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EXPERIMENTS ON THE CRITICAL
IONIZATION VELOCITY INTERACTION
IN WEAK MAGNETIC FIELDS

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Abstract

The critical ionization velocity interaction is studied experimentally in a configuration with a magnetized plasma stream colliding with a stationary neutral gas cloud. In all previous experiments of this kind the magnetic field (1) has had a component transverse to the plasma flow and (2) has been strong in the sense that the electron gyro frequency, eB/m_e , has exceeded or been approximately equal to the plasma frequency, ω_{pe} . Both these conditions play an important role in existing theories of the critical velocity interaction. The present experiments are performed to determine whether or not such interaction is possible when one of these conditions is not fulfilled, namely when the magnetic field is weak ($eB/m_e \ll \omega_{pe}$). Experiments have been performed both with a transverse and longitudinal (aligned with the plasma flow) magnetic field. It is found that in both cases the critical ionization velocity effect either disappears or becomes too small to be distinguishable among classical collisional processes.

1. Introduction

The critical ionization velocity phenomenon involves the interaction between a plasma and a neutral gas in relative motion. It was originally predicted by Alfvén (1954), who proposed that when the relative velocity exceeds a certain critical value, v_c , the gas should be rapidly ionized and the relative motion braked - even if the density is so low that the momentum exchange by collisions between plasma and neutral-gas particles is negligible. Since Alfvén's original hypothesis many experiments have confirmed the existence of this effect over a wide range of experimental parameters (see for example the review by Danielsson, 1973).

Experiments to study the interaction in its most pure form have used a configuration where a magnetized plasma streams through a stationary neutral gas cloud (Danielsson, 1970; Danielsson and Brenning, 1975; Mattoo and Venkataramani, 1980). The theory for this geometry has been developed by Sherman (1969, 1972) and Raadu (1975, 1978), who argue that the mechanism is driven by a circular process where the modified two-stream instability described by Buneman (1962) plays a central role in energizing the electrons. The theory applies to the case $\omega_{ge} > \omega_{pe}$, where the electrons are accelerated primarily parallel to the magnetic field. While there is ample experimental confirmation of the interaction in the presence of a transverse magnetic field (which in the case relevant to Alfvén's original hypothesis) it has not been experimentally determined how strong the magnetic field needs to be and whether a magnetic field component transverse to the plasma flow is necessary. In view of the theories just mentioned it is especially important to establish whether the critical velocity interaction occurs at all when the magnetic field is either aligned with the plasma flow or so weak that $\omega_{ge} \ll \omega_{pe}$. The experiments reported here address this question.

2. The Experimental Device

The apparatus is of the same type as that used in the experiments where the critical ionization velocity mechanism was studied by Danielsson (1970), and Danielsson and Brenning (1975). We will here refer to these experiments as the "previous experiments". Detailed descriptions of the devices can be found elsewhere (Danielsson, 1970; Brenning et al., 1980).

Both devices are electrodeless plasma guns of the conical theta pinch type, which give pulses of plasma emitted during very short time intervals. In such a shot, a hydrogen plasma is generated and accelerated into a drift tube along a magnetic field, see Figure 1. The magnetic field can either be flow-parallel in the whole tube or gradually change direction to be transverse in the region where the observations are made. In this region, called the "interaction space", a cloud of helium is injected by means of a fast electromagnetic valve, and the interaction between the helium cloud and the plasma stream is studied. The streaming velocity is in both cases around $3 \cdot 10^5 \text{ms}^{-1}$, which is well above the critical velocity for helium ($3.5 \cdot 10^4 \text{ms}^{-1}$). So far, the previous and the present experiments are very similar. The main differences are that the magnetic field is weaker (0.015 T) and that the plasma density is higher in the present experiments. A consequence of this is that the ratio ω_{ge}/ω_{pe} now is as low as 0.05 as compared with about unity for the previous experiments. Another difference which might be of importance is that the walls in the interaction space were in contact with the plasma in the previous experiments only. Some parameters for the two experiments are given in Table I.

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

The electric field is measured by floating double probes connected through 1 Mohm voltage dividers to difference amplifiers. 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, which gives the average density along a line almost coincident with the light path to the spectrograph, which is along the x-axis in Figure 1. The interferometer, which is described in a separate report (Lindberg and Eriksson, 1980), is an improved version of Hotston and Seidl's (1965) interferometer. 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 line and one for the He II 4686 Å line. The absolute intensities of these two lines give information about different parts of the electron energy distribution. The 3889 Å line is

mainly excited by electrons in the energy range 25 - 75 eV. Under the assumption that these electrons have a Maxwellian distribution, the strength of this line can be interpreted in terms of the temperature of the bulk of the electrons. The 4686 Å line on the other hand is in this experiment excited mainly by non-thermal high-energy ($W_e \gtrsim 125$ eV) electrons. The evaluation of the spectroscopic measurements, which is rather complicated, is discussed elsewhere (Brenning, 1980a; Brenning *et al.*, 1980).

3. Experimental Observations

The most striking observations in the previous experiments are the braking of the plasma to a small fraction of the original velocity and the rapid heating of the electrons from originally 5 - 10 eV to typically 100 eV (Danielsson, 1970; Danielsson and Brenning, 1975).

In the present experiments the plasma stream velocity and the electron energy distribution are studied over the whole range of helium densities from very low up to such high densities that the plasma stream is stopped by binary collisions. The spatial extension of the gas clouds are different in the two experiments, see Table I, and this has to be taken into account when comparing the results. The interaction is more concentrated both in space and in time in the previous experiments. Since we want to compare features where collisions with the neutrals (ionization, elastic collisions etc.) are important, we use the integrated helium density $\int n_{\text{He}} dz$ along the plasma stream from the boundary of the helium cloud to the point of observation ($z = 0$ in Figure 1). This is the number of neutrals passed by the plasma per unit area (perpendicular to z) of the drift tube. Since the plasma velocities are almost equal in the two experiments, this parameter directly reflects the probabilities for all kinds of binary collisions between plasma particles and helium atoms. The integrated helium density is calculated from the separately measured helium density distribution.

3.1 Plasma Velocity

We first discuss the case where the magnetic field is transverse to the plasma flow, which is directly comparable with the old experiments. In this case, the velocity is monitored by measuring

the electric polarization field $\underline{E} = -\underline{v} \times \underline{B}$ near the center of the helium cloud. The result is displayed in Figure 2, which shows the electric field as a function of time for different integrated helium densities. The plasma is ejected from the gun during a short time interval around $t = 0$, and then expands almost freely between the gun and the interaction space (Lindberg, 1976). This implies that the velocity, and hence the induced electric field, can be derived from the time of flight. The hyperbolas drawn with dashed lines in Figure 2 are obtained this way.

A braking to the critical velocity of helium would correspond to a decrease in the electric field from the value in the absence of helium, 5 - 10 kV/m, to 520 V/m (for a magnetic field of 0.015 T). The results in Figure 2 show no indication of such a braking, except at such high helium densities that binary collisions explain the result. Three integrated helium densities of interest are marked with arrows in the figure:

- (a) $\int n_{\text{He}} dz = 5 \cdot 10^{17} \text{ m}^{-2}$, which in the previous experiments corresponded to a braking to half the original velocity,
- (b) $\int n_{\text{He}} dz = 3 \cdot 10^{18} \text{ m}^{-2}$, which in the previous experiments corresponded to a complete braking to the critical ionization velocity, and
- (c) $\int n_{\text{He}} dz = 2 \cdot 10^{19} \text{ m}^{-2}$. At this density we expect the plasma to be stopped by binary collisions between protons and helium atoms.

3.2 Electron Energy Variation during the Interaction

A characteristic feature of the critical velocity interaction is that it is accompanied by a dramatic heating of electrons to suprathermal energies. In the present experiments, no such electron heating is seen for any helium density. The results are displayed in Figures 3 and 4, which show the changes in electron density and energy distribution as the density in the helium cloud is varied.

Figures 3a and 3b show the results for flow-parallel magnetic field. For integrated helium densities below $4 \cdot 10^{18} \text{ m}^{-2}$, the plasma density is uninfluenced by the presence of helium. At higher helium densities the plasma density increases almost linearly in time (Figure 3a). This increase is not an effect of ionization. A calculation of the ionization rate from the electron energy distribution (which is obtained spectroscopically)

shows that ionization can contribute not more than 10 - 15% of the observed density increase. The remainder can be understood as the result of an accumulation of plasma that has been stopped by elastic collisions between protons and helium atoms. The electron temperature (from the 3889 Å line intensity) is shown in Figure 3b for three different helium densities. The only effect due to the presence of helium is a slight temperature increase in the first arriving plasma for higher helium densities. Background light at 4686 Å made it impossible to measure the density of electrons with energies above 125 eV when the magnetic field was parallel to the flow. Only an upper limit was obtained; these electrons are fewer than 1% of the total electron population for all helium densities.

The results for transverse magnetic field are shown in Figures 4a - 4c. The increase in plasma density at high helium densities is greater than for the case with flow-parallel magnetic field (Figure 4a). Still, only a part (less than 30%) of this density increase comes from ionization. The more rapid accumulation of plasma compared to the case with flow-parallel field is interesting. The explanation can probably be found in the way momentum is exchanged between the protons that are stopped by collisions and the rest of the plasma. From a macroscopic viewpoint, this momentum exchange is carried by $\underline{i} \times \underline{B}$ forces, which can have components parallel to the plasma flow (and therefore brake the plasma) only when the magnetic field is transverse.

The changes in electron temperature (Figure 4b) are similar to those for flow-parallel magnetic field. There is almost no effect when the integrated helium density is below $3 \cdot 10^{18} \text{ m}^{-2}$, which in the previous experiments was associated with electron energies of typically 100 eV. Only at much higher densities is there a significant temperature increase, and then only in the first arriving plasma. This increase shows a large variation between different shots of the plasma gun, as indicated by bars in Figure 4b. For some shots the observed temperature can be as high as 20 eV, but this occurs only at such high helium densities that the plasma is effectively stopped by binary collisions. This heating can therefore not be taken as an indication of a critical ionization velocity interaction of the type observed in the old experiment.

The density of high-energy electrons obtained from the 4686 Å line intensity confirms this. In the undisturbed plasma stream, the fraction of hot electrons is as large as 20 - 25% in the first arriving plasma, and then decreases with time to typically 10% after 10 μs of plasma flow (Figure 4c). These suprathermal electrons are probably accelerated in the region where the magnetic field curves from flow-parallel to transverse (Brenning *et al.*, 1980). The presence of hot electrons in the undisturbed plasma stream is expected to be favourable for a possible critical ionization velocity interaction; it would trigger the interaction by providing initial ionization. In spite of this, the density of suprathermal electrons does not increase at any helium density. When the helium density is sufficiently high, the electrons are cooled by inelastic collisions with helium atoms, and the fraction of high-energy electrons decreases (Figure 4c).

4. Discussion

The observed absence of critical ionization velocity interaction in the present experiment should be considered in the context of the theory by Sherman and Raadu. According to this theory, it is the kinetic energy available in relative motion between the plasma and the newly formed stationary helium ions that is the source of energy for the electron energization. This relative motion drives a modified two-stream instability that decreases the relative velocity and transfers part of the released energy to the electrons.

In our experiment, we can find the helium ionization rate from the spectroscopically obtained electron energy distribution, while the relative velocity is found from the electric probe measurements. It is therefore possible to calculate the available energy from measured quantities. The rate of production of initially stationary helium ions by ionization is $n_e n_{\text{He}} S_i$, where S_i is the electron impact ionization rate coefficient $\langle \sigma_i v_e \rangle$. (Stationary helium ions are also produced by charge exchange collisions between the ions in the plasma and the helium atoms. This contribution is negligible in our experiment as long as the electron temperature is above 5 eV.) The kinetic energy in the relative motion between the stationary helium ions and the streaming plasma is $m_{\text{He}} v^2/2$ per helium ion, provided that the helium ions

are few compared to the ions in the plasma stream. This energy can be transferred to other groups of particles as the stationary ions are accelerated to the plasma stream velocity. We now introduce a free parameter, K , which we define as the fraction of the energy that is transferred to the electrons during the experimental time. The value of K depends on the mechanism that accelerates the new ions; it must always lie between 0 and 1. The result of our calculations will be a determination of the value of K in our experiment.

We can now write down the equation for the energy change in the electron population,

$$\underbrace{\Delta \left(n_e \frac{3kT_e}{2} \right)}_{\text{change in electron energy}} = K \int_{-\infty}^z \underbrace{n_e n_{\text{He}} S_i}_{\text{rate of He}^+ \text{ ion production}} \underbrace{\frac{m_{\text{He}} v^2}{2}}_{\text{energy per He}^+ \text{ ion}} \frac{dz}{v} \quad (1)$$

When the changes in S_i , n_e and v during the penetration into the neutral gas cloud can be neglected, this is reduced to

$$\Delta kT_e = K \frac{S_i m_{\text{He}} v}{3} \int_{-\infty}^z n_{\text{He}} dz \quad (2)$$

As an example, we will consider the case with transverse magnetic field, when the integrated helium density along the plasma stream to the center of the helium cloud is $\int n_{\text{He}} dz = 3 \cdot 10^{18} \text{ m}^{-2}$, at a time $t = 6 \mu\text{s}$ after the emission of the plasma from the plasma gun. With $S_i = 4.3 \cdot 10^{-15} \text{ m}^3 \text{ s}^{-1}$ and $v = 4.5 \cdot 10^5 \text{ ms}^{-1}$, we obtain the temperature change from Eq. (2) as a function of the energy transfer factor K :

$$\Delta kT_e = K \cdot 81 \quad (\text{eV}) \quad (3)$$

If an optimally efficient energy transfer mechanism were at work ($K = 1$), the electron temperature would be increased to $kT_e \approx 100 \text{ eV}$ corresponding to an average electron energy of 150 eV. The observed temperature increase in the thermal part of the population is around 1 eV, while the density of high-energy electrons is

unchanged (Figure 4b, c). This corresponds to a transfer to the electrons of only 1% of the energy in relative motion between plasma and newly ionized helium. Calculations for other helium densities and times after plasma emission give similar results. The modified two-stream instability, when operating, is expected to transfer energy much more efficiently than this. In computer simulations by Ott et al. (1972) and McBride et al. (1972), 28% of the energy was transferred to the electrons. According to Raadu (1978), the fraction can be as large as 40% depending on which particular mode of the instability that is excited. These theoretical results are in good agreement with the results from the previous experiments by Danielsson and Brenning, where the fraction of energy transferred to the electrons is estimated to lie between 10% and 50% (Brenning, 1980b).

4. Summary

The experiment has been performed in a configuration where critical ionization velocity interaction has previously been observed in the presence of a strong transverse magnetic field. It differs from the previous experiments in the respects that the magnetic field can be also parallel to the plasma stream and that the electron gyrofrequency is much smaller than the electron plasma frequency. Another difference is that the walls here are further removed from the plasma. The result of these changes is that the critical ionization velocity interaction disappears. We have particularly looked for two characteristic features, braking of the plasma and energization of the plasma electrons. Braking of the plasma occurs only when the neutral gas density is so high that the deceleration can be understood as the result of binary collisions between the plasma ions and the neutral gas atoms, while electron energization is marginal compared to that which has earlier been observed in experiments with the same geometry.

Our results cannot be immediately compared with the theory by Sherman and Raadu, which requires $\omega_{ge} > \omega_{pe}$. The absence of the critical ionization velocity interaction in our experiment, where we have $\omega_{ge} \ll \omega_{pe}$, does suggest that there

in this case exists no alternative mechanisms which can effectively drive the interaction for hydrogen plasma - helium gas impact experiments of the type discussed here. It should be pointed out that the situation with $\omega_{ge} \ll \omega_{pe}$ does not altogether exclude the operation of a modified two-stream instability; it only excludes the case discussed by Sherman and Raadu, in which the instability heats the electrons by acceleration preferentially along the magnetic field. The modified two-stream instability has actually also been invoked to explain the critical ionization velocity interaction in another type of experiments, where the interaction is observed also in the parameter range $\omega_{ge} \ll \omega_{pe}$ (e.g. Piel et al., 1980). These experiments differ in many respects from the pulsed experiments discussed here; the critical ionization velocity is observed as an upper limit to the rotational velocity which can be obtained in a continuously rotating, not fully ionized plasma. Another difference is that the plasma in their experiments is of the same species as the neutral gas, so that the interaction is influenced by resonant charge exchange collisions.

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	Previous Experiment	Present Experiment
Plasma	Hydrogen	Hydrogen
Neutral Gas	Helium	Helium
Plasma Stream velocity	$\approx 3 \cdot 10^5 \text{ ms}^{-1}$	$\approx 3 \cdot 10^5 \text{ ms}^{-1}$
Magnetic Field	0.2 T, only transverse	0.015 T, both parallel and transverse
Plasma Density	$\approx 3 \cdot 10^{17} \text{ m}^{-3}$	$\approx 2 \cdot 10^{18} \text{ m}^{-3}$
ω_{ge}/ω_{pe}	≈ 1	≈ 0.05
Walls	In contact with plasma	Not in contact with plasma
Radius of helium cloud	$\approx 0.025 \text{ m}$	$\approx 0.2 \text{ m}$

Table I. A comparison of parameters in the interaction space between the previous and the present experiment.

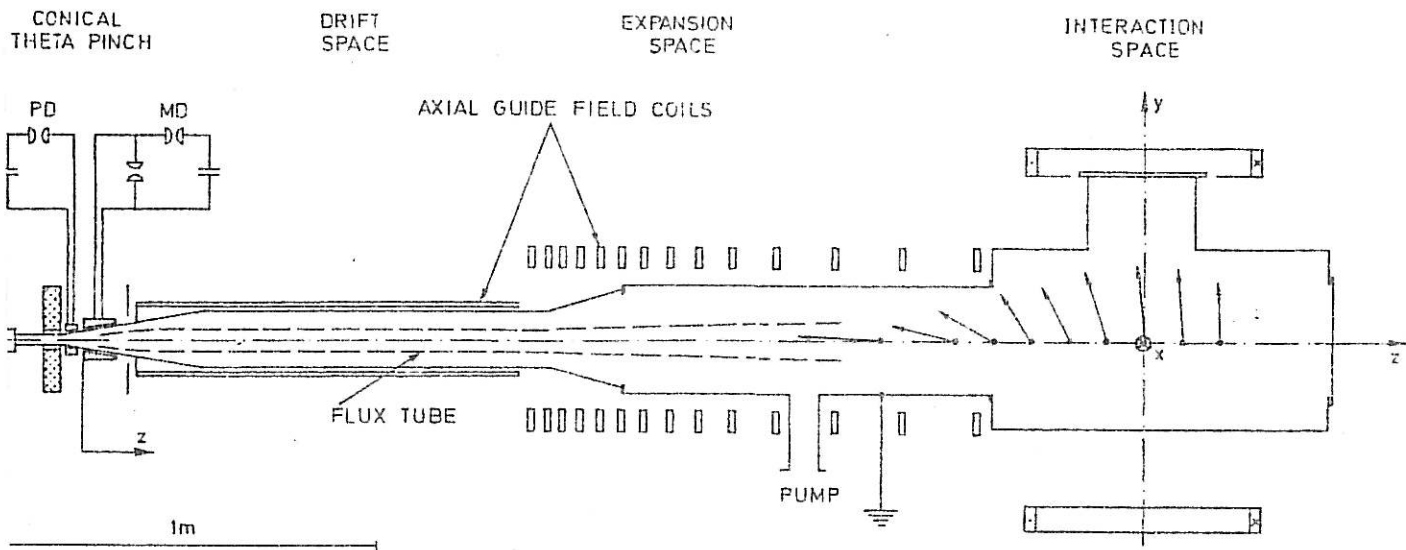
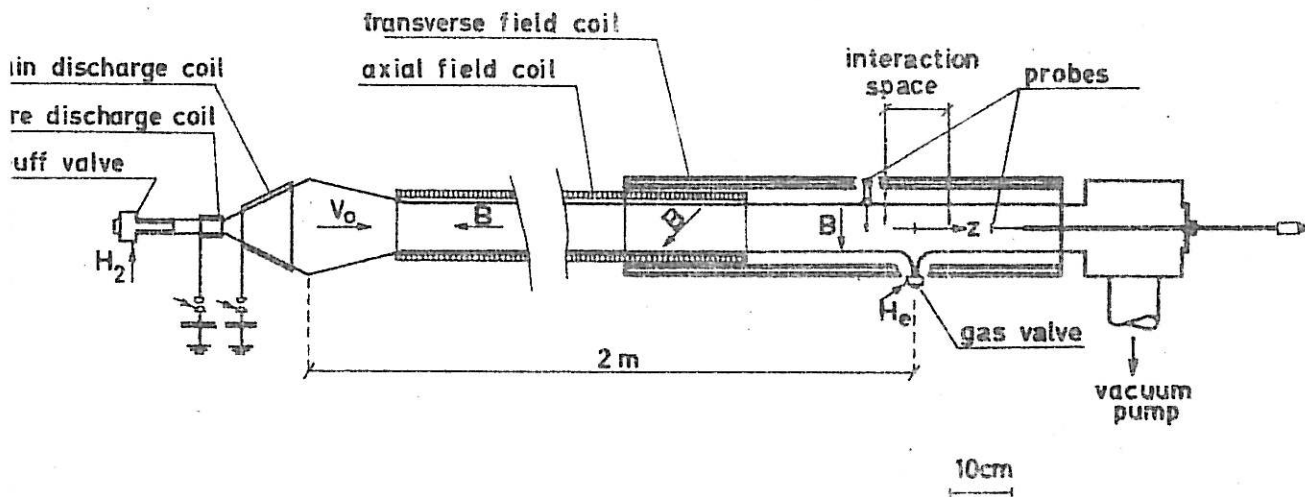


Fig. 1 Experimental devices. Upper figure: the apparatus used by Danielsson (1970) and Danielsson and Brenning (1975). Lower figure: the apparatus used in these investigations.

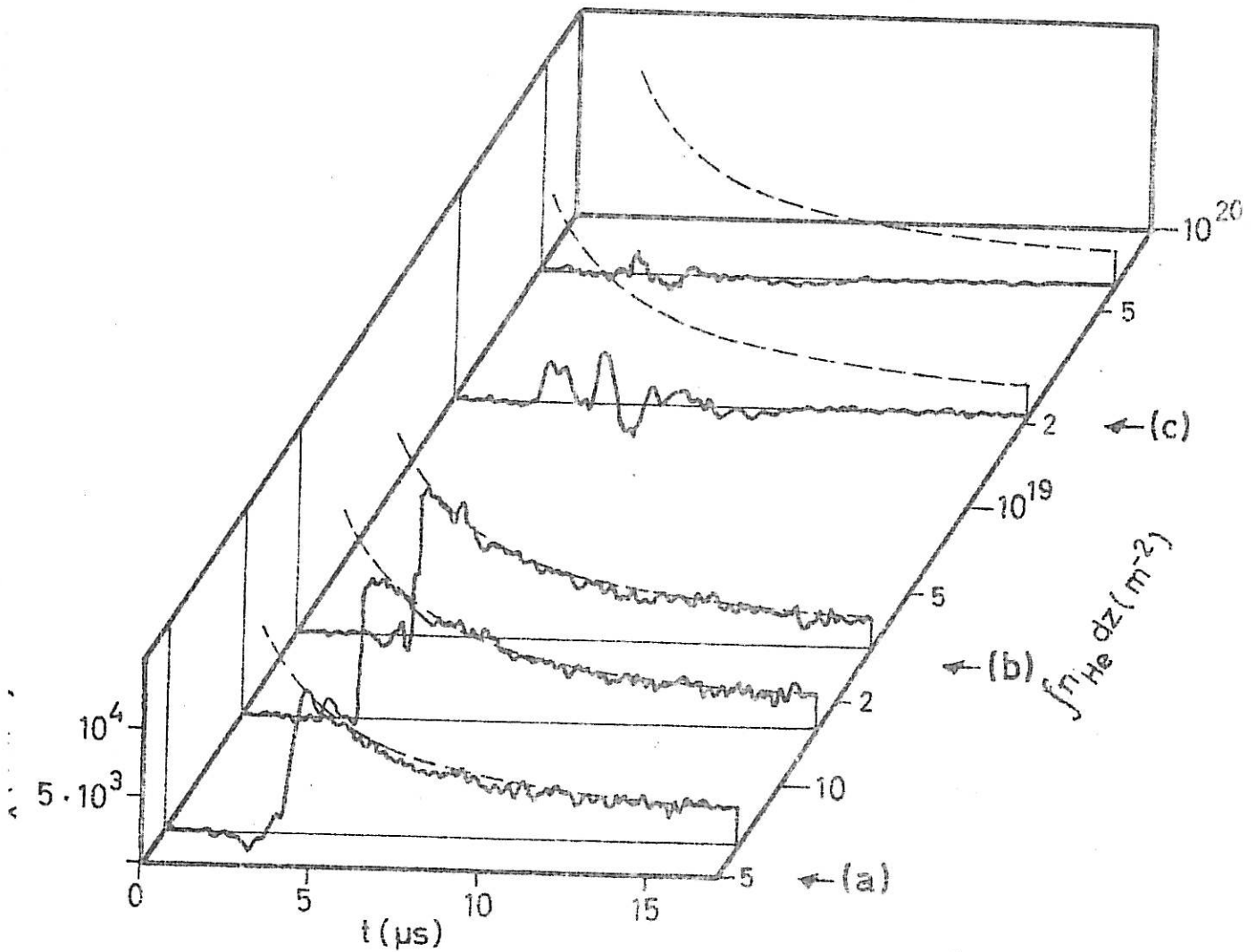
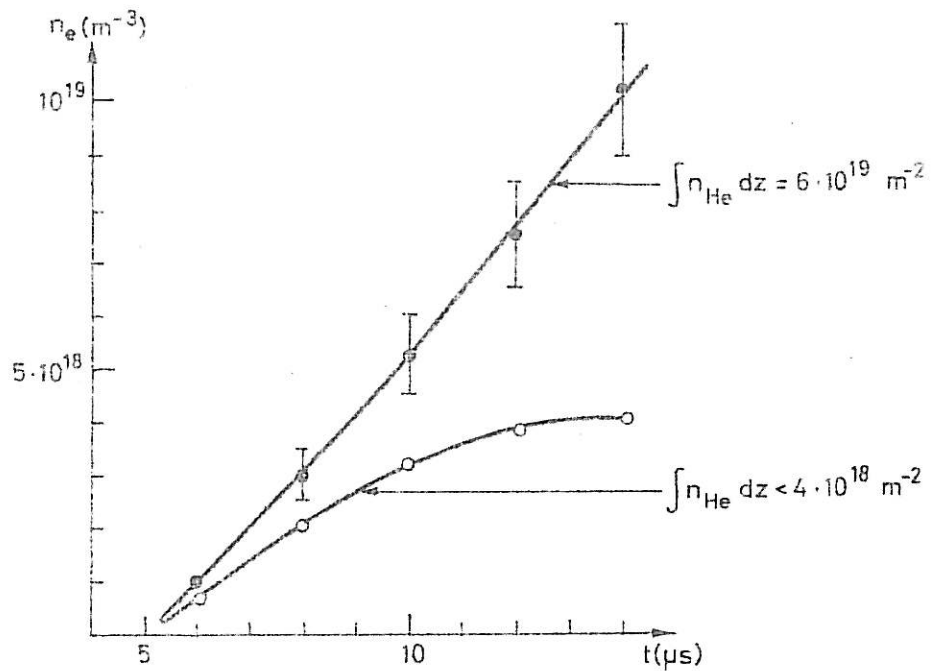


Fig. 2 Interaction in transverse magnetic field. The curves show the polarization field $\underline{E}_p = -\underline{v} \times \underline{B}$ at $(x, y, z) = (0, 0, 5.7 \text{ cm})$ for different helium densities. (a), (b) and (c) mark integrated densities $\int n_{\text{He}} dz$ corresponding to:
 (a) braking in the old experiment to half the original velocity,
 (b) braking in the old experiment to the critical velocity (which in this figure would give $E_x = 520 \text{ Vm}^{-1}$), and
 (c) the helium density at which braking of the plasma through classical collisions is expected.

(a) Electron density at the center of the helium cloud for different helium densities. The error bars denote uncertainty of measurement.



(b) Temperature of the assumed thermal part of the electron population ($W_e \lesssim 75$ eV) for different helium densities. From the 3889 Å line intensity.

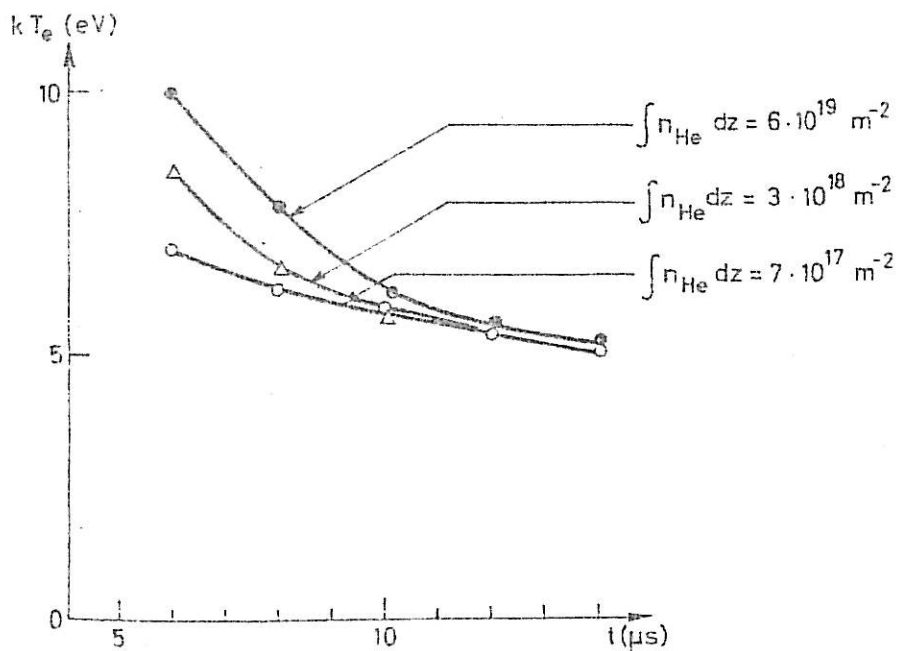
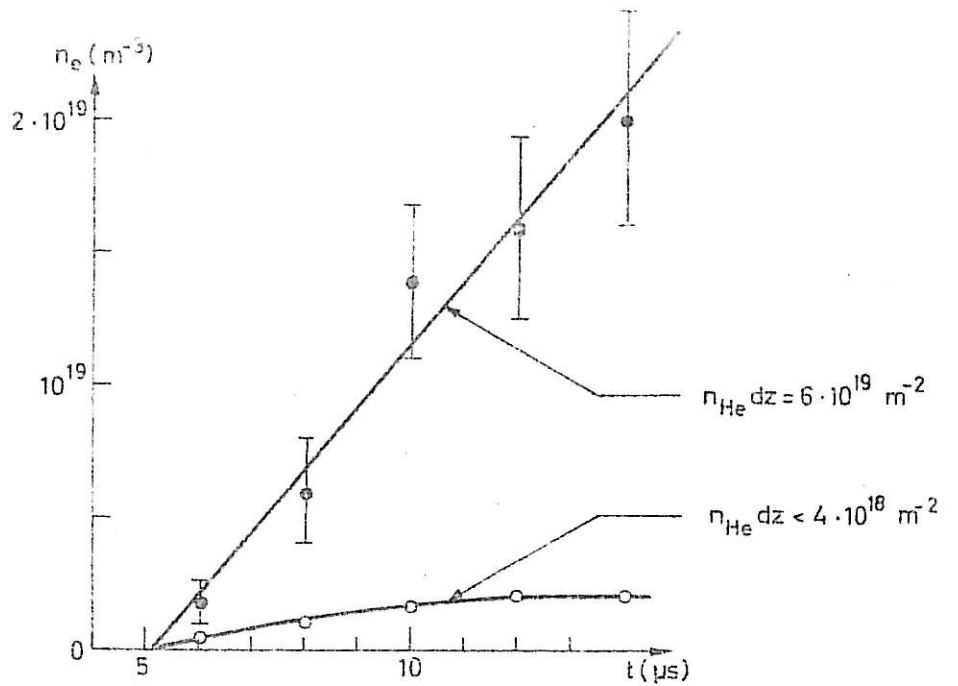
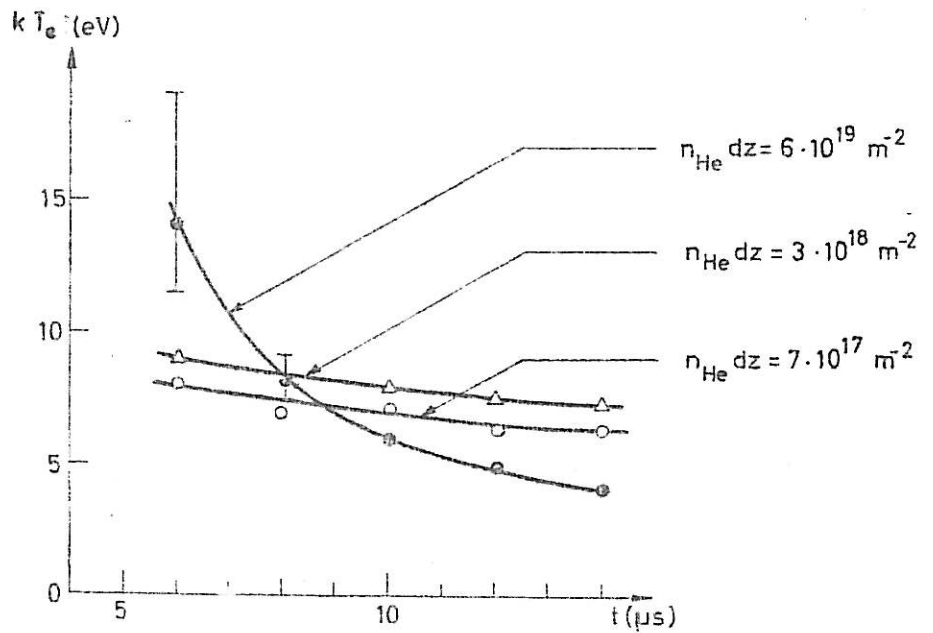


Fig. 3 Results for flow-parallel magnetic field. $t = 0$ is the time when the plasma is ejected from the plasma gun.

(a) Electron density at the center of the helium cloud for different helium densities. The error bars denote uncertainty of measurement.



(b) Temperature of the assumed thermal part of the electron population ($W_e \leq 75$ eV). The bars denote shot-to-shot variations. From the 3889 Å line intensity.



(c) The fraction of high-energy ($W_e > 125$ eV) electrons from the 886 Å line intensity as a function of time for different helium densities. The bars denote shot-to-shot variations except for the lowest fractions (<1%), where there is also an uncertainty of measurement.

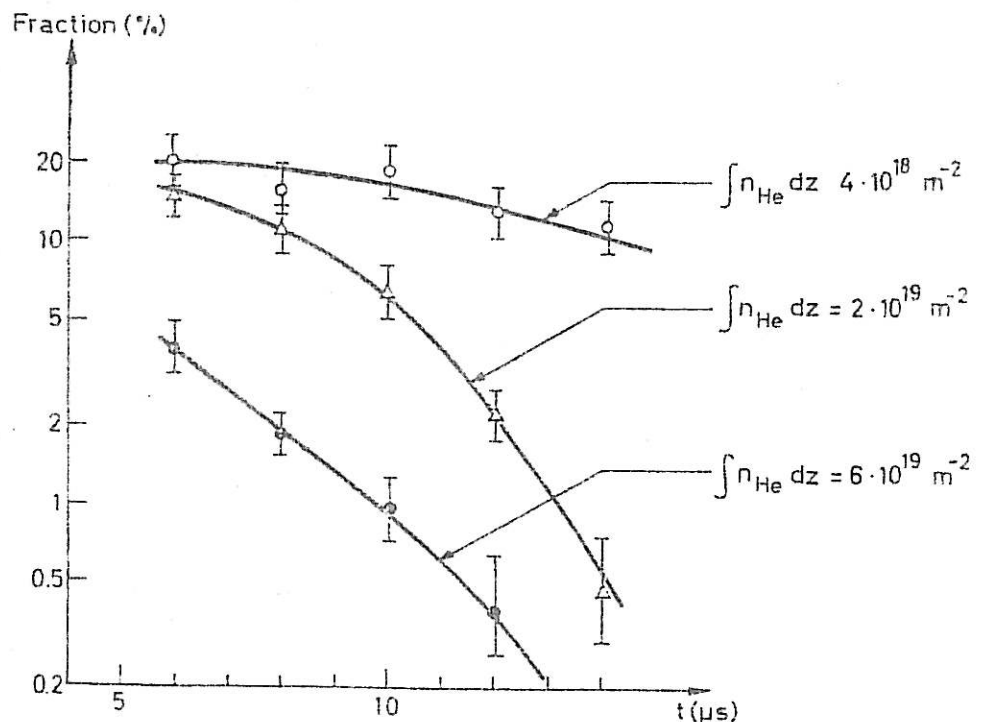


Fig. 4 Results for transverse magnetic field. $t = 0$ is the time when the plasma is ejected from the plasma gun.

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Key words: Collisionless plasma, Plasma flow, Critical ionization velocity, Critical velocity, Electron energization, Suprathermal electrons.