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EXPERIMENTS ON THE MAGNETIC FIELD AND NEUTRAL DENSITY LIMITS ON CIV INTERACTION

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Abstract

A series of experiments on the critical ionization velocity (CIV) interaction in the impact configuration are reported, where the plasma density, the neutral density and the magnetic field strength have been varied. A combination of microwave interferometry and spectroscopy has been used to measure the plasma density and to study the electron energy distribution. The efficiency of the CIV process is evaluated as function of (1) the ratio between the Alfvén velocity and the plasma stream velocity, and (2) the ratio between the ionization frequency and the ion gyro frequency. In the parameter range studied so far, efficient electron heating is found only when both these parameters exceed unity.

1. Introduction

The purpose of the experiments reported here is to investigate how the energy transfer efficiency η in CIV interaction varies with two dimensionless parameters which reflect the magnetic field strength and the neutral gas density: (1) the ratio V_A/V_0 between the Alfvén velocity and the plasma stream velocity and (2) the ratio ν_i/ω_{gi} between the ionization frequency and the ion gyro (angular) frequency. Both these parameters have been discussed in the literature. According to Papadopoulos (1982) and Brenning (1985), a value of $V_A/V_0 > 1$ is required for efficient CIV interaction. Concerning ν_i/ω_{gi} there is some controversy: Formisano et al (1982) require $\nu_i/\omega_{gi} > 1$ for efficient CIV interaction, while others (Haerendel, 1986, Brenning, 1986) claim that the limit in some cases could be much lower.

2. The experiment

The plasma is generated by a plasma gun of the conical theta pinch type, which gives a hydrogen plasma stream with 10-20 μs duration, and a velocity about 200 km/s. As neutral gas we used helium, with a critical velocity of 35 km/s. The apparatus has been described elsewhere (Brenning et al., 1981). In a series of experiments, the plasma density was varied between 5 10^{16} and 2 10^{18} m^{-3}, the transverse magnetic field strength between 0.0075 T and 0.03 T, and the neutral helium density between 2 10^{18} m^{-3} and 5 10^{20} m^{-3}. The covered range in V_A/V_0 was 1.1 - 4.2, while ν_i/ω_{gi} was varied between 0.03 and 1.5. The plasma velocity was measured by floating double probes (Brenning et al., 1981) while the plasma density was determined from a combination of Langmuir probes and microwave interferometry (Brenning, 1984). The electron energy distribution was observed through the absolute strengths of the He I lines at 3889 Å (threshold 23.0 eV) and 4686 Å (threshold 75.6 eV).

The limits to the studied parameter range were determined by the reliability of the spectroscopic measurements: at high neutral and plasma densities, the build-up of the metastable level 2^3S in helium influences the 3889 Å line strength by two mechanisms, (1) through direct excitation of the line from 2^3S, and (2) through imprisonment of the 3889 Å radiation. At low neutral and plasma densities, the 4686 Å line became very weak; at the lower limits of our study we measured a few photons per μs in single-shot measurements, and had to verify the presence of the line by taking line profiles with many-shot averages.

For each combination of plasma stream density n_e and transverse magnetic field strength B, we made a series of experiments with varied helium density n_{He}. The measurements were recorded digitally and stored in a VAX 11/750 computer, which also was used to calculate the column plasma density across the plasma stream from the phase shift of the transmitted microwave signal (Brenning, 1984). The final computer output for each shot with the plasma gun was the effective excitation rate coefficients S_{3889} and S_{4686} (i. e., excitations per m^{-3}, divided by n_{He} and n_e) as function of time. Together, these two lines give a good estimate of the high-energy part of the electron energy distribution, since the 3889 Å line is mainly excited by electrons in the 25 - 100 eV range, while the excitation rate of the 4686 Å line has a threshold at 75 eV, and is about constant above 100 eV.

3. Results

We divide the observations into three groups depending on the neutral helium column density $\int nHedz$ along the plasma flow to the z coordinate where the measurements were made:

1. *Low column density*, $\int n_{He}dz < 5\ 10^{17}\ m^{-2}$: the plasma stream is expected to be uninfluenced by the presence of helium, even if a very efficient ($\eta = 1$) mechanism for CIV heating operates.
2. *Medium column density*, $5\ 10^{17} < \int n_{He}dz < 10^{19}$: the CIV mechanism could get ignited, provided that a mechanism to feed back energy to the electrons exists.
3. *High column density*, $\int n_{He}dz > 10^{19}\ m^{-2}$: the plasma stream would be stopped by elastic (proton-helium) collisions even in the absence of CIV interaction. Also, the electron energy loss time (for inelastic collisions with neutral He) is shorter than the transit time of the plasma into the neutral gas.

The line strengths measured at low column density give information about the undisturbed plasma stream: the 3889 Å line had a strength corresponding to a thermal distribution with $kT_e = 5 - 10$ eV (varying with the plasma density, the magnetic field, and the time of evaluation of each shot). The 4686 Å line was several orders of magnitude stronger than expected from such a thermal distribution. It shows an overpopulation in the high-energy tail ($W_e > 100$ eV) containing 5 - 20 % of the electrons (again varying with n_e, B and t). The presence of this energetic population necessitates special care in evaluation of the results: on one hand, this high-energy population should be well suited to trigger the CIV interaction by initial electron impact ionization. On the other hand, we had to make certain that any observed ionization can not be attributed to these already-present energetic electrons (i.e., without the CIV effect). In order to study this latter possibility in more detail, we have constructed the following model for the interaction, where the input is the measured values of S_{3889}, S_{4686}, n_{He} and v for low column density, and the output is the same set of parameters as function of the penetration depth $\int n_{He} dz$ into the neutral cloud:

The electrons are divided into three populations: cold (n_e), monoenergetic ($n_{e(50)}$) at $W_e = 50$ eV which excites mainly the 3889 Å line, and monoenergetic ($n_{e(100)}$) at $W_e = 100$ eV which excites the 4686 Å line. A factor η of the energy $m_{He}v^2/2$ released in each ionization is divided equally between the two hot populations. The factor η is varied between different runs of the model. The hot populations are depleted through ionization and line excitation; electrons which are lost from the 100 eV population are added to the 50 eV population. The electrons which are lost from the 50 eV population are added to the cold population. Momentum conservation, and continuity for the hydrogen flow in the z direction, give the velocity and the plasma density.

The calculated values of S_{3889}, S_{4686}, n_e and v from the model were compared to the experimental values, all as functions of the neutral column density $\int n_{He} dz$. For low and medium column densities, the experimental results were best fitted by an η value close to zero: instead of triggering the CIV effect, the high-energy population density (as reflected by the 4686 Å line) falls, as function of ∫nHedz, at a rate determined by ionization and excitation in the neutral helium gas. The observed velocity and plasma density also closely fit the same model. The clearest evidence for a low η value is found in the measurements of plasma density from the microwave interferometer. This is illustrated in Fig. 1, which compares the measurements to model calculations with $\eta = 0$, 0.25 and 0.5. The $\eta = 0$ curve fits the observations within 10 - 15 %.

Our conclusion is that for low and medium neutral column densities we have found a clear absence of CIV interaction in the parameter range studied so far: v_i/ω_{gi} was in the range 0.01 - 0.1, and V_A/V_0 in the range 1.1 - 4.2. Furthermore, these results show that it is vitally important in this type of experiment to know how many energetic electrons there are in the original plasma stream; the ionization due to an already-present high-energy tail could otherwise be misinterpreted as evidence of CIV interaction.

In the region of high neutral column density we find the first evidence for strong electron heating. Unfortunately, our model does not include elastic (proton-helium) collisions, which must be of dominating influence in this range. We are therefore limited to presenting the measurements without comparison to a model.

Fig. 2 shows the measured S_{3889} for a series of experiments made with one and the same plasma stream, but with B and n_{He} varied. There is clear evidence in Fig. 2 of some efficient heating mechanism. The highest measured value of S_{3889} (at $\int n_{He} dz = 5\ 10^{19}$ m^{-2}, $V_A/V_0 = 4.2$)

is $S_{3889} = 0.9\ 10^{-16}$ m^3/s. As a comparison, the highest possible value of S_{3889}, which occurs about $kT_e = 30$ eV, is between 1.2 10^{-16} and 2 10^{-16} m^3/s, depending on the population density of the metastable state 2^3S. Values of ν_i/ω_{gi} are also given in Fig. 2. The efficient heating mechanism seems to start operating when ν_i/ω_{gi} exceeds unity, just as proposed by Formisano et al. (1982).

The heating mechanism has to compete with rapid cooling through ionization and He line excitation: $t_{cool} = 0.14$ µs at the highest neutral density, $\int n_{He} dz = 5\ 10^{19}$ m^{-2}, while the time of transit through the neutral cloud to the observation point is 0.5 - 1 µs. In the total absence of electron heating, the S_{3889} value would therefore be expected to approach zero for the highest neutral column densities. We conclude that some heating mechanism operates at $\int n_{He} dz = 5\ 10^{19}$ m^{-2} for all four values of V_A/V_0 in Fig. 2., and that it becomes increasingly more efficient as V_A/V_0 increases above unity. The latter conclusion is supported by the density of high-energy ($W_e > 100$ eV) electrons, as derived from the 4686 Å line strength: For the highest neutral densities we found that $n_e(W_e{>}100\ \text{eV})/n_e$ increases from a value below 0.2 % at $V_A/V_0 = 1.1$ to about 2 % for $V_A/V_0 = 4.2$. All these observations agree well with the view (Papadopoulos, 1982, Brenning, 1985) that CIV interaction requires a subalfvénic flow.

4. Acknowledgements

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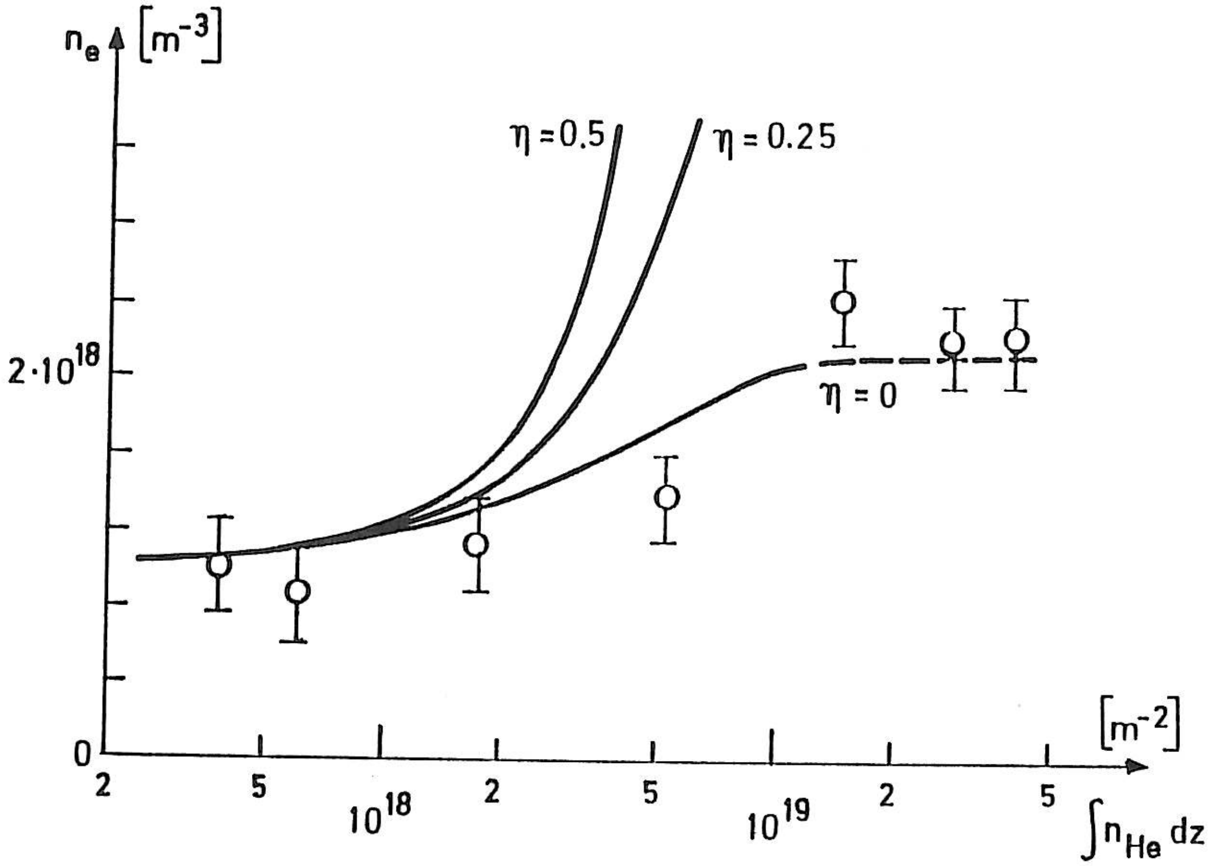
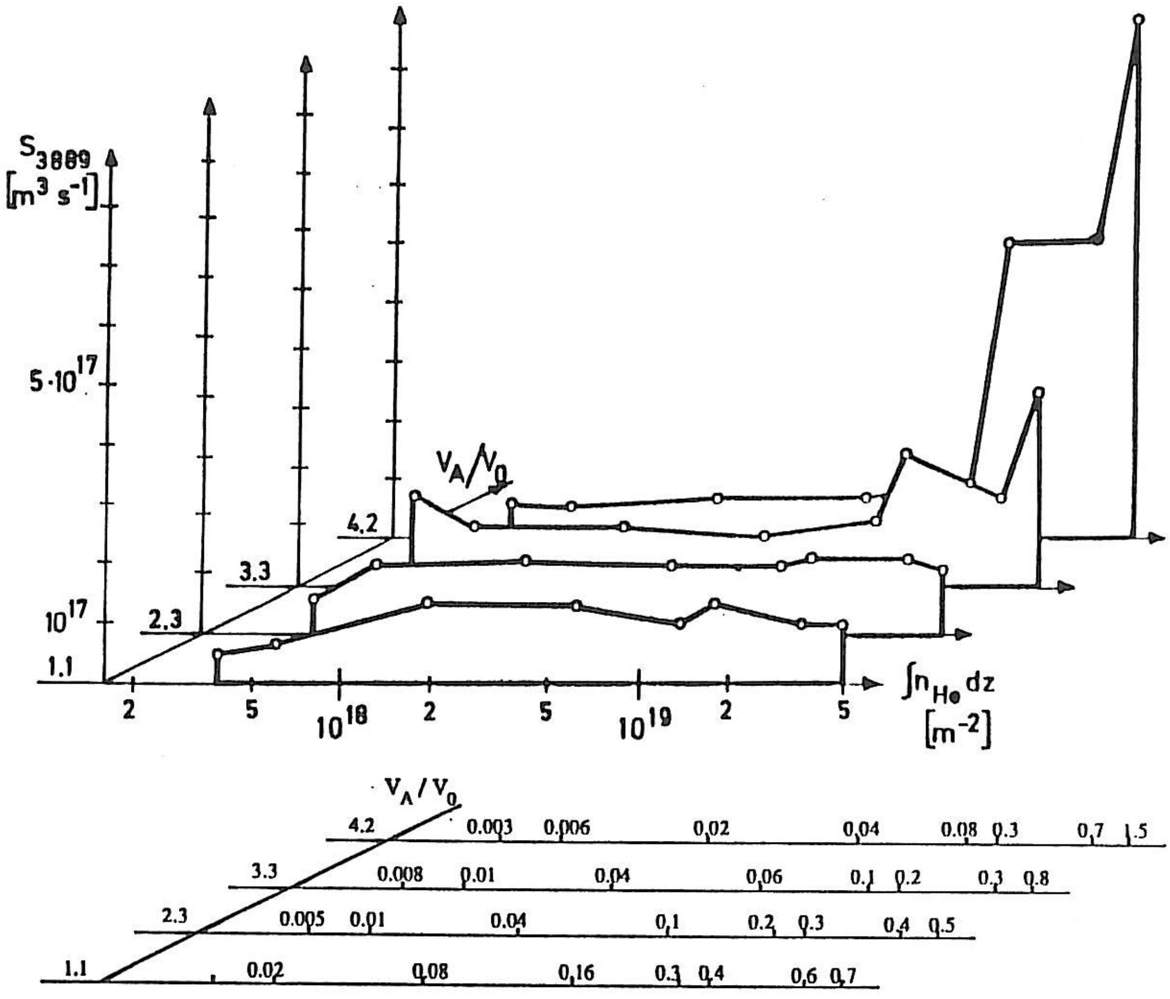


Fig. 1. Solid curves: Theoretical values of the plasma velocity v, as function of $\int n_{He}dz$, for a plasma stream which enters the neutral gas with a velocity, density, and electron energy distribution derived from the experimental results at low neutral column densities. η denotes the energy transfer efficiency to the electrons. The curve is dashed where it is uncertain due to the influence of elastic (proton-helium) collisions. Circles: experimental values, for a plasma stream with $V_A/V_0 = 2.3$.



Values of v_i / ω_{gi} corresponding to the circles in the upper figure

Fig. 2. Upper fig.: measured values of S_{3889} in a series of experiments where the plasma stream density is constant. The different curves correspond to different magnetic field strengths: =.0075 T, 0.015 T, 0.0225 T and 0.03 T. The error is typically $\pm$ 30 % of the measured values except for the highest S_{3889} (above 5 10^{-17} m^3 s^{-1}), the error is about $\pm$ 10%. Lower fig.: the corresponding values of the quantity v_i / ω_{gi} .

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Key words: Critical Ionization Velocity, Critical Velocity, Plasma Neutral Gas interaction