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ON THE ROLE OF THE MAGNETIC FIELD STRENGTH IN CRITICAL IONIZATION VELOCITY INTERACTION

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Abstract

A lower limit to the magnetic field strength required for critical ionization velocity interaction, according to the theory by Sherman and Raadu, is found to correspond to the requirement $v < v_A(1+\beta_e)^{1/2}$, which can also be expressed as $\omega_{pe}/\omega_{ce} < (c/v)((1+\beta_e)m_e/m_i)^{1/2}$. This limit is found to agree, within the experimental uncertainties, with the experimental results. An upper limit to the magnetic field strength is also found, corresponding to the requirement $\omega_{pe}/\omega_{ce} >> (m_e/m_n)^{1/2}$.

1. INTRODUCTION

The critical ionization velocity (CIV) interaction is a phenomenon which has been demonstrated in a number of experiments (e.g. Fahleson, 1961; Danielsson and Brenning, 1975; Himmel et al, 1976; Axnäs, 1977). The phenomenon occurs in situations where a plasma and a neutral gas are in a state of relative motion across a magnetic field. In the interaction the electrons are heated, the neutrals are ionized, and the relative velocity between plasma and neutral gas is reduced.

The interaction is found to occur only when the velocity component across the magnetic field exceeds the critical ionization velocity, v_c, which is given by

$$v_c = (2eU_i/m_n)^{1/2}, \qquad (1)$$

where U_i and m_n are the ionization potential and the mass of the neutrals. There are also restrictions on the magnetic field strength; if the field is too weak, the interaction disappears (Brenning, 1981; Venkataramani, 1981). We will in this paper discuss, from a theorethical piont of view, in what range of magnetic field strengths the CIV interaction can be expected to occur.

The heating of the electrons is a central aspect of the CIV phenomenon. The energy that drives the interaction comes from the relative motion between the ions and the neutrals, and is "released" when the neutrals are ionized. The observed high ionization rates are only possible if a large part of this released energy is transferred to the electrons by some collective process. It is now generally believed that the energy-transferring mechanism usually is one of the lower hybrid instabilities (Sherman, 1973; Möbius et al., 1979; Haerendel, 1982). In the theory of Sherman (1973) and Raadu (1978) it is the modified two-stream instability (MTSI), driven by the relative motion between the electrons and the newly ionized neutrals, which form a beam in the plasma frame.

Sherman-Raadu's theory has some interesting consequences for the parameter range within which the CIV phenomenon can be expected to occur. If the magnetic field is too strong (or the plasma density too low), the growth rate of the MTSI is so low that the ionized neutrals have time to start gyrating and form an isotropic distribution in the plane perpendicular to the magnetic field. Such a distribution would give a very poor efficiency in the energy transfer to the electrons, only 2.5 % according to the quasilinear calculations by Formisano et al, (1982) and Galeev and Chabibrachmanov (1983). The CIV interaction would therefore probably disappear, or appear only above a much higher threshold velocity than that given by Eq.(1).

On the other hand, the interaction would be expected to disappear also if the magnetic field is too weak (or the plasma density too high), since the purely electrostatic MTSI is stabilized by electromagnetic effects if the flow velocity is superalfvenic (McBride and Ott, 1972; McBride et al, i972).

CIV-interaction according to the theory of Sherman and Raadu can therefore be expected to occur only in a limited range of magnetic field strengths and plasma densities. We will here derive simple expressions for the limits to these ranges with the use of the dimensionless parameter

$$\omega_{pe}/\omega_{ce} = (n_e/B^2)^{1/2}(m_e/\varepsilon_0)^{1/2}, \qquad (2)$$

and compare the result to the experimental observations.

2. AN UPPER LIMIT TO THE MAGNETIC FIELD STRENGTH

In the MTSI, the electrons are most effectively heated by the modes at the "equal effective mass angle", given by $\cos^2\theta = m_e/m_i$, where θ is the angle between the wave vector and the magnetic field. For the case where all electrons drift with respect to all ions, these modes have the growth rate $\gamma = \omega_{lh}/2$, where the lower hybrid frequency ω_{lh} is given by $\omega_{lh} = \omega_{pi}(1+\omega_{pe}^2/\omega_{ce}^2)^{-1/2}$.

The ionized neutrals will be prevented from forming a ring-type distribution if $\gamma \gg \omega_{ci}$. This condition is always satisfied when $\omega_{pe}/\omega_{ce} > 1$, which gives $\omega_{lh} = (\omega_{ce}\omega_{ci})^{1/2}$. When $\omega_{pe}/\omega_{ce} < 1$, the lower hybrid frequency is equal to the ion plasma frequency. Therefore, $\gamma \gg \omega_{ci}$ when $\omega_{pi}/\omega_{ci} \gg 1$, i.e. when

$$\omega_{pe}/\omega_{ce} \gg (m_e/m_n)^{1/2}. \qquad (3)$$

m_n is here used instead of m_i since the MTSI is driven by the drift berween the electrons and the newly ionized neutrals. One should therefore use the mass of the neutrals, if this is different from the ion mass. Since Eq. (3) was obtained under the assumption that all ions drift with respect to all electrons, it is a necessary, but not sufficient, condition on ω_{pe}/ω_{ce}, if the MTSI shall heat electrons efficiently. A related and stricter condition is obtained if the ionization is so slow that the plasma density is much higher than the density of the beam (in the plasma frame) of the ionized neutrals (Brenning, 1985).

3. A LOWER LIMIT TO THE MAGNETIC FIELD STRENGTH

When the magnetic field is so strong that $\omega_{pe}/\omega_{ce} < 1$, the MTSI heats the electrons mainly in the direction along the magnetic field (Sherman, 1969).For weaker magnetic fields,

$\omega_{pe}/\omega_{ce} < 1$, electron heating is still possible; the energy then goes into a sloshing motion of the electrons, perpendicular to both the magnetic field and the wave vector (Raadu, 1982).

The electrostatic MTSI is stabilized by electromagnetic effects if the magnetic field is weak enough. The condition for stabilization depends on θ . At the "equal effective mass angle", corresponding to the most efficient electron heating, the stabilization occurs when $v > v_A(1+\beta_e)^{1/2}$ (Mc Bride _et al_, 1972). The ion-ion streaming instabilities that operate at weaker magnetic fields heat mainly the ions. The condition for efficient electron heating therefore is

$$v < v_A(1+\beta_e)^{1/2}. \tag{4}$$

With the use of Eq.(2), this can be rewritten into

$$\omega_{pe}/\omega_{ce} < (c/v)((1+\beta_e)m_e/m_i)^{1/2}, \tag{5}$$

where c is the velocity of light.

4. COMPARISON WITH EXPERIMENTS

According to the previous sections, efficient electron heating by the MTSI is possible only in the parameter range

$$(m_e/m_n)^{1/2} << \omega_{pe}/\omega_{ce} < (c/v)((1+\beta_e)m_e/m_i)^{1/2}, \tag{6}$$

where the left inequality is derived from $\gamma >> \omega_{ci}$, and the right from $v < v_A(1+\beta_e)^{1/2}$.

Sherman-Raadu's theory is probably best applicable to the impact experiments, where a plasma with supercritical velocity is made to collide with a stationary gas cloud. There are four laboratory experiments of this kind; unfortunately, the experimental errors are rather large in the parameter range (weak magnetic fields) of most interest here. In the experiment by Danielsson and Kasai (1968), the magnetic field strength is uncertain with a factor 2-3, and the electron temperature varied between 3 and 20 eV. The uncertainties due to this are marked in Fig. 1. In both the experiments by Danielsson and Brenning (1975) and by Venkataramani (1981), the magnetic field was varied across the limit where CIV interaction disappears. However, the electron temperature before interaction, and the plasma density, were only measured for much higher field strengths. The data in Fig. 1 for these two experiments is therefore calculated from the rather crude assumption that these quantities were independent of the magnetic field strength.

Only the experiments by Brenning (1981) has accurately measured plasma parameters close to $\omega_{pe}/\omega_{ce} = (c/v)((1+\beta_e)m_e/m_i)^{1/2}$, but only in the parameter range where CIV interaction is not expected to occur. The efficiency in energy transfer to the electrons was in this experiment found to be less than 1 %.

Fig. 1 shows a comparison between the limits set by Eq. (6) and the laboratory results . xxxx denotes clear interaction, ---- irreproducible interaction, and OOOO absence of interaction. In all the experiments, the left-hand condition in Eq. (6), $(m_e/m_n)^{1/2} << \omega_{pe}/\omega_{ce}$, is satisfied with a wide margin, even if the neutral gas is hydrogen, which gives the strongest limitation on ω_{pe}/ω_{ce}.

The comparison between the experiments and the right-hand condition of Eq. (6) is more interesting. In all four experiments it agrees well (within a factor of two) with the experimental observations of when CIV interaction occurs. In the experiments by Danielsson and Brenning (1975), Brenning (1981) and Venkataramani (1981) $\beta_e << 1$, so the condition

$v < v_A(1+\beta_e)^{1/2}$ in practice becomes $v < v_A$. Only in the experiment by Danielsson and Kasai (1968) is $\beta_e > 1$, and the two conditions become different. Using the average values for the uncertain quantities (B and T_e) in this experiment we find $v = 2.5v_A$, while $v \approx v_A(1+\beta_e)^{1/2}$. This is therefore the only CIV experiment where efficient electron heating has been observed in a superalfvenic flow. The experimental uncertainties are, however, so large that one must regard this as only an indication of the validity of the factor $(1+\beta_e)^{1/2}$ in Eq. (6).

5. SUMMARY

The modified two-stream instability (MTSI) is stabilized by electromagnetic effects when $v < v_A(1+\beta_e)^{1/2}$. If this instability is the energy-transferring mechanism in the critical ionization velocity interaction, one should expect $v < v_A(1+\beta_e)^{1/2}$ to give a lower limit to the magnetic field strength. The experimental results in the impact configuration agree, within the experimental uncertainties, with this condition; the importance of the factor $(1+\beta_e)^{1/2}$ is indicated, but not convincingly shown, by the experiments by Danielsson and Kasai (1968).

However, the experimental uncertainties are generally rather large. A well diagnostizised experiment across the limit $v = v_A(1+\beta_e)^{1/2}$ remains to be made.

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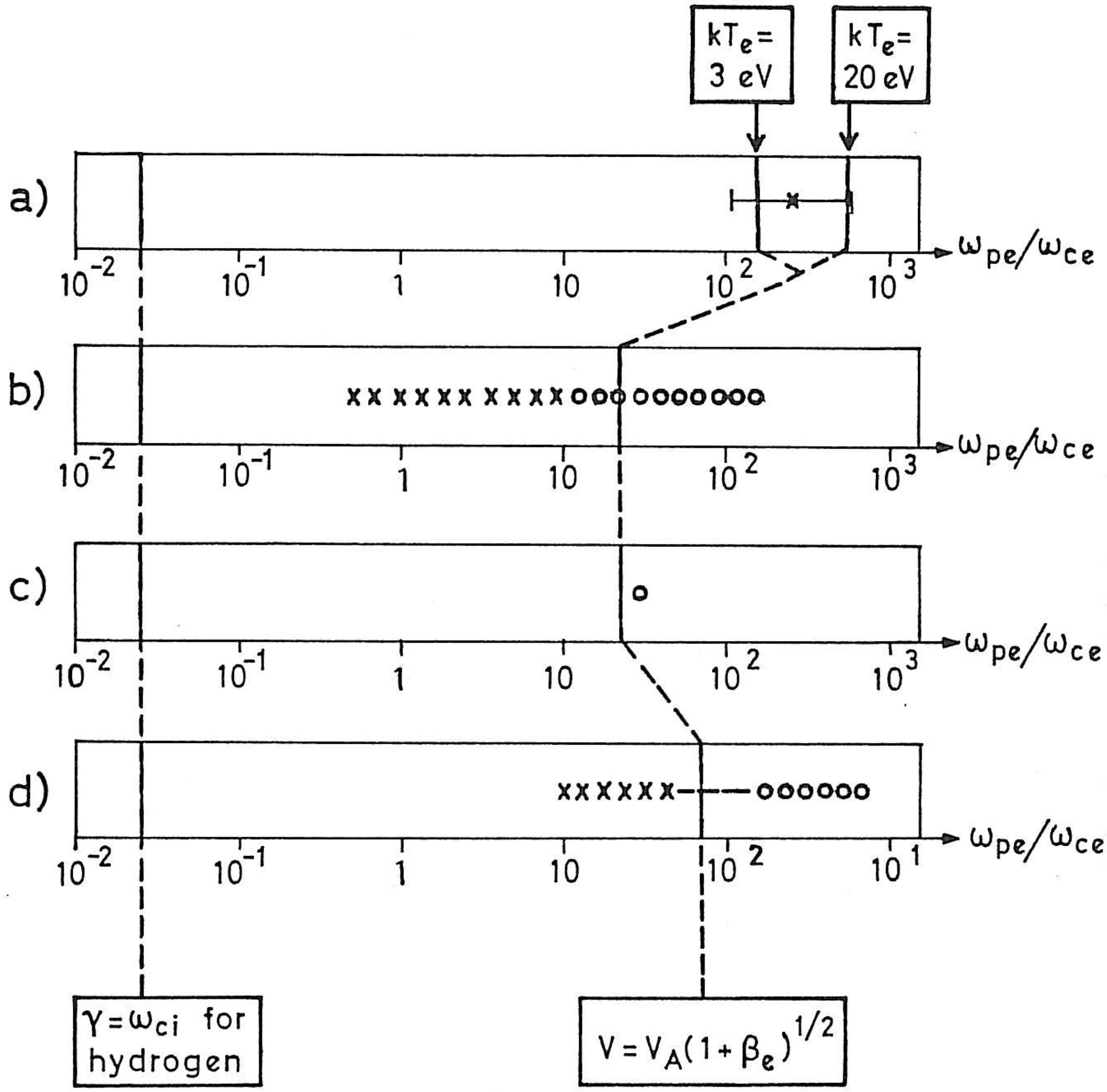

Fig. 1. Comparison between experimental results and the limits to CIV interaction given by Eq. (5). Notations: xxxx = clear interaction; ---- = irreproducible or weak interaction; OOOO = no interaction. The error bar in the experiment by Danielsson and Kasai shows the uncertainty in ω_{pe}/ω_{ce} due to the uncertainty in the magnetic field strength.
a: Danielsson and Kasai (1968); b: Danielsson and Brenning (1975); c: Brenning (1981); d: Venkataramani (1981).

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Key words: Critical velocity, Critical ionization velocity, Modfied two-stream instability.