REVIEW OF IMPACT EXPERIMENTS ON
THE CRITICAL IONIZATION VELOCITY

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Abstract

The impact experiments on the critical ionization velocity \( v_c \) interaction are reviewed. In these experiments, a highly ionized plasma impacts on a neutral gas cloud. \( v_c \)-interaction is observed only when the magnetic field, and the neutral gas density, are above certain critical limits. The values of these limits, however, differ between the experiments. The extrapolation of the laboratory results to space applications is also discussed.
1. Introduction

The critical ionization velocity \( \nu_c \) hypothesis was first put forward by Alfvén (1954). He proposed that when the relative velocity between a magnetized plasma and a neutral gas exceeds the value \( \nu_c \), given by

\[
\frac{m_n \nu_c^2}{2} = eU_i
\]  

(1)

(where \( m_n \) and \( U_i \) are the mass and ionization potential of the neutral gas), the ionization rate of the gas should increase abruptly. The strong coupling due to ionization would then limit the relative velocity to \( \nu_c = (2eU_i/m_n)^{1/2} \). Since Alfvén's original hypothesis, the \( \nu_c \)-phenomenon has been observed in many laboratory experiments. These experiments fall naturally into two groups, the discharge experiments and the impact experiments.

In the discharge experiments, an electric field is applied across a magnetic field. This gives the plasma a drift velocity relative to the neutral gas, which in the simplest case becomes \( \nu_d = E \times B/B^2 \). As long as the plasma is not fully ionized, this drift velocity is generally found to be limited to the critical ionization velocity.

In the impact experiments, the plasma usually has an initial velocity \( \nu_o \gg \nu_c \) and is braked to \( \nu \approx \nu_c \) when the plasma collides with the neutral gas cloud. In the process, the plasma electrons are heated, and the neutral gas is rapidly ionized by electron impact ionization.

There is a fundamental difference between these two types of experiments. The discharge experiments require an external energy source, which is not necessary in the impact experiments; the energy that is needed for electron heating and ionization can in the latter experiments be taken from the kinetic energy in the plasma stream.
The $v_C$-phenomenon has been proposed to operate in a number of situations in the ionospheres and magnetospheres of the planets, and in the solar wind (e.g. Lindeman et al., 1974; Ssuka, 1977; Cloutier et al., 1978; Petelski et al., 1980; Formisano et al., 1982; Haerendel, 1982). These applications are all basically of the "impact type", with initial relative velocity above $v_C$, and without an external energy source.

The main results of the laboratory impact experiments are described in Sections 2-6 below. In Section 7 the laboratory results are summarized and compared, and some problems in the extrapolation of the laboratory results to space situations are briefly discussed.

The range of parameters investigated in the different experiments are illustrated by use of a parameter plot, shown in Fig. 1. The vertical axis shows the dimensionless quantity $\omega_{ge}/\omega_{pe}$, which is proportional to $B/\sqrt{T}$. There is a crude proportionality between $\omega_{ge}/\omega_{pe}$ and $\beta^{-1/2}$: $\beta = n_e (kT_e + kT_i) 2\mu_0 / B^2$ and $\omega_{ge}/\omega_{pe} = (e_o B^2)/(m_e n_e)^{1/2}$ can be combined to

$$\beta = 4 \cdot 10^{-6} \frac{kT_e + kT_i}{(\omega_{ge}/\omega_{pe})^2} \quad (2)$$

where $kT_e$ and $kT_i$ are in electron volts.

The horizontal axis of the parameter plot shows the column neutral gas density $\int n_dz$ through the neutral gas along the plasma flow. This permits a direct comparison between situations with neutral gas clouds of different densities and spatial extents, since the probability for a plasma particle to collide during the penetration into the neutral gas is proportional to $\int n_dz$, independent of whether the neutral gas cloud is dense and small or thin and extended.
We only expect $v_c$-interaction over a limited range of $\int n_n \, dz$. This can be illustrated by the case of a hydrogen plasma penetrating into a helium cloud, as in the experiments by Danielsson (1970), Danielsson and Brenning (1975) and Brenning (1981):

At high values of $\int n_n \, dz$, a plasma stream can be stopped in a neutral gas cloud by ordinary binary collisions, without any $v_c$-interaction. The momentum transfer cross section for 200 eV protons in helium gas is $\sigma_{\text{coll}} \approx 3 \times 10^{-20} \text{ m}^2$. The ion mean free path $(n_n \sigma_{\text{coll}})^{-1}$ is then equal to the neutral cloud extension $\int dz$ when $\int n_n \, dz \approx 3 \times 10^{19} \text{ m}^2$.

A corresponding low-density limit can be found if we consider the case where a plasma electron barely has time to ionize once during the passage through the neutral gas cloud, even if the electron temperature is so high that the ionization rate is at maximum. (This corresponds to the Townsend condition for the beam-plasma discharge used by e.g. Haerendel, 1982.) For a plasma stream penetrating into a helium gas cloud at the critical ionization velocity of helium, this limit becomes $\int n_n \, dz \approx v_c / <\sigma_{i e} v>_{\text{max}} \approx 10^{18} \text{ m}^2$.

These low- and high-density limits are drawn in Fig. 1, illustrating that $v_c$-interaction is only expected in a range of $\int n_n \, dz$ covering less than two orders of magnitude, when hydrogen plasma colliding with helium gas is considered. Both limits, of course, vary with the neutral gas used, and with the plasma stream velocity.

The low-density "Townsend condition" for a number of gases is given in Table I. It is calculated from the maximum of the electron impact ionization rate coefficient and the critical ionization velocity for each gas, from

$$ (\int n_n \, dz)_{\text{min}} = \frac{v_c}{<\sigma_{i e} v>_{\text{max}}} $$

(3)
2. The experiments by Danielsson and Kasai, 1966-1968

The experiments by Danielsson (1966) and Danielsson and Kasai (1968) were not made with \( v_c \)-interaction as the aim of the study, but still shows many interesting features. The aim was instead to simulate the interaction between a comet and the solar wind. The apparatus is shown in Fig.2. A stream of hydrogen plasma was produced in a Josephson-type plasma gun, giving a stream of plasma with \( n_e = 10^{19} \text{ m}^{-3} \), \( kT_e \approx 3 \text{ ev} \) and \( v_0 \approx 6.10^4 \text{ ms}^{-1} \). No external magnetic field was applied, but the plasma carried a non-reproducible frozen-in magnetic field of 0.002-0.005 T from the gun. The neutral gas was produced by sublimation from a \( \phi = 1 \text{ cm} \) piece of dry ice, giving a CO\(_2\) cloud with \( n_n \approx 5.10^{19} \text{ m}^{-3} \) at the surface, the density decreasing as the inverse square of the radius.

In the interaction they observed a luminous halo around the dry ice, see Fig.3. The luminous front extended 1-2 cm in front of the dry ice, and formed a tail behind.

The velocity of the produced CO\(_2^+\) ions was studied by streak photography and time-of-flight measurements. The CO\(_2^+\) ions were found to obtain velocities around \( 10^4-2.10^4 \text{ ms}^{-1} \), that is, 13-26% of the original plasma stream velocity. The plasma velocity was reported to decrease to \( 1.7.10^4 \text{ ms}^{-1} \) behind the luminous front, in front of the dry ice. This corresponds to a decrease from \( v_0/v_c = 7.8 \) to \( v/v_c = 2.2 \).

The electron temperature was deduced from the time of appearance of CII and CIII lines, and was found to increase from \( kT_e = 3 \text{ ev} \) to \( kT_e = 20 \text{ ev} \) in the interaction.

Fig.4 shows their results drawn in the parameter plot. The solid double line indicates braking of the plasma stream, and the wavy line electron heating. The open circles show when no interaction was observed.
This experiment differs from the other impact experiments in two important respects. One is that the velocity of the newly formed ions has been measured. The question of pick-up of new ions is one of the key questions of v\_c -interaction. If we only consider the motion perpendicular to the magnetic field, there are basically two scenarios for ion pick-up. First, one could imagine that the ions start to move in cycloidal orbits, which means that they, in the frame of reference of the plasma, move in gyrocircles with the full plasma-neutral gas relative velocity. This would, however, not immediately release any energy for electron heating. The other scenario is that some collective process picks up the ions quickly compared to the gyration time. Their gyrational energy in the plasma's frame of reference would then be less than in the first scenario. The difference in gyrational energy could be used for e.g. heating of the electrons.

InDanielsson and Kasai's experiment, the ions are accelerated ten times more rapidly than expected from the "gyrational pick-up" model, which strongly indicates that collective processes are at work. This agrees with their observations of electron heating from kT\_e = 3 eV to kT\_e = 20 eV.

The other interesting feature of this experiment is that the plasma stream here has a larger cross section area than the neutral gas cloud, by a factor of about 50. This might explain the fact that the v\_c -interaction here is observed at far lower magnetic fields than in the other experiments, where the plasma stream cross sections are of the same size as the neutral gas clouds.

3. The experiments by Danielsson and Brenning, 1970-1975

The apparatus used in the experiments by Danielsson (1970) and Danielsson and Brenning (1975) is shown in Fig.5. A conical theta pinch plasma gun produced a hydrogen plasma stream with n\_e ≈ 3.10^{17} \text{ m}^{-3}, kT\_e = 5-10 eV and a velocity v\_e ≈ 3.10^{5} \text{ ms}^{-1}, around 9 times v\_c for the neutral gas, which was helium. The neutral gas formed a cloud of diameter about 5 cm, n\_n ≈
Observations were made both in varying transverse magnetic field strengths, and with varying initial velocities of the plasma stream. Both plasma stream velocity and electron energy were measured.

Figs. 6a-6c show the velocity measurements at two different magnetic field strengths, 0.18 T and 0.36 T. The velocity was measured both by floating double probes (measuring $E_p = -v \times B$) in the neutral gas cloud, and by time-of-flight measurements behind the gas cloud, with consistent results. Fig. 6a shows the neutral gas density profile along the central axis of the drift tube, while Fig. 6b shows the velocity. The deceleration starts earlier with stronger magnetic field, indicating a more efficient interaction in that case. The velocity at a fixed point in the neutral gas cloud is found to have an interesting time dependence, shown in Fig. 6c: there is an initial transient of supercritical penetration with a time duration of about 0.5 μs, followed by a plateau with constant velocity. This plateau is in this example close to the critical velocity, since the measurement was made in the rear part of the helium cloud.

The measurements with varying initial velocity were all made with a magnetic field of 0.44 T. Fig. 6c shows the velocity 1 cm behind the center of the gas cloud ($\int n_d z = 6.10^{18} m^{-2}$) plotted against the initial velocity. There is no deceleration of the plasma for $v_o < v_c$, while the relative deceleration increases with the original velocity above $v_c$.

We now turn to the measurement on the electron energy. The diagnostics are relative and absolute measurements on neutral and ionized helium lines, measurements of the polarization of neutral helium lines, and ion beam probe measurements. The electron energy was found to increase from the original 5-10 eV to around 100 eV, with a time delay with respect to the arrival of the plasma of 0.5 μs. The density of hot electrons was found to be greater than the original plasma density by a factor of about 3 (spectroscopic measurements) or a factor of 2-12 (ion beam probe). The electron velocity
distribution was also found to be anisotropic, with a preferential direction along the magnetic field lines (from the polarization measurements).

These results were all obtained with a hydrogen plasma with $v_o \approx 9 \, v_c$, and with a strong transverse magnetic field. Two other, less extensively studied, experiments were also made:

The gases were interchanged, so that a helium plasma impacted on a hydrogen cloud. In this case, the plasma was only decelerated to around half the original velocity. Emission of the He II lines indicated that the electrons were heated also in this case.

The interaction was also studied for weaker magnetic fields. The electron heating was found to be rather independent of the magnetic field strength down to $B = 0.02 - 0.05 \, T$, corresponding to $\omega_{ge}/\omega_{pe} \approx 0.2$ (or $\beta = 10^{-2} - 10^{-3}$). Below this limit, the light from ionized helium decreased by more than a factor of 50, indicating that the electrons were not heated if the transverse magnetic field was too weak.

Fig. 7 shows the results in the parameter plot. As before, the wavy lines show electron heating, while the solid double lines show retardation of the plasma stream to below $1/e$ of the original velocity. Both were observed when $\int n_e \, dz > 2 \times 10^{18} \, \text{m}^{-3}$. This is a surprisingly low value, only twice the low-density limit ("Townsend condition") for when $v_c$-interaction can be expected.

4. The experiment by Brenning, 1981

In the experiment by Brenning (1981), the result is essentially negative in the sense that $v_c$-interaction did not occur. Fig. 8 shows the apparatus, which is similar to the one used by Danielsson and Brenning. A conical theta pinch plasma gun produces a hydrogen plasma stream with density $n_e \approx 2 \times 10^{18} \, \text{m}^{-3}$ and velocity $v_o = 3 \times 10^5 \, \text{ms}^{-1}$. The transverse magnetic field is 0.015 T, which gives $\omega_{ge}/\omega_{pe} \approx 0.03$.
(\(\beta \approx 0.04\)). The neutral gas was helium, and the neutral density was varied from such a low value that the plasma stream was uninfluenced, up to such a high value that the plasma stream was stopped by binary collisions with the neutrals. The velocity was measured by floating double probes, and the electron energy was studied by spectroscopic means, which made it possible to measure both the temperature of the bulk of the electrons, and the density of the high-energy (\(W_e \geq 100\) eV) electron population.

In spite of the absence of \(v_C\)-interaction in this experiment, two aspects are of interest here: the electron energy distribution in the undisturbed plasma flow, and the calculation of a quantitative measure of the energy transfer to the electrons.

Before the penetration into the transverse magnetic field, the plasma stream had a thermal population of electrons with \(kT_e = 6-8\) eV. In the region with transverse magnetic field, this was drastically changed: A population of high-energy electrons with energies above 100 eV developed, comprising up to 20% of the total electron population. These hot electrons must have been created by the penetration into the transverse field, by some mechanism which could transfer energy from the ions in the plasma stream to the electrons. A similar phenomenon might occur in the other impact experiments on \(v_C\)-interaction, since the plasma stream in all experiments moves along a magnetic field which then turns to a transverse field in the region where the neutral gas cloud is situated. The presence of such a hot "runaway-like" electron population might easily escape detection by Langmuir probes, but would certainly influence the interaction very strongly. It could, for example, trigger the interaction by strong initial ionization of the neutral gas.

Fig. 9 shows the effect on the electron energy distribution from interaction with neutral gas clouds of different densities. No additional electron heating indicating \(v_C\)-interaction was observed. A quantitative measure of the
energy transfer was also calculated from the data in Fig.9; it was found that less than 1% of the energy that becomes available by electron impact ionization of the neutrals was transferred to the electrons. As a comparison, the corresponding energy transfer in the experiments by Danielsson and Brenning is calculated from the experimental results to lie in the range 17% to 70% (Brenning 1982).

Fig.10 shows the parameter range investigated in this experiment.

5. The experiments by Kubo et al., 1971-1973

Kubo et al. (1971, 1973) have made plasma stream impacts on clouds of CO₂, He and Ar, and observed both plasma stream deceleration and electron heating. No external magnetic field was applied. The neutral gas density in these experiments was much larger than in the other impact experiments, 10^{22} - 5.10^{22} m^{-3}, which means that plasma stream deceleration is expected from binary ion-neutral collisions, even without any v_i -interaction. The results are explained by the authors in terms of a snowplow shock model. The range of parameters covered in these experiments is also shown in Fig.10.


The experiments by Mattoo and Venkataramani (1980), Venkataramani and Mattoo (1981a,b) and Venkataramani (1981) cover a wide range of experimental parameters. Fig.11 shows the apparatus, a coaxial plasma gun capable of producing plasma flows with densities in the range 10^{17} - 10^{19} m^{-3}, and flow velocities v_o = 2.10^3 - 9.10^4 ms^{-1}. They used 13 different combinations of plasma and neutral gas species, and varied the magnetic field strength from zero up to 0.1 T. They also studied the interaction at various combinations of small, dense neutral gas clouds and extended, thin clouds. The velocity was measured by floating double probes and by time-of-flight methods, and the potential and currents in the plasma by probes. There are no measurements of the electron
energy during the interaction; probe measurements in the undisturbed plasma flow gave $kT_e \approx 10$ eV for the bulk of the plasma, while the high-energy tail could not be resolved.

6.1 The threshold velocity for interaction

Fig. 12 shows the velocity 2 cm behind the center of the neutral gas cloud, when hydrogen plasma impacted on argon, and when argon plasma impacted on hydrogen. The initial plasma velocity was varied over the range $v_o/v_C \approx 0.1$ to $v_o/v_C \approx 10$. The aim was here to determine the threshold velocity for interaction; a theory by Varma (1978) predicts a higher threshold velocity than $v_C$ for the case when the plasma ion mass is smaller than the neutral mass. The experimental result is quite clear, and shows that $v_C$ indeed is the true threshold for interaction. The final plasma stream velocity, for initial velocity, $v_o > v_C$, is here more clearly limited to $v_C$ than in the experiment by Danielsson (1970), cf. Fig. 6d.

6.2 The deceleration scale length

Studies of the interaction at various neutral gas cloud densities and extents were made with many combinations of plasma and neutral gas. These experiments were all made with the plasma stream velocity $v_o = 10^5$ ms$^{-1}$, and with a transverse magnetic field strength of 0.1 T. A theoretical deceleration scale length $L$ is introduced, which shows what deceleration one could expect from the pick-up of newly formed ions. This scale length can be thought of as the distance into the neutral gas the plasma would penetrate, if the velocity remained at the original value $v_o$, before the mass density of the picked-up ions equals the mass density of the original ions in the plasma stream. The underlying assumptions are that the new ions are immediately picked up by the plasma stream, and that the electron temperature is so high that the ionization rate is at maximum. This gives

$$ L = v_o \frac{1}{n_n \chi_{i, \text{max}}} \frac{M_i}{M_n} $$

(4)
where $\chi_{i,\text{max}}$ is the maximum value of the ionization rate coefficient $\langle \sigma v \rangle$, and $M_i$ and $M_n$ are the ion and neutral mass, respectively. This deceleration scale length, of course, only gives a rough estimate of the real deceleration; momentum exchange to the surrounding is disregarded, as well as other types of collisions than electron impact ionization.

An experimental scale length (the distance required for a velocity decrease to $1/e$ of the original stream velocity) was determined for neutral gas cloud scale lengths $L_n$ and densities $n_n$ from $L_n = 2-5$ cm, $n_n = 10^{20}$ m$^{-3}$ to $L_n \approx 50$ cm, $n_n \approx 2 \times 10^{17}$ m$^{-3}$. For $n_n > 10^{19}$ m$^{-3}$, the experimental result is in approximate agreement with the theoretical deceleration scale length. For lower $n_n$ (corresponding to more extended neutral gas clouds) this is not the case; the plasma was decelerated over a far shorter distance, by up to several orders of magnitude, than given by Eq.4. Alternative explanations to this rapid deceleration (charge exchange collisions, particle losses to the walls, possible sources of increased neutral gas density) were examined in detail. The fast deceleration remains unexplained.

Another interesting observation was the effect of the relative mass of ions and neutrals; Eq.4 predicts a strong dependence on this quantity. A slight effect in the expected direction was found, but never more than a factor 3, and seemingly independent of the exact values of the masses. Most striking is the example with hydrogen and argon, where interchange of the gases is expected from Eq.4 to influence the deceleration scale length with a factor $(40/1)^2 = 1600$; the observed factor is in the range 4-8, the exact value depending on the neutral gas density.

6.3 The sheath of the front of the plasma stream

A new phenomenon, which has been discovered in these experiments, is the development of a space-charge sheath structure. Measurements of the floating potential and the electric field parallel to the stream show that a potential
hill develops at the front of the plasma stream at the penetration into the neutral gas. This structure is correlated with the deceleration of the plasma stream; it does not appear when the neutral density is so low, or the magnetic field so weak, that the plasma is not decelerated. Measurements of the plasma stream velocity and the sheath potential are shown in Fig. 13 together with an idealized model of the sheath. In this case, the sheath is 5 cm thick and moves with the critical ionization velocity at the front of the plasma stream. Associated with the sheath is a current loop, measured with Rogowski coils. This current is understood as electron "inertia" Hall currents, an interpretation which is in agreement with the observed potential structure. The $i \times B$ forces due to this current is of the right order of magnitude to give the observed plasma deceleration in the back side of the potential hill, while it would accelerate the stream at the very first leading edge.

When the neutral density is lowered, the sheath thickness increases slightly, from 5 cm at $n_n = 10^{19} \text{ m}^{-3}$ to 11 cm at $n_n = 10^{17} \text{ m}^{-3}$. Still, the sheath is located at the front of the plasma stream, while also the much later-arriving plasma is braked. With increasing sheath thickness, the potential remains constant, and therefore the electric field component parallel to the flow decreases.

Another observation concerning the sheath was made by changing the plasma ion component, and thus the kinetic energy in the flow (the flow velocity was kept constant). The sheath potential then varied in the range 50 - 200 Volts, with increasing potential for increasing ion energy.

Fig. 14 shows the range of parameters investigated by Venkataramani and Mattoo. The plasma is decelerated, and the sheath structure develops, when the magnetic field is $> 0.03$ T. For magnetic field strengths in the range 0.005-0.03 T, the interaction was irreproducible, while it disappeared for $B < 0.005$ T. The column density $\int n \, dz$ plotted in Fig. 14 is here the neutral density times the measured scale length for
deceleration. Due to the many combinations of plasma and neutral gas used, each value of the neutral number density corresponds to a range of column densities.

7. Summary and discussion

Fig. 15 shows all the experimental results in the same parameter plot. In view of the differences between the experiments it is not surprising that they don't agree perfectly. It is, however, possible to distinguish two groups of experiments:

The first group consists of the experiments marked (a) and (c), and most of the experiments marked (b) in Fig. 15 (Danielsson (1970), Danielsson and Brenning (1975), Brenning (1981), Vankataramani and Mattoo (1980a,b; 1981)). They have the following features in common:

1. The transverse magnetic field is applied externally.
2. The neutral gas cloud cross section is of the same order as the plasma stream cross section.
3. The neutral gas cloud extension along the plasma flow is of the same order as the width of the plasma stream.

The results from these experiments agree on the following points:

1. When the magnetic field is so weak that $\omega_{ge}/\omega_{pe} < 0.2$, $v_c$-interaction is not observed, or is irreproducible and weak. ($\omega_{ge}/\omega_{pe} = 0.2$ can be recalculated into a value of $\beta$ by use of Eq. (2):

<table>
<thead>
<tr>
<th>$kT_e + kT_i \approx 10$ eV</th>
<th>$\beta = 0.001$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT_e + kT_i \approx 100$ eV</td>
<td>$\beta = 0.01$</td>
</tr>
</tbody>
</table>

2. When $\omega_{ge}/\omega_{pe} > 0.2$, $v_c$-interaction is observed for $\int n \, dz > 2.10^{17} g_{i}^{2} \, m^{-2} \, c^{-2}$, and can be qualitatively understood from the theoretical deceleration scale length $L$. $V_c$-interaction is always found when the penetration length
into the neutral gas cloud exceeds \( L \) by a factor 1-3. Since the theoretical scale length is calculated from the assumption of the highest possible electron impact ionization rate, this indicates that the interaction as a whole usually is very efficient, when the critical limits for \( \frac{\omega_e}{\omega} \) and \( \int n \, dz \) are exceeded.

The second group of experiments differs from the first mainly in the relative size of the plasma stream and the neutral gas cloud:

1. In some of the experiments of Venkataramani and Mattoo (1980b), marked (b) in Fig.15, the plasma deceleration length was far shorter, by up to several orders of magnitude, than the theoretical deceleration scale length. In these experiments, the neutral gas extent along the plasma flow was always much greater than the width of the plasma stream. (This does not, however, prove conclusively that the plasma beam width/neutral cloud extent is the relevant parameter; there are no experiments where these are of the same order at very low \( n_n < 10^{19} \text{ m}^{-3} \) neutral gas densities).

2. The experiments by Danielsson (1966) and Danielsson and Kasai (1968), marked (e) in Fig.15, were made in an apparatus without an external magnetic field, and with a plasma stream cross section area a factor 50 greater than the neutral cloud. In these experiments, plasma deceleration and electron heating were observed at very weak magnetic fields, with \( \frac{\omega_e}{\omega} \approx 0.005 \) (\( \beta \) goes up from about 1 to about 3 in the interaction), but still within a range of \( \int n \, dz \) consistent with the theoretical deceleration scale length.

This second group of experiments clearly shows that one must be very careful, if the laboratory experiments shall be used as a basis for extrapolations to other parameter ranges and configurations, e.g. in space physics. In particular, one has to consider differences in the relative extents of the plasma and the neutral gas carefully. Some space applications of the \( v_c \)-phenomenon are drawn in the parameter plot of Fig.16.
It is clear that the space applications generally correspond to quite different parameter regimes than the laboratory experiments. There are also important differences in the geometry, most important probably that the plasma streams in the laboratory experiments are limited in all three dimensions. This is schematically illustrated in Fig. 17 (top). The plasma stream has a leading edge, which in the experiments usually is found to develop some structure as shown in Fig. 17 (bottom): Danielsson and Brenning (1975) found an initial peak in the velocity, followed by an approximately constant plateau close to the critical velocity. Venkataramani (1981) found a space charge sheath structure with an associated current loop. The question is what would happen in a steady-state situation, where the plasma flow is continuous. It is possible that the experiments after the passage of the leading edge can be seen as good approximations of such a continuous flow; the measured velocities settle down to constant values, which do not seem to depend on the distance to the leading edge. Also, the electron energy measurements by Danielsson and Brenning show a delay in the appearance of hot electrons during the initial velocity peak, after which the electrons remain hot in the rest of the plasma flow.

The limited extent of the plasma stream transverse to the flow can have several effects. The instabilities that can transfer energy to the electrons might be influenced, as well as the electron cooling. In an extended plasma, hot electrons can escape from the interaction region by motion along the magnetic field lines. Electron flow along the magnetic field lines could also neutralize the space charge sheaths that develop on the sides of the plasma stream in the experiments. This would couple the plasma in the interaction region to a much larger volume of surrounding plasma, as discussed by Haerendel (1982). Currents flowing transverse to the magnetic field lines into the surrounding plasma might have a similar effect.
Another problem in extrapolations from the laboratory experiments to space applications is that the instabilities are also influenced by other parameters than those chosen for the parameter plot in this paper. As discussed by Galeev (1981), the energy transfer to the electrons is most effective when the new ions, in the plasma frame of reference, can be approximated by a beam. In that case Galeev finds that the fraction $\eta$ of the energy released in the ionization of the neutrals that goes to the electrons can be as high as $2/3$. There are also other estimates: Raadu (1978) has made an extrapolation from the linear phase of the modified two-stream instability, and found $\eta$ up to 0.4, while Ott et al. (1972) and McBride et al. (1972) from computer simulations report $\eta = 0.28$.

The energy transfer will be less effective if the new ions have time to start gyrating and develop a ring-type distribution in the plasma frame of reference. Galeev obtained $\eta = 0.025$ in that case, which means that the relative velocity must exceed $v_c$ by a factor $\times 6.3$ in order to give a positive energy balance for the electrons.

In the laboratory experiments, the ion gyro period $m_i^{-1}$ is usually greater than the time of transit $t_{\text{tr}}$ of the plasma through the interaction region, and as a consequence the new ions will not have time to start gyrating during the duration of the experiment. When $t_{\text{tr}} > m_i^{-1}$, the development of a ring-type distribution of new ions could be prevented either if the ionization time (per electron) $t_i$ is smaller than the ion gyro period, $m_i^{-1} \ll t_i$ (Galeev, 1981), or if the growth rate of the instability is large enough, $\gamma / m_i^{-1} \gg 1$. This latter condition is also coupled to the ionization time, since $\gamma$ depends on the density of new ions; the question is whether the density of new ions produced during a time much shorter than $m_i^{-1}$ would give an instability growth rate $\gamma \gg m_i^{-1}$. In that case, the ring-type distribution would not have time to develop.
The energy transfer efficiency is thus (both when $\omega_i \tau_i$ and when $\gamma/\omega_i$ is considered as the important parameter) related to the quantity $\tau_i \omega_i$, which depends on the electron temperature and the neutral density/magnetic field ratio. This dependence on the neutral gas density is not reflected by the parameter $\int n \, dz$, which therefore has a limited applicability for comparisons across the parameter limits $\tau_{tr} = \frac{1}{\omega_i}$ and $\tau_i = \frac{1}{\omega_i}$. The efficiency of energy transfer must then be determined individually in each case.

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Alfvén’s Critical Velocity of the Interaction of a Neutral
Gas with a Moving Magnetized Plasma


<table>
<thead>
<tr>
<th>Neutral gas</th>
<th>H</th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Ba</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\langle n_n dz \rangle_{\text{min}})</td>
<td>1.5 (\cdot 10^{18})</td>
<td>1.2 (\cdot 10^{18})</td>
<td>1.4 (\cdot 10^{17})</td>
<td>5.1 (\cdot 10^{16})</td>
<td>1.1 (\cdot 10^{16})</td>
<td>1.4 (\cdot 10^{16})</td>
</tr>
</tbody>
</table>

Table I. The low-density limit for \(\int n_n dz\) (Townsend condition for hot electrons, \(v = v_c\)).
The plasma electrons don't have time to ionize during the passage through the neutral gas cloud.

**Example**

$H^+ \rightarrow He$ impact

The plasma ions can be stopped through binary collisions with the neutrals.

$\int n_n \, dz = \text{column gas density}$

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Fig. 1. Parameter plot.
Plasma: Hydrogen, stream cross section $\phi \approx 30 \text{ cm}$.

$$n_e \approx 10^{19} \text{ m}^{-3}, \quad kT_e \approx 3 \text{ eV}, \quad v_o \approx 6 \cdot 10^4 \text{ ms}^{-1}$$

Magnetic field: $B \approx 0.005 \text{ T}$, frozen-in, irreproducible.

Neutral gas: CO$_2$ cloud, $\phi \approx 5 \text{ cm}$, $n_n \approx 10^{19} \text{ m}^{-3}$.

Fig. 2-3. The experiments by Danielsson and Kasai, 1968.
Fig. 4. The results of Danielsson and Kasai (1966-1968) drawn in the parameter plot. The solid double line indicates deceleration of the plasma stream, and the wavy line electron heating. The open circles show when no $v_c$-interaction was observed.
Plasma: Hydrogen

\[ n_e \approx 3 \cdot 10^{17} \text{ m}^{-3}, \quad kT_e = 5-10 \text{ eV}, \quad v_o = 3 \cdot 10^5 \text{ ms}^{-1}. \]

Magnetic field: \( B = 0-0.44 \text{ T}, \) transverse.

Neutral gas: Helium cloud, \( \phi \approx 5 \text{ cm}, \quad n_n \approx 10^{20} \text{ m}^{-3}. \)

Fig. 5. The device used by Danielsson (1970) and Danielsson and Brenning (1975).
Fig. 6. Neutral gas density profile (a), plasma velocity variations in space (b) and in time (c), and the plasma velocity after deceleration, given as a function of the initial velocity (d). From Danielsson (1970) and Danielsson and Brenning (1975).
Fig. 7. The results of Danielsson (1970) and Danielsson and Brenning (1975) drawn in the parameter plot. The solid double lines indicate deceleration of the plasma stream, and the wavy lines electron heating. The open circles show when no $v_c$-interaction was observed.
**Plasma:** Hydrogen
\[ n_e \approx 2 \cdot 10^{18} \text{ m}^{-3}, \ kT_e = 5-10 \text{ eV}, \ v_o \approx 3 \cdot 10^5 \text{ m s}^{-1}. \]

**Magnetic field:** \( B = 0.015 \text{ T}, \) both longitudinal and transverse.

**Neutral gas:** Helium cloud, \( \varnothing \approx 0.2 \text{ m}, \ n_n = 10^{18}-5 \cdot 10^{20} \text{ m}^{-3} \)

Fig. 8. The device used by Brenning, 1981.
Fig. 9 The effect on the electron energy distribution from interaction with neutral gas clouds of varying density. From Brenning, 1981.
Fig. 10. The results of Brenning (1981) and Kubo et al. (1971) drawn in the parameter plot. The solid double lines indicate deceleration of the plasma stream, and the wavy lines electron heating. The open circles show when no v_e-interaction was observed.
Plasma: H, N, O, Ne, Ar
\[ n_e = 10^{18} - 10^{19} \text{ m}^{-3}, \; kT_e \approx 10 \text{ eV}, \; v_o = 2 \cdot 10^3 - 9 \cdot 10^4 \text{ ms}^{-1}. \]

Magnetic field: B = 0-0.1 T, transverse.

Neutral gas: H\(_2\), N\(_2\), O\(_2\), Ne, Ar
\[ n_n = 2 \cdot 10^{17} - 10^{20} \text{ m}^{-3}, \; \text{scale length 2 cm - 50 cm}. \]

Fig. 11. The device used by Venkataramani and Mattoo, 1979-81.
Fig. 12. Deceleration of plasma streams with initial velocities in the range $0.1 \, v_c - 10 \, v_c$. 

Plot of the argon plasma velocity 2 cm behind the centre of the hydrogen gas cloud against its initial velocity. The solid line represents Alfvén's critical velocity.

Plot of the hydrogen plasma velocity 2 cm behind the centre of the argon gas cloud against its initial velocity. The solid and dashed lines represent Alfvén's critical velocity and the threshold velocity, respectively.
Scematic model of the sheath at the front of the plasma stream

Fig. 13. The sheath at the front of the plasma stream observed by Venkataramani, 1981.
Fig. 14. The results of Venkataraman and Mattoo (1979-1981) drawn in the parameter plot. The solid double lines indicate deceleration of the plasma stream.
a. Danielsson and Brenning; 1970, 1975. $n_n = 10^{20} \text{ m}^{-3}$.
b. Venkataramani and Mattoo; 1979-81. $n_n = 2 \times 10^{17} - 10^{20} \text{ m}^{-3}$.
c. Brenning; 1981. $n_n = 10^{18} - 10^{20} \text{ m}^{-3}$.
d. Kubo et al; 1971. $n_n = 10^{22} \text{ m}^{-3}$.
e. Danielsson and Kasai; 1968. $n_n = 5 \times 10^{19} \text{ m}^{-3}$.

Fig. 15. Parameter plot, showing the results of all the experiments. The solid double lines indicate deceleration of the plasma stream, and the wavy lines electron heating. The open circles show when no $v_c$-interaction was observed.
Fig. 16 Parameter plot, showing space applications of $v_c$-interaction. The wavy lines indicate observed electron heating, and the dashed lines theoretical studies.

(a) Lindeman et al. (1974). Solar wind-neutral gas cloud interaction at the lunar surface.
(b) Möbius et al. (1979), Axnäs (1980). A proposed experiment with a Xe gas cloud release in the ionosphere.
(c) Peteliski et al. (1980). A computer calculation of possible $v_c$-interaction between the distant solar wind and the interstellar neutral gas.
The structure at the front of the plasma stream

Danielsson and Brenning

Venkataramani and Mattoo

Fig. 17. Illustration of some of the difficulties in extrapolating the laboratory results to space applications.
REVIEW OF IMPACT EXPERIMENTS ON THE CRITICAL IONIZATION VELOCITY

Nils Brenning
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The impact experiments on the critical ionization velocity ($v_c$) interaction are reviewed. In these experiments, a highly ionized plasma impacts on a neutral gas cloud. $v_c$-interaction is observed only when the magnetic field, and the neutral gas density, are above certain critical limits. The values of these limits, however, differ between the experiments. The extrapolation of the laboratory results to space applications is also discussed.

Key words: Critical velocity, Critical ionization velocity, Alfvén's critical velocity.