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ENERGIZATION OF ELECTRONS IN A
PLASMA BEAM ENTERING A CURVED
MAGNETIC FIELD

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Abstract

Earlier experiments have indicated that suprathermal electrons appear when a collisionless plasma flowing along a magnetic field enters a region where the magnetic field is curved. In the present investigation newly developed methods of He-spectroscopy based on the absolute intensities of the He I 3889 Å and He II 4686 Å lines are utilized to study the electron temperature and to estimate the population of non-thermal electrons. The density of helium added for the diagnostic purpose is so low that the flow is not disturbed. It is found that the intrusion of the plasma into a curved or transverse field gives rise to a slight increase (15-20%) in the electron temperature and a remarkable increase in the fraction of non-thermal (>100 eV) electrons from below 1% to as much as 20-25% of the total electron population. There are also indications that the energization of electrons is particularly efficient on that side of the plasma beam which becomes polarized to a positive potential when entering the curved field. The experiments are confined to the case of weak magnetic field, i.e. only the electrons are magnetically confined. New details of the electric field and potential structure are presented and discussed. Electric field components parallel to the magnetic field are likely to energize the electrons, probably through the run-away phenomenon. Details of the microwave interferometer used to measure the density are described in a separate report.

1. Introduction

When a collisionless plasma beam moving in a longitudinal magnetic field suddenly enters a region where the magnetic field is bent, the plasma beam is deflected in the opposite direction to the bend. It also contracts to a flat structure parallel to the plane of the magnetic field (Lindberg and Kristoferson 1971, 1972). If the bend is more abrupt and goes over to a purely transverse magnetic field, the reverse deflection is not so pronounced, and a plasma flow in transverse field is obtained (Lindberg 1976). A detailed report on the observed phenomena together with a qualitative discussion of the physical processes was published by Lindberg (1978). Similar observations were made by Tanaka et al (1972) and Komori et al (1977, 1979) under quite different experimental conditions.

Phenomena of this kind could be of great interest in many contexts, e.g. in space physics for studies of the interaction of space plasma with cosmical bodies, for model experiments simulating such phenomena, and in fusion research.

The reverse deflection is understood as an effect of the induced electric field $\underline{E} = -\underline{v} \times \underline{B}$ when the plasma enters the region with a transverse magnetic field component. As measurements have shown (Lindberg 1978, p. 211) part of this electric field propagates upstream in the beam where it gives rise to an $\underline{E} \times \underline{B}$ -drift of all particles, which results in the reverse deflection. An observation of particular interest is the occurrence of a supra-thermal electron flux directed upstream in the region of flow-parallel field, on that side of the plasma beam which becomes polarized to negative potential (Lindberg and Kristoferson 1971, 1972). On the basis of a discussion of the current system and potential distribution in the plasma Lindberg (1978) postulated the existence of a similar, more intense electron flux directed downstream on the opposite side of the plasma beam, which is polarized positive.

In the present investigation we have utilized recently developed methods of helium spectroscopy (Brenning 1977, 1979) to study the electron energy distribution. The electric field and potential distribution is measured by high impedance probes and discussed

in connection with the current system set up in the plasma.

We study three cases, one where the magnetic field is purely longitudinal, one where the magnetic field changes to purely transverse, and one where it makes an angle of 45° with respect to the original direction of the flow. In order to isolate the effects caused by the transition, we first examine the plasma for the first case, where the magnetic field is parallel also at the end of the flow. The time-of-flight from the plasma source is sufficiently long to ensure thermalization of the electrons with energies < 100 eV, while the energy distribution for higher energies still could be non-Maxwellian. With use of the spectroscopic methods it is found that the thermal part of the electron energy distribution has a temperature of 5-7 eV, and that less than 1% of the electrons have energies > 125 eV.

When the magnetic field is changed to be transverse at the end of the flow, the electron energy distribution becomes drastically altered in the region of transverse field. The fraction of the electrons with $W_e \gtrsim 125$ eV is increased to up to 25% of the total population for the first arriving plasma. This high-energy fraction then decreases in time to typically 10% after 10 μ s of plasma flow. We have also found that the electron energy distribution is influenced differently on the two sides of the beam that are polarized to positive and negative potential in the transverse \underline{B} -field. The temperature in the thermal part of the population increases with typically 1 eV to 6-8 eV. The electron-electron collision time is sufficiently short to keep the low-energy part of the electron population ($W_e \lesssim 10$ eV) at least approximately Maxwellian during the transition from flow-parallel to transverse field.

The only available energy source for the observed electron heating in transverse \underline{B} field is the kinetic energy of the ions in the plasma stream, which is around 7000 eV per ion in the first arriving plasma, and then decreases in time to 100-200 eV after 10 μ s of plasma flow. The energy transfer to the electrons may be due to electric field components parallel to the magnetic field arising in the connection region between the parallel and the transverse magnetized plasma.

2. Experimental device and diagnostics

The plasma source is a conical theta pinch device, Fig. 1. A cloud of hydrogen is let in by a fast acting gas valve in the conical coil. Discharge of a small capacitor (PD) pre-ionizes the gas. The plasma is then produced by a heavy, damped sinusoidal current in the main coil, MD (32 kV, 150 kA, 300 kHz), and a beam of fully ionized plasma is ejected in the axial direction in a fraction of a microsecond. The plasma is injected into a section of longitudinal magnetic field, the "drift space", Fig. 1, with $B \approx 0.1$ T, where a certain thermalization takes place, at least among the electrons. Then follows a section of expanding magnetic field. Finally the plasma enters the "interaction space", where the magnetic field can be either longitudinal, ($B = 0.015$ T), tilted 45° with respect to the plasma flow direction, or purely transverse.

The comparatively weak magnetic field has the consequence that the electrons only are confined by the magnetic field and can be expected to obey adiabatic theory, while the ions are confined by charge separation electric fields. The plasma flow in the interaction space has a time duration of typically 10-20 μ s, with a flow velocity that decreases with time ($3 \cdot 10^5$ ms $^{-1}$ for the first arriving plasma, $1.5 \cdot 10^5$ ms $^{-1}$ after 10 μ s of flow). The maximum plasma density in the interaction space is $2 \cdot 10^{18}$ - $4 \cdot 10^{18}$ m $^{-3}$. The coordinate system x, y, z referred to in the text has its origin in the center of the interaction space.

All measurements in this experiment are made in the interaction space, a distance of 2.7 m from the gun. The diagnostic methods are electric field and density probes, microwave interferometry and spectroscopic line intensity measurements.

The electric field is measured by double probes with 0.6 mm rods separated 20 mm and connected through 1 Mohm voltage dividers to difference amplifiers, Fig. 2. Electron density is measured with biased floating double probes (20-30 V) connected to current transformers (Lindberg 1976), and with a 4 mm microwave interferometer, as an average along a line almost coincident with the light path to the spectrograph. The interferometer is an improved version of Hotston and Seidl's (1965) interferometer, described in a separate report (Lindberg and Eriksson 1980).

For the spectroscopic measurements, the interaction space, Fig. 1, is filled with a cloud of helium which is let in by a fast-acting gas valve. The gas density has been kept so low that the plasma flow and the electron energy distribution are uninfluenced by the presence of the helium gas.

The light from the helium cloud is analyzed in a 1.5 m spectrograph. Two channels are used, one for the He I 3889 Å (3^3P-2^3S) line and one for the He II 4686 Å (4^2F-3^2D , etc.) line. The photomultipliers are individually calibrated against a tungsten ribbon lamp.

3. Spectroscopic measurements

3.1 Evaluation of line intensities

In the prevailing parameter range the evaluation of the measured line intensities is far from straightforward. One first needs measurements of the projected electron density in the light path of the spectrograph, since electron impact is the dominating excitation process. These are obtained individually for each shot from the microwave interferometer. One also has to consider the detailed excitation processes that lead to excitation of each line. The 3889 Å line was chosen because it is unique among the He I lines in the respect that this can be done with some accuracy for our plasma parameters (Brenning 1977, 1979). Since the plasma density is too high for coronal excitation balance to apply, and too low for models based on local thermal equilibrium, the line strength is determined by a complicated network of excitations from the ground state and from the metastable levels, collision-induced transitions between excited levels, and spontaneous radiative transitions including cascading. This problem has been studied by Brenning (1979), who gives methods by which the secondary processes can be taken into account for the 3889 Å line.

The problem is in our experiment complicated by the fact that the metastable level population n_{2^3S} , which strongly influences the line strength, is not constant in time but gradually builds up from zero during the experiment. Therefore, it is necessary to use an iterative procedure to obtain the electron temperature: first, a rough measure $T_e(t)_1$ of the electron temperature as a function of time is obtained from the 3889 Å line intensity

under the assumption that n_{2^1S} is zero. From $T_e(t)_1$, a first approximation of $n_{2^1S}(t)$ is then calculated by integration of the rate equation for excitation to and from 2^1S . The next step is to use this value of $n_{2^1S}(t)$ to obtain $T_e(t)_2$, and so on. This iterative process converges very rapidly, and it has never been necessary to carry the calculations further than two steps. The temperature obtained this way is necessarily an average, since it is based on the integrated light intensity and electron density across the beam.

For the 4686 Å line, the excitation process is much simpler. Excitation from the metastable levels can always be disregarded, and excitation from the ground state of the He^+ -ion is negligible if $n_{\text{He}^+}/n_{\text{He}}$ is $\ll 0.1$. Due to the short time duration of our experiment, $n_{\text{He}^+}/n_{\text{He}}$ is always < 0.01 , so that only excitations from the ground state needs to be considered. We can therefore use the cross section for excitation measured by Hughes and Weaver (1964) with only a small correction (a factor of 1.5) to take into account the fact that the $n = 4$ levels of the He^+ -ion are degenerated in our experiment, but not in the collision chamber used by Hughes and Weaver. Degeneration of the $n = 4$ levels is caused both by electron impact and, for the case of transverse magnetic field, by Stark mixing due to the induced electric field. The effect of spatial variations in the excitation of the 4686 Å line is discussed in section 4.1.

3.2 The neutral gas density

The helium spectroscopic methods can only be used as a reliable diagnostic tool if the gas density is so low that the presence of the gas does not influence the properties of the plasma. This assumption can be tested experimentally if we examine how measured quantities vary with helium gas density. The most interesting observation in this experiment is the occurrence of suprathermal electrons for the case of transverse magnetic field. Fig. 3 shows the spectroscopically determined fraction of $W_e > 125$ eV electrons as a function of n_{He} . The constancy of this fraction at low helium densities confirms that the helium gas does not influence the plasma at the low densities (around $5 \cdot 10^{18} \text{ m}^{-3}$) used for the helium spectroscopic measurements.

For higher helium densities, "critical-velocity" interaction between the plasma and the neutral gas may occur (see e.g.

Danielsson and Brenning, 1975). Experiments at such high densities are described in a separate report (Brenning 1980).

In that report, the conclusion that the plasma flow is undisturbed at low helium densities is discussed in more detail.

4. Results of the spectroscopic measurements.

4.1 Thermalization of electrons

For the interpretation of the spectroscopic measurements it is essential to know to what extent one can expect thermalization among the electrons during the 10-20 μs time-of-flight from the gun to the interaction space.

During the expansion of the plasma the density decreases from a very high initial value where all the plasma is compressed in the gun, down to typically $2 \cdot 10^{18} \text{ m}^{-3}$ for the plasma that arrives in the interaction space. For an estimate of the electron thermalization time τ_{ee} for different energies, we use as an average during the expansion $n_e \approx 10^{19} \text{ m}^{-3}$. This gives $\tau_{ee} \approx 2 \text{ } \mu\text{s}$ for 100 eV electrons, $\tau_{ee} \approx 6 \text{ } \mu\text{s}$ for 200 eV electrons and $\tau_{ee} \approx 10 \text{ } \mu\text{s}$ for 300 eV electrons (Spitzer, 1962). We can therefore assume a good thermalization among the $W_e < 100 \text{ eV}$ electrons and a decreasing degree of thermalization with increasing energy. The electron energy distribution for energies above $\approx 300 \text{ eV}$ can be completely non-Maxwellian.

For the case with transverse magnetic field the question is whether the collision time is sufficiently short to ensure that the low-energy part of the population is kept Maxwellian during the transition from flow-parallel to transverse field. For the bulk of the thermal population this seems to be the case. The electron-electron collision time for 7 eV electrons is typically 0.5 μs , which is to be compared to the 2.5 μs it takes the plasma to drift from the region where the magnetic field starts to curve to where the spectroscopic measurements are made. We therefore evaluate the measurements under the assumption that the low-energy ($W_e > 30 \text{ eV}$) part of the electron population is not significantly changed from a Maxwellian by the transition.

The spectroscopic measurements are well suited to distinguish between the low-energy part of the electron distribution and the non-Maxwellian high energy tail. The cross section for excitation of the He I line (3889 Å) has a sharp maximum close to the threshold energy (23 eV), and decreases very rapidly with increasing energy. This line therefore is excited by the assumed Maxwellian part of the electron population.

The He II line (4686 Å) has an excitation cross section that increases rapidly from threshold (75 eV) to a maximum around 125 eV, after which it decreases slowly with increasing energy. The energy dependence above 125 eV is such that the product σv_e is remarkably independent of the electron energy (it varies less than 10% between 125 and 400 eV). The intensity of the 4686 Å line is therefore closely proportional to the total number of electrons with energies > 125 eV, independent of their energy. This makes the interpretation simple also for the case when the fraction of high-energy electrons varies spatially in the light-emitting region as discussed in section 4.4. The 4686 Å line intensity then yields the correct fraction of high-energy electrons if both the total electron density and the density of high-energy electrons are integrated across the plasma beam.

4.2 Flow-parallel magnetic field

Fig. 4 summarizes the results for flow-parallel magnetic field. Fig. 4(a) shows the plasma density as a function of time at the center of the interaction space $(x, y, z) = (0, 0, 0)$, and Fig. 4(b) shows the electron temperature kT_e , obtained from the 3889 Å line intensity. For these measurements the helium density was kept so low ($4 \cdot 10^{18} \text{ m}^{-3}$) that the plasma was uninfluenced by the presence of the helium. It is noted that the electron temperature decreases with time from 7 eV to 5 eV during 8 μs of plasma flow. Background light at 4686 Å made it impossible to measure the density of electrons with energies above 125 eV. We can only conclude with certainty that these electrons are fewer than 1% of the total electron population, since the contribution to the 4686 Å line intensity otherwise would have been measureable above the background.

4.3 Transverse magnetic field

The results for transverse magnetic field are shown in Figs 5(a-c). The 4686 Å radiation is much stronger than for parallel magnetic field, and the problem with background radiation is eliminated. The thermal part of the population is found to be somewhat hotter (typically 1 eV) than for the case with purely flow-parallel magnetic field, but shows the same time dependence with a temperature decrease from 8 eV to 6 eV during 8 μ s of plasma flow.

However, the effect on the high-energy electrons is extremely pronounced (Fig.5(c)). The fraction of electrons with energies >125 eV is typically 20% for the first arriving plasma, and then decreases with time to reach 10% after 10 μ s of plasma flow. The shot-to-shot variation is rather large; typically $\pm 4\%$, as indicated with bars in Fig.5(c).

Since these measurements were made with the spectrograph looking along the x-axis, the results in Figs 5(b) and 5(c) represent averages across the plasma beam.

4.4 Curved magnetic field

In this case our interest has particularly been focussed on the electron velocity distributions in the two boundaries of the beam, which become polarized negative and positive. Earlier Faraday cup measurements showed a backwards flux of energetic electrons in the negatively polarized side of the plasma beam (Lindberg and Kristoferson 1971, 1972; Lindberg 1978). In the positively polarized side of the beam the Faraday cup could not be used because of the obscuring downstream flow of plasma. However, a discussion of the electric circuit within the plasma gave strong arguments that a similar and even more energetic downstream flux of electrons might be expected in the positively polarized side of the beam.

To investigate this, experiments have now been made with the spectrograph looking parallel to the y-axis at different x-positions, $x = -4$ and $x = +4$ cm. In this case the plasma takes the shape of a flat structure approximately parallel to the y-axis. Then it becomes impossible to measure the density along the light path by means of the microwave interferometer because

of refraction of the microwave beam. With known plasma density, the 3889 Å line gives the temperature, while the 4686 Å line gives the density of suprathermal electrons. When the density cannot be measured, it is still possible to draw some conclusions from the line intensities, but instead of one temperature and one density of high-energy electrons the result is a set of possible combinations of these quantities.

In our case we find that the 4686 Å/3889 Å line intensity ratio varies with typically a factor of two across the beam from $x = +4$ to $x = -4$ cm. This can be understood if the plasma on the positively polarized side has:

- (a) a lower temperature, e.g. a temperature difference of 2 eV across $\Delta x = 8$ cm would correspond to equal densities of high energy electrons on both sides,
- (b) the same temperature but a higher density of high-energy electrons (a factor of 2),
- (c) a higher temperature. In this case, the density of high energy electrons must be increased by more than a factor of 2.

On the basis of our experimental data it is not yet possible to choose between these alternatives, but it is clear that the electron energy distribution is influenced differently on different sides of the plasma beam by the transition from flow-parallel to oblique or transverse magnetic field.

However we see no obvious reasons why the electron temperature should become lower in the positive side of the beam than elsewhere. On the contrary the temperature might rise, because electrons entering a region with higher potential are likely to gain kinetic energy. These arguments support the alternative (c). e.g. that both the electron temperature and, even more, the density of energetic electrons increase. This result, as well as the case (b) are consistent with a (downstream) flux of energetic electrons in the positive side of the plasma, even more energetic than the upstream flux in the negative side of the plasma. This would support the predictions by Lindberg (1978).

5. Electric field and potential

5.1 Lateral variation of the electric field

Magnetic measurements show very small changes ΔB of the magnetic field and small dB/dt as well. This implies that $\text{curl } \underline{E}$ is small, which has the consequence that the electric field is essentially the gradient of a potential, and that electric field components in the y- and z-directions also must exist, in addition to the induced x-components.

A characteristic property of the plasma gun is that the plasma is sent out in a short time interval ($< 0.5 \mu s$) and then expands almost freely in the flow-parallel magnetic field. This implies that the flow velocity u at a distance s from the gun can be simply derived from the time of flight: $u = s/(t - t_{em})$, where t_{em} is the emission time. When moving in the longitudinal magnetic field the plasma has cylindrical symmetry and there is no potential across the beam. When it enters the region with a transverse magnetic field component, we expect a transverse electric field to be induced:

$$\underline{E} = -\underline{u} \times \underline{B} = - \frac{sB}{t-t_{em}} \underline{y} \quad \underline{x} \quad (1)$$

giving rise to a potential difference across the beam. Local measurements of E_x at various points along the x-axis (the $\underline{u} \times \underline{B}$ -direction) show good agreement with this theoretical hyperbola only for the first few microseconds after the arrival of the plasma, Fig. 6. Later on the measured field differs quite much, and may be smaller as well as higher than the expected value.

If, however, the field is measured as an average across the main part of the beam, Fig. 6(a), the agreement is good. On that side of the beam which is polarized to positive potential, the field becomes stronger than expected, Fig. 6(b), and on the negative side it becomes weaker, Fig. 6(c), and may even become zero or negative. Fig. 6 applies to the case of purely transverse magnetic field but similar results are obtained in the case with curved field. The situation is clarified if we use a coordinate system following the plasma; the induced field then

vanishes and we are left with transverse electric fields directed inwards from both sides, forming an approximately parabolic potential trough. This trough serves to confine the ions, which are not confined by the magnetic field in the region with transverse component.

5.2 Potential distribution and particle energies

In the laboratory system the potential distribution becomes highly unsymmetric: In the negatively polarized side of the beam the potential becomes only slightly negative with respect to the upstream plasma, while a high positive potential develops on the positive side (300-1000 V). This can be understood as a consequence of the different magnitudes of particle energies: For the electrons the thermal energy dominates, and even this is quite small, 5-10 eV. If collisions are disregarded this would imply that electrons do not have kinetic energy enough to enter a region with much more negative potential than corresponds to their energy. The ions on the contrary, have high energies, 300 - 1000 eV, mainly as directed energy, and are therefore able to penetrate and cross a region with correspondingly high positive potential. This view was supported by measurements with an ion energy analyzer (Lindberg 1978, p. 215). Ions of a certain energy, sent out simultaneously from the gun, were found to enter the analyzer later when this was placed on the side with positive potential, because they spend longer time with reduced velocity when passing the region with positive potential.

In this context two interesting questions arise, namely how electrons enter the region with positive potential, and how their energy changes. Energetically an energy gain corresponding to the local potential would be possible; in any case it seems likely that the most energetic electrons are to be found on the positive side of the beam. This argument speaks in favour of the alternative (c) in §4.4.

5.3 The skew feature of the reverse deflection

The observation that the transverse electric field which is set up in the plasma has a strong variation in the lateral (x-) direction may also explain why the plasma cross-section

under certain conditions appears skew or tilted in the region of curved field. This was observed by Lindberg and Kristoferson (1972) when the beam cross-section was made visible by letting the plasma collide with a framework of thin glass wires, which emitted light when hit by the plasma. One of those pictures is reproduced in the perspective sketch, Fig. 7 (the shadowed area). In this case the plasma gun was operated with negative magnetic bias field in the gun, which resulted in an initially somewhat wider plasma beam. It is seen that the reverse deflection is strongest on that side which is polarized to positive potential (the $x < 0$ side), where also the E_x -field in the interaction space is strongest. Since the reverse deflection is caused by the upstream E_x -field, we conclude that the lateral variation of the E_x -field is preserved when this field propagates upstream.

6 The electric current system

Electric circuit aspects are often neglected but nevertheless very important in plasma physics (Alfvén 1979, 1980). Although we do not understand the processes by which the plasma enters the region with transverse field, we have to face the experimental fact that one part of the plasma beam has a great potential difference across itself while another part (upstream) has none or very small potential difference. The region with great potential difference can be seen as a "generator region", trying to send currents into loops upstream as well as downstream (if plasma is present there). As discussed by Lindberg (1978) regions with electric field components parallel to the magnetic field can be expected and electrons may be accelerated in these regions, e.g. by the run-away process ("weak field run-away") (Alfvén and Fälthammar 1963). This could give rise to fluxes of non-thermal electrons directed upstream and downstream.

Because of the comparatively weak magnetic field used in our experiments we could expect only the electrons to be magnetically confined and obey adiabatic theory, while the ions must be confined by electric charge separation fields. This is consistent with the potential trough discussed in §5.1. This aspect also gives a possibility to estimate longitudinal current densities on the basis of the measured electric field. The current density is com-

posed of the average drift motions of ions and electrons $\underline{j} = ne(\underline{u}_i - \underline{u}_e)$. For the ions the velocity is approximately the flow velocity, for the electrons it is mainly the electric drift velocity: $\underline{u}_e = \underline{E} \times \underline{B}/B^2$. Considering for simplicity the case with purely transverse B-field, Fig.6, we find that in the negative side of the beam the current is mainly carried by the ions, which have the full flow velocity \underline{u} , while the electrons are almost at rest. In the positive side the ions are slowed down somewhat in accordance with the positive potential, but the electron drift velocity exceeds the flow velocity \underline{u} . As a rough order of magnitude estimate we find, in the negative side, assuming the electrons at rest, $\underline{j} \approx ne\underline{u}$, and a typical value would be $3 \cdot 10^4 \text{ Am}^{-2}$. Measurements with Rogowski coils indicate currents of the right sense and approximately the same order of magnitude, 10^4 Am^{-2} . Since the electric drift, which is the dominant drift component, is independent of the actual particle energies, the drift velocity should be almost the same for thermal and non-thermal electrons, namely $\underline{u}_e = \underline{E} \times \underline{B}/B^2$.

Upstream, in the region with flow-parallel magnetic field, currents of the same order of magnitude are expected for continuity reasons. If carried by an average relative drift between all the electrons and the ions only a small relative velocity would be required, comparable to the flow velocity. This is at least a factor of 20 less than the average velocity of the non-thermal electrons ($> 125 \text{ eV}$) which have been indicated by the spectroscopic measurements. Although the upstream density of the non-thermal electrons has not been accurately measured, they can hardly be expected to form uni-directed beams as stated by Lindberg (1978), except initially when accelerated by the parallel electric field components, but rather to oscillate in the direction of the magnetic field or to have a more isotropic distribution. To answer these questions further investigations are required, e.g. polarization measurements on spectral lines (Danielsson and Lindberg 1974).

7 Summary and discussion

Our spectroscopic investigations, together with previous investigations by Lindberg (1978), show that the electron velocity distribution can change drastically when a collision-

less plasma moves from a flow-parallel into a curved or transverse magnetic field. The most interesting observation is the appearance of non-thermal high-energy electrons both upstream and downstream of the region where the magnetic field changes direction. In the upstream region there is a flux of high-energy electrons on that side of the plasma stream which is polarized to negative potential. This flux is directed upstream (Lindberg 1978). In the region of curved or transverse field the fraction of high-energy electrons is up to 20-25% of the plasma density. There are also strong indications that the density of high energy electrons is higher on the positively polarized side of the beam than on the negatively polarized side, and these are likely to form a flux directed downstream. The energy comes from the ions, but still only a small fraction of the ion energy is transferred to the electrons. We think the phenomena observed, i.e. the reverse deflection of the plasma beam, and the energization of electrons, are of a general character, and should be expected in a wide density range. The main requirements should be that the plasma is collisionless and that the directed kinetic energy of the ions greatly exceeds the energy of the electrons, as previously discussed by Lindberg (1978). An open question is whether the fact that in our experiments the ions are not magnetically confined is of decisive importance. It could be argued that the adiabatic condition is always much better fulfilled for electrons than for ions because of the mass ratio, and particularly when the ion energy exceeds the electron energy. Judging from the experiments of Tanaka et al. (1972) and Komori et al. (1977, 1979), at least the phenomenon of reverse deflection occurs also when the conditions for adiabatic ion motion are reasonably well fulfilled.

The theoretical understanding of what happens at the transition to curved or transverse magnetic field is still very vague, and has so far only been discussed on very general principles. It is obvious that the plasma does not behave like a fluid with infinite conductivity, because then it should not be able to move from one region, having no appreciable potential variations across the plasma (the upstream region), into another region where a great potential difference is set up across the plasma

by the induced field. We meet the same difficulty if we apply the drift approximation theory to the electrons and assume no electric fields parallel to the magnetic field, because then the electrons should drift along equipotential surfaces. This indicates that electric field components parallel to the magnetic field exist, and these will provide a mechanism for energizing the electrons, probably by the run-away phenomenon. However, a stationary run-away process would not be possible; in order to accelerate electrons to the observed energies within the transition region (0.5 m) an electric field parallel to B of more than 250 Vm^{-1} would be required. This could very well be set up, but the problem is that already a field of 50 Vm^{-1} would cause run-away of all electrons in less than one microsecond, which is in contradiction with the observations.

We have as a first approach tried to treat the plasma motion as a stationary flow and have disregarded various instabilities that might occur. For instance the run-away process could be dynamic, and take place in a region that moves along the beam, forming a kind of "run-away wave" as discussed by Lindberg (1978). Another possibility is that the accelerated electrons very soon become scattered due to electron-ion two-stream instabilities, as suggested by Budker (1956) and Buneman (1958). Such processes are discussed in relation to experiments on anomalous conductivity by Clark and Hamberger (1979). The presence of instabilities in our experiments is indicated by violent fluctuations on all measured quantities.

It is also conceivable that electrostatic double layers (Torvén 1979, 1980, Block 1978, Carlqvist 1979, 1980) could develop in the regions with parallel electric field.

Another important question concerns the width of the plasma beam. Since the total induced voltage across the beam could hardly exceed a value corresponding to the energy of the most energetic ions, Lindberg (1978) concluded that the width should be comparable to the ion gyro radius in the transverse field, and thus not be related to the initial beam width. This is in agreement with our experiment, but we have not been able to make a systematic investigation using initially wider beams. It might happen that such a beam would split up in a number of beams, as observed in an experiment by Marcović and Scott (1971).

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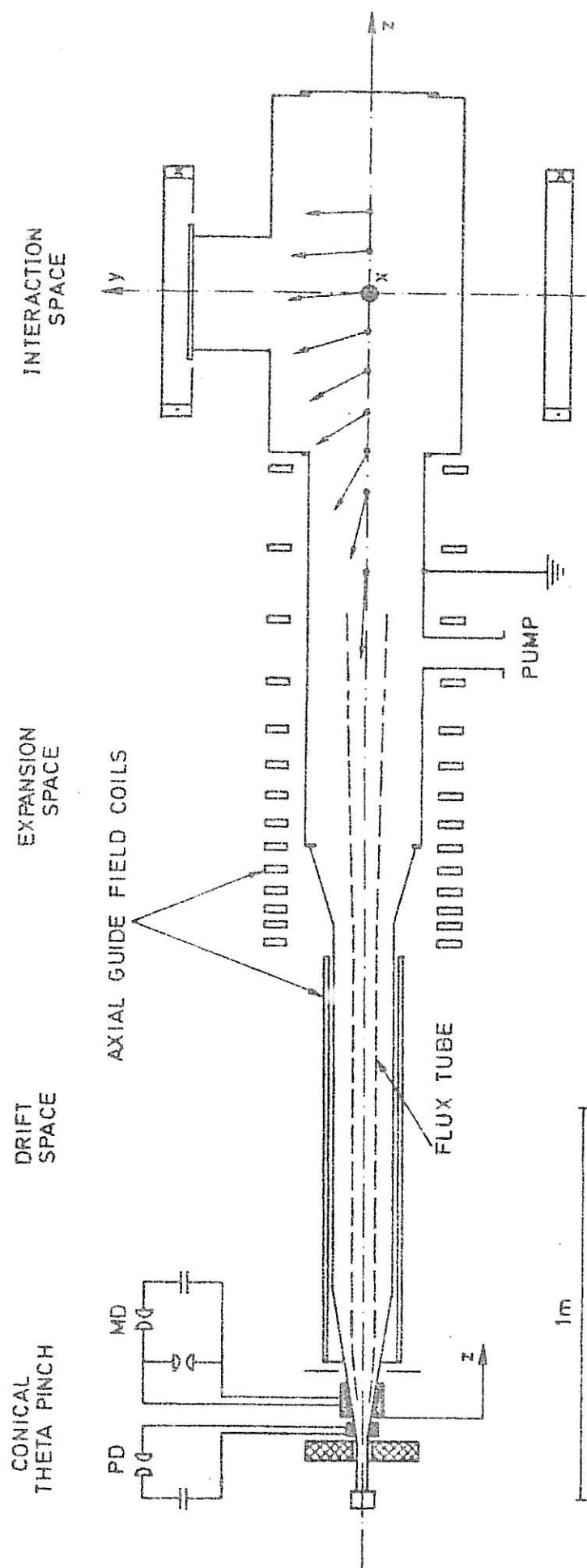


Fig. 1 Cross-section of the apparatus with coordinate axes and vectors indicating the structure of the magnetic field transition.

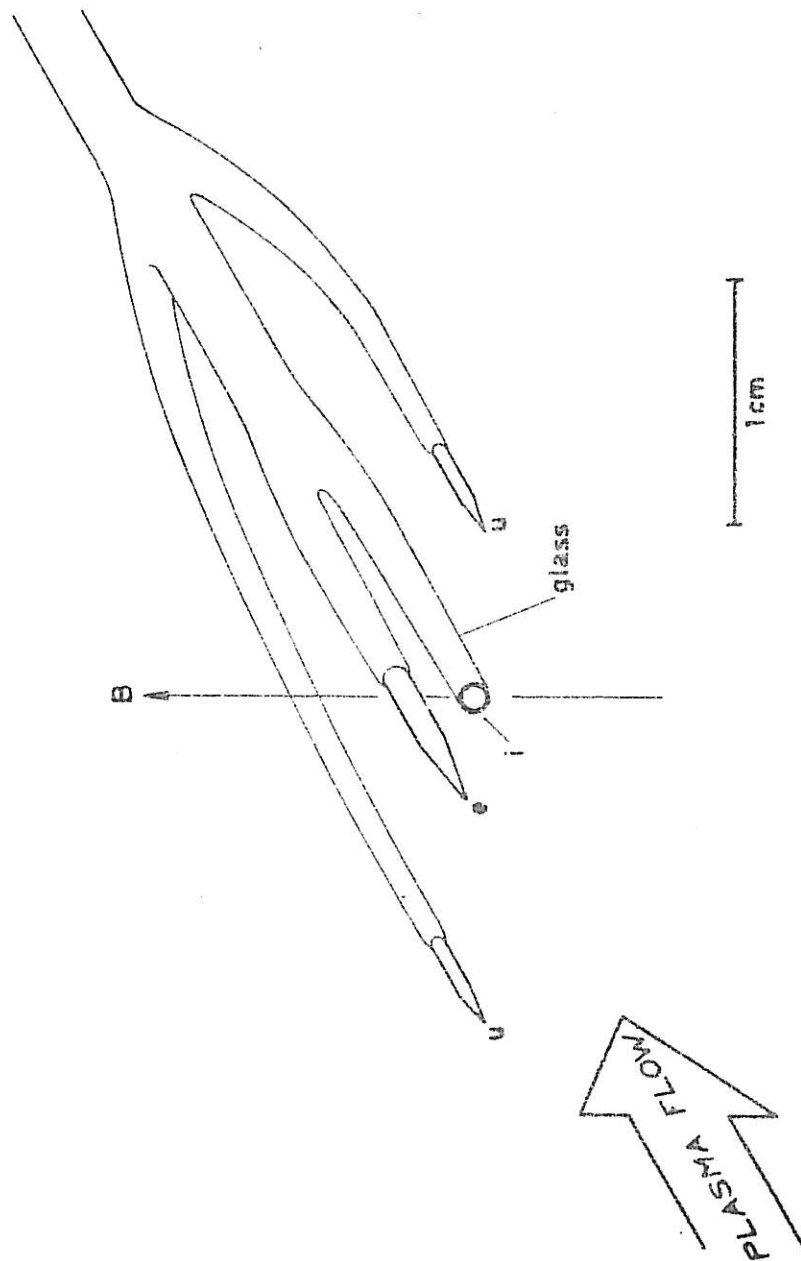


Fig. 2 Combined probe for measurements of both electric field and plasma density. The electric field is measured by the floating double probe u-u connected to a difference amplifier, and the plasma density is measured by the biased (20-30V) floating double probe e-e connected to a current transformer.

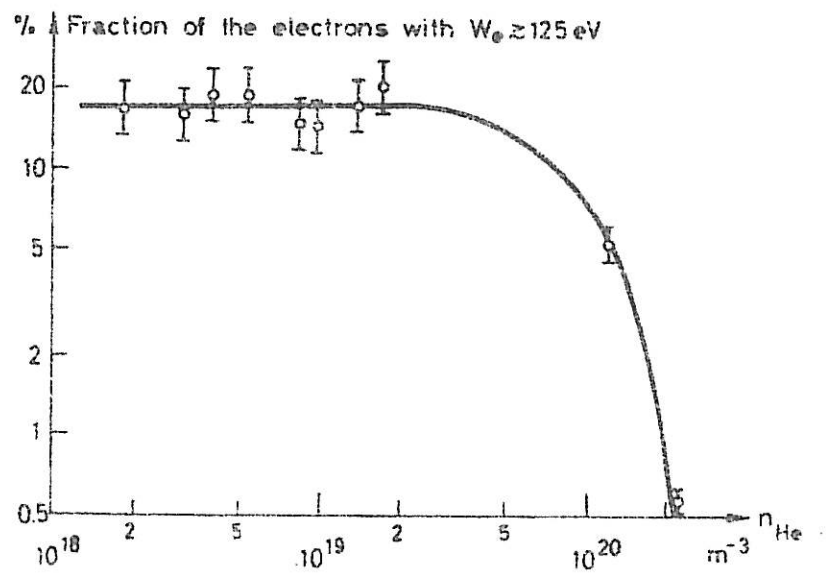


Fig. 3 The fraction of hot ($W_e > 125 \text{ eV}$) electrons for transverse magnetic field and for different helium densities. The measurements are made $6 \mu\text{s}$ after the arrival of the plasma.

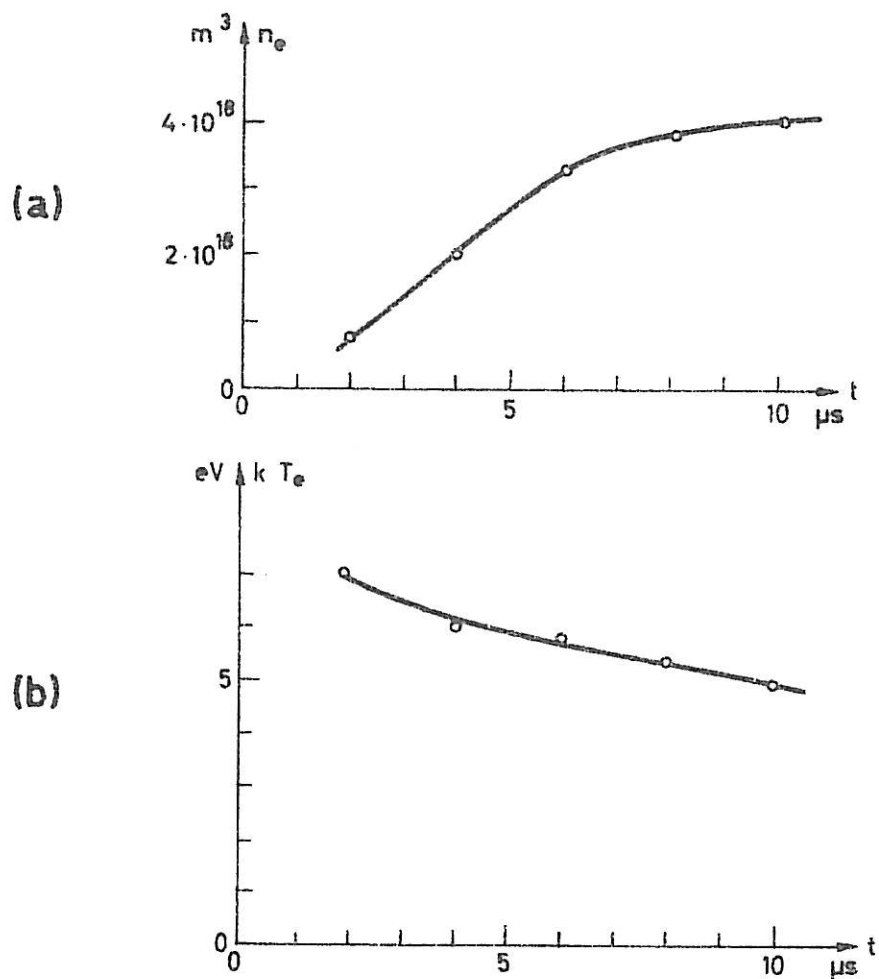


Fig. 4 Plasma parameters in the interaction space for flow-parallel magnetic field and low helium density ($4 \cdot 10^{18} m^{-3}$). $t = 0$ is chosen to be when the plasma arrives at $z = 0$.

(a) The electron density from combined probe and microwave measurements

(b) The temperature of the thermal part of the electron population ($W_e < 100 eV$).

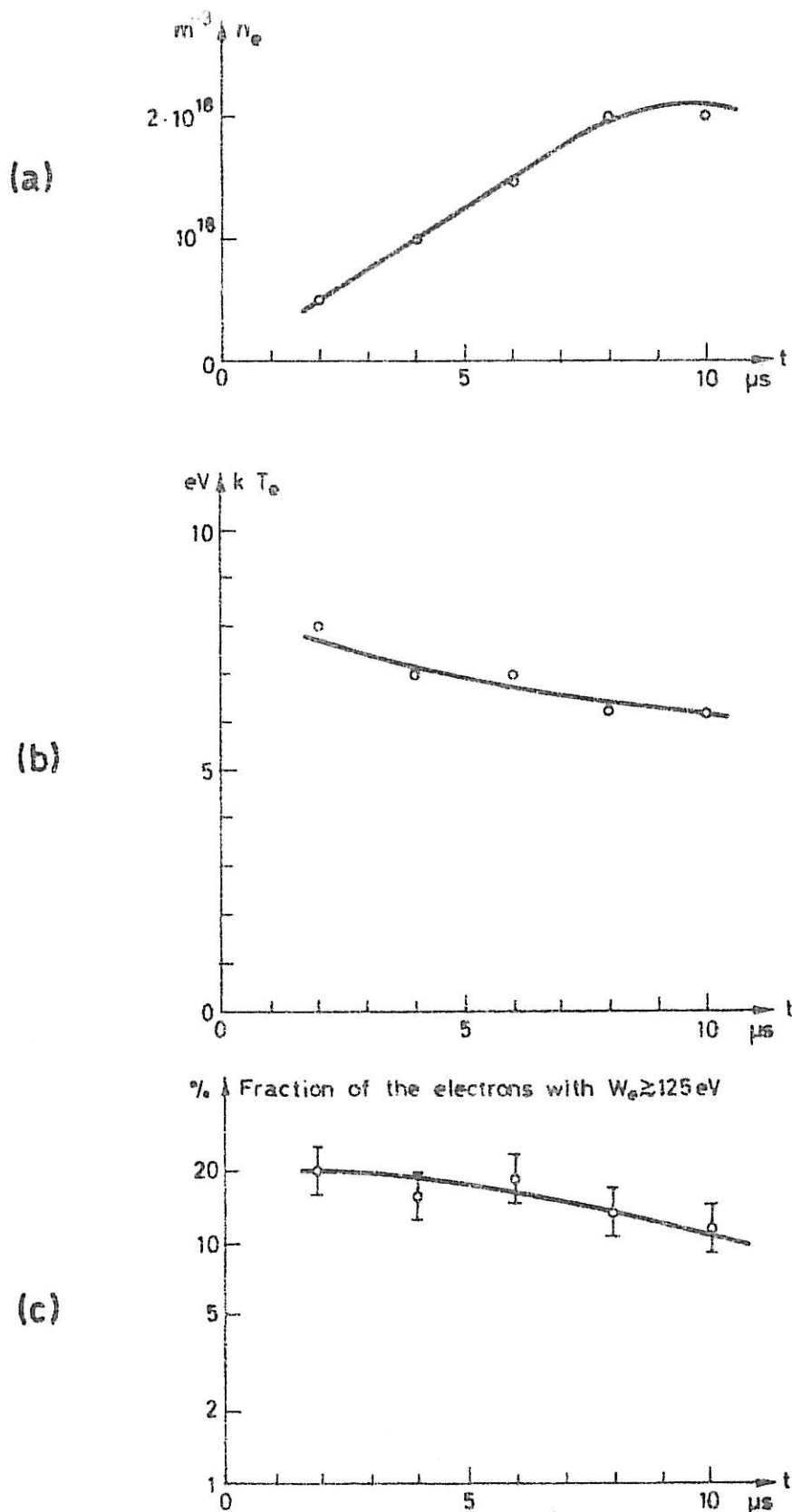


Fig. 5 Plasma parameters in the interaction space for transverse magnetic field and low helium density. $t = 0$ is chosen to be when the plasma arrives at $z = 0$.

(a) The electron density from combined probe and microwave measurements

(b) The temperature in the assumed thermal part of the electron population

(c) The fraction of high-energy ($W_e > 125 \text{ eV}$) electrons

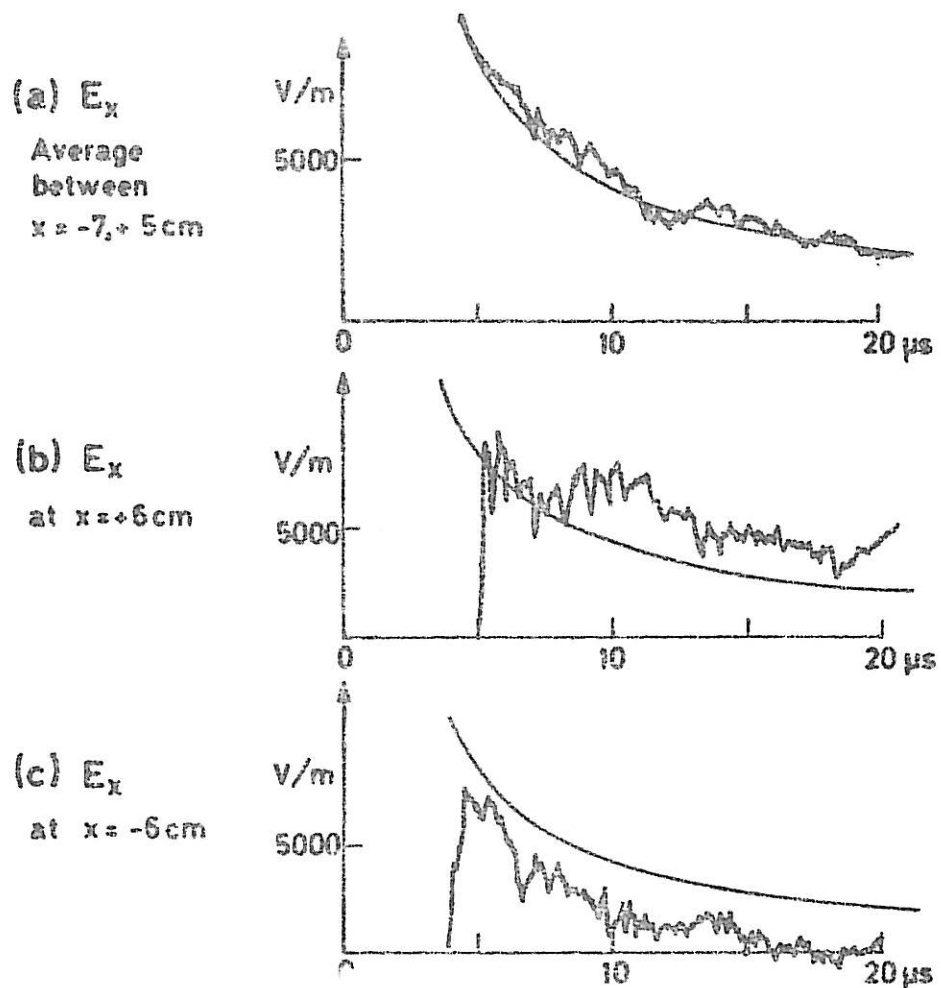


Fig. 6 Transverse induced electric field E_x , measured
 (a) as an average across the whole plasma beam
 (b) locally in the side of the beam polarized to positive potential,
 (c) locally in the side of the beam polarized to negative potential.

The plasma moves in a transverse magnetic field $B_y = -0.02$ T. The hyperbolas indicate the expected induced field $E_{xo} = -sB_y/(t-t_{em})$.

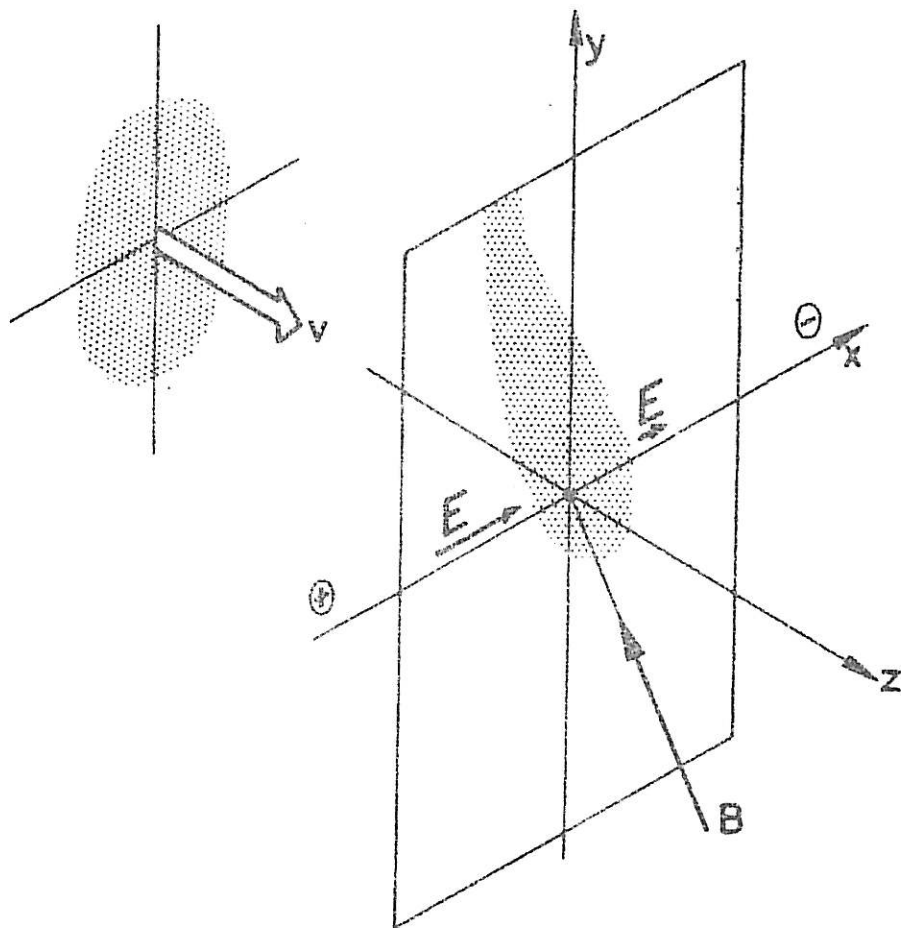


Fig. 7 Perspective sketch illustrating an initially cylindrical plasma beam (in longitudinal magnetic field) entering a curved field. The cross-section changes to a flat skew structure, illustrated by the shaded area (from a photographic observation). The reverse deflection of the beam (upwards) is seen to be strongest on that side where the transverse electric field E_x is strongest, i.e. on the side polarized to positive potential.

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ENERGIZATION OF ELECTRONS IN A PLASMA BEAM ENTERING A CURVED
MAGNETIC FIELD

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Earlier experiments have indicated that suprathermal electrons appear when a collisionless plasma flowing along a magnetic field enters a region where the magnetic field is curved. In the present investigation newly developed methods of He-spectroscopy based on the absolute intensities of the He I 3889 Å and He II 4686 Å lines are utilized to study the electron temperature and to estimate the population of non-thermal electrons. The density of helium added for the diagnostic purpose is so low that the flow is not disturbed. It is found that the intrusion of the plasma into a curved or transverse field gives rise to a slight increase (15-20%) in the electron temperature and a remarkable increase in the fraction of non-thermal (>100 eV) electrons from below 1% to as much as 20-25% of the total electron population. There are also indications that the energization of electrons is particularly efficient on that side of the plasma beam which becomes polarized to a positive potential when entering the curved field. The experiments are confined to the case of weak magnetic field, i.e. only the electrons are magnetically confined. New details of the electric field and potential structure are presented and discussed. Electric field components parallel to the magnetic field are likely to energize the electrons, probably through the run-away phenomenon. Details of the microwave interferometer used to measure the density are described in a separate report.

Key words: Collisionless plasma, Plasma flow, Plasma magnetic field interaction, Electric parallel field, Electron energization, Suprathermal electrons, Plasma diagnostics, Plasma spectroscopy, Helium spectroscopy.