962, Electrodeless Plasma Gun, Nuclear Fusion: 1962 Supplement, part 2, p. 675.

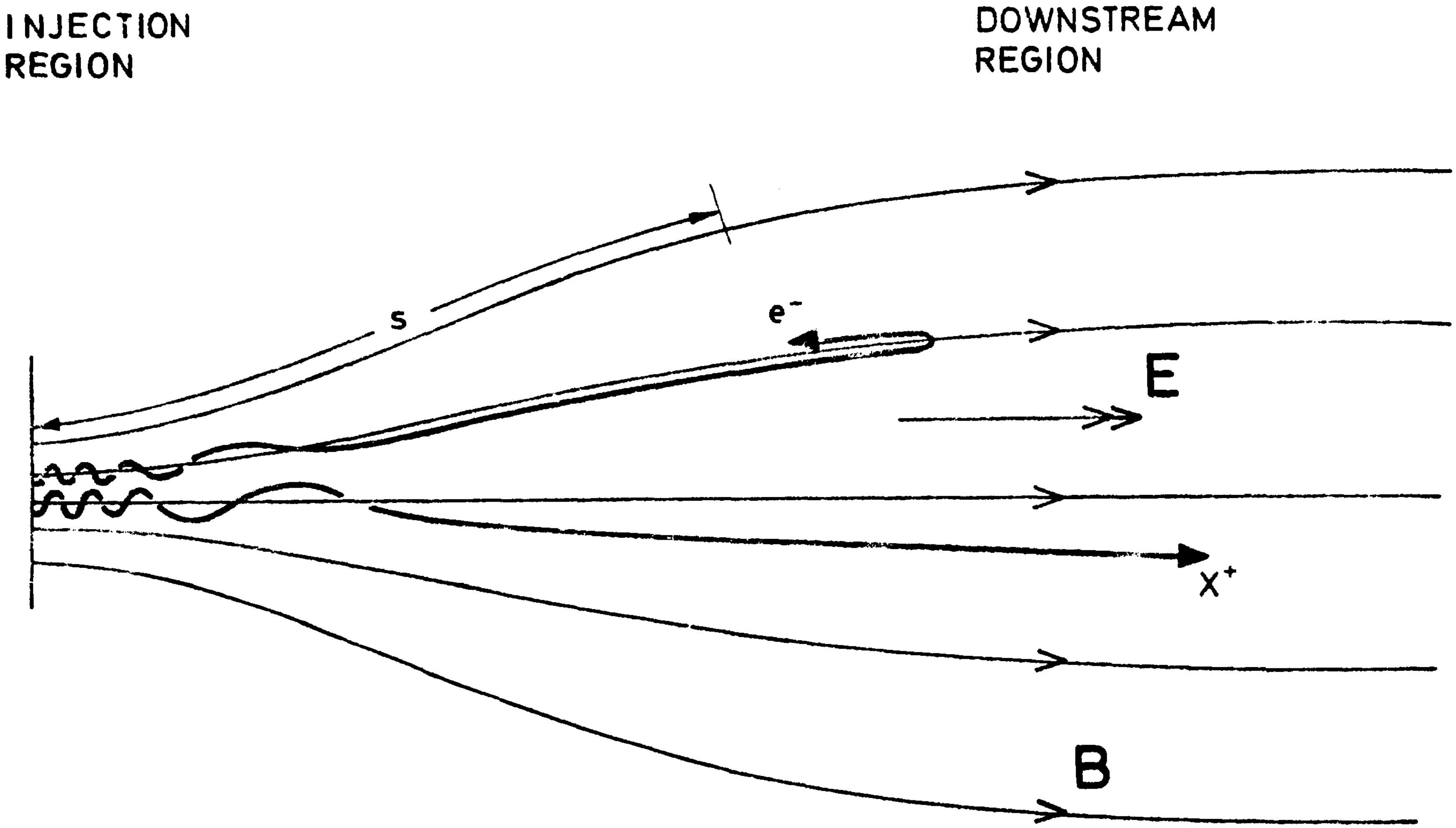

Fig. 1

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EXPANSION OF A PLASMA INJECTED FROM AN ELECTRODELESS GUN ALONG A MAGNETIC FIELD

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The dynamics of a plasma injected from an electrodeless plasma gun (conical theta pinch) into a longitudinal magnetic field is studied theoretically. For the experiments referred to, conditions are collisionless for the ions and range from collision dominated to collisionless for the electrons. During the expansion of the injected plasma the electrons are trapped by an ambipolar electric field maintaining charge neutrality and a magnetic mirror at the gun. The development of the ion and electron distribution functions for the completely collisionless case is considered in detail. Assuming that the acceleration of the ions is negligible and taking the action integral over an electron oscillation to be an adiabatic invariant self similar solutions are found. The electrons lose energy adiabatically as a result of the plasma expansion and it is suggested that a re-thermalisation process must operate in experimental situations to account for the observed electron energies.

Key words: Plasma source, plasma dynamics, adiabatic invariant, Vlasov equation, ambipolar electric field.