TRITA-EPP-76-02

VELOCITY LIMITATIONS IN COAXIAL PLASMA GUN EXPERIMENTS WITH GAS MIXTURES

Ingvar Axnäs

April 1976

Department of Plasma Physics
Royal Institute of Technology
S-100 44 Stockholm 70, Sweden

VELOCITY LIMITATIONS IN COAXIAL PLASMA GUN EXPERIMENTS WITH GAS MIXTURES

Ingvar Axnäs

Department of Plasma Physics, Stockholm, Sweden

Abstract

The velocity limitations found in many crossed field plasma experiments with neutral gas present are studied for binary mixtures of H_2, He, N_2 O_2, Ne and Ar. The apparatus used is a coaxial plasma gun with an azimuthal magnetic bias field. The discharge parameters are chosen so that the plasma is weakly ionized. In some of the mixtures it is found that one of the components tends to dominate in the sense that only a small amount (regarding volume) of that component is needed for the discharge to adopt a limiting velocity close to that for the pure component. Thus in a mixture between a heavy and a light component having nearly equal ionization potentials the heavy component dominates. Also if there is a considerable difference in ionization potential between the components, the component with the lowest ionization potential tends to dominate.

Introduction

It is a well established experimental fact that velocity limitations occur in $\underline{E} \times \underline{B}$ discharges. These velocity limitations are predominantly determined by the gas used in the experiment and comparatively unaffected by other experimental parameters such as neutral gas density, plasma density (discharge current) and magnetic field. This behaviour of the E x B discharge indicates that regarding particle balance we may have a situation illustrated schematically in Fig. 1. The E/B of the point where the two curves intersect each other is comparatively independent of the inclination of the loss curve. The loss curve should be strongly dependent on the discharge parameters. The measured values of E/B are also in good agreement with the so-called critical ionization velocity of plasma - neutral gas interaction, proposed by H. Alfvén 1954, before it was discovered experimentally. (See also Alfvén and Wilcox 1962.)

$$u_c = \left(\frac{2eV_i}{m_n}\right)^{1/2} \qquad (1)$$

where $-e$ = electron charge

V_i = ionization potential

m_n = neutral particle mass

Thus the critical ionization velocity of a magnetized plasma moving with respect to a neutral gas is reached when the energy of motion of the neutrals in a coordinate system, where the the plasma is at rest, equals the ionization energy. Values of the critical velocity for different gases are shown in Table 1. Review articles on the critical ionization velocity phenomenon are given by Danielsson (1973) and Sherman (1973).

The critical ionization velocity seems at least experimentally to be a gas property. It is then of interest to determine E/B for a mixture of gases. This has to some extent been done earlier by Eninger (1966) for H_2-N_2 mixtures. The present paper summarizes the results of systematic experiments on the critical ionization velocity as a function of the mixing ratio for several different binary gas mixtures.

Discharge parameters

The apparatus used in this experiment is a coaxial plasma gun with an azimuthal magnetic bias field and a radial discharge current. The gun and the experiments performed in pure gases using this have been described in earlier papers (Wilcox et al., 1964, Eninger 1966, Axnäs 1972).

As a first step it seems reasonable to choose gas mixtures with components having notable differences in measured E/B (critical ionization velocity). The discharge parameters have been chosen so that we have:

a) a weakly ionized gas
b) good azimuthal symmetry in the current sheet
c) possibilities to compare the results with those of earlier experiments.

The parameters chosen are:

discharge current: 100 A
filling pressure: 0.1 torr
magnetic field: 0.1 - 1 T.

Choosing the discharge current equal to 100 A will make the discharge run in the faster of the two modes found in molecular gases (Eninger, 1966).

The experimental method

The components of the gas mixture were mixed in a mixing tank at a pressure of about 800 torr. From the mixing tank the gas mixture was continuously let into the gun via a variable leak. The filling pressure of the gun was adjusted partly with the variable leak and partly by choking the pump (and thus varying the pumping speed). In principle such a system could cause an enrichment of one of the components in the gun. The lighter gas will leak faster through the leak but will on the other hand be pumped out faster from the gun.

In order to investigate possible enrichment the gun was filled in three different ways with a gas mixture (10% Ar, 90% He in the mixing tank).

1) continuous gas inlet from the tank and choked pumping (the standard method)
2) gas inlet from the tank but no pumping
3) the components were mixed in the gun (no enrichment possible)

The mass ratio m_{Ar}/m_{H_2} of the components of this mixture is large and it would thus be comparatively sensitive to enrichment. Fig. 2 shows the measured E/B as a function of the composition. From this diagram (which will be described and discussed more later in this report), it is clear that E/B of the He-Ar mixture is sensitive to a change in the composition.

The measured values of E/B in the three different cases however agree within the experimental error. It is therefore concluded that enrichment is of minor importance in this experiment.

The evaluation of the burning voltage data to obtain E/B is carried out in the same way as in earlier coaxial plasma gun experiments (Eninger 1966).

Results

In Figs. 2-6 (upper diagrams, circles) the experimentally obtained ratio E/B for a gas mixture discharge is shown as a function of the neutral gas composition (expressed in volume per cent). In the diagrams below the calculated relative production frequencies of different ion species are shown as functions of the neutral gas composition. In order to see how sensitive the choice of electron energy distribution is to the shape of the ion production curves, two different assumptions of the distribution have been used to calculate the ion production functions:

1) (Dotted curves in Figs. 2-5). The electrons are assumed to be thermal with a temperature giving a total ionization frequency $\nu_i = 10^6\ s^{-1}$ per electron. This value of the ionization frequency is in good agreement with experimental values obtained for H_2 (Axnäs 1972) and later also for other gases. The electron temperatures necessary will vary from $3.6 \cdot 10^4$K (pure Ar) to $8.4 \cdot 10^4$K (pure He). To calculate the ionization frequencies the following formula (SI units) has been used (von Engel 1955 p. 260, Lehnert 1966a)

$$\nu_i = n_n\ 1092a\ \left(\frac{2e}{\pi m_e}\right)^{1/2} V_i^{3/2} \cdot \chi^{3/2}\ \left(1+\frac{1}{2\chi}\right)\exp\left(\frac{-1}{\chi}\right) \qquad (2)$$

where $\chi = \frac{kT_e}{eV_i}$

k: Boltzmann's constant

T_e: electron temperature

a: a constant with a numerical value 0.754 times that given by von Engel

2) (Solid curves in Figs. 2-5). The electrons are assumed to be monoenergetic with an energy well above any

ionization potential relevant in this experiment (W_e = 40 eV).

The different gas mixtures could be divided into three groups:

1) The components have roughly the same ionization potential but considerably different molecule (atom) weights (H_2-N_2, H_2-O_2 and H_2-Ar) Fig. 2.

2) One component has much larger ionization potential (He-N_2, He-O_2, He-Ar, Fig. 3; H_2-He, H_2-N_e, Ne-Ar, Fig. 4)

3) The differences regarding both molecular weight and ionization potential are not large. (He-Ne, N_2-Ar, and O_2-Ar, Fig. 5).

An experimental result common to all mixtures is that E/B for any composition has a value between those for the pure components.

From Fig. 2 it is clear that in the first group the heavier component dominates i.e. a relatively small amount (regarding volume) of the heavier component brings the E/B of the mixture close to that for the pure heavy component. In the second group the component with the lowest ionization potential dominates in most cases. In the Ne-Ar mixture (Fig. 4) this effect is not so pronounced and in the H_2-Ne mixture (Fig. 4) none of the components dominates. In the third group the molecular gases O_2 and N_2 dominate in mixtures with Ar (Fig. 5). In the He-Ne mixture (Fig. 5) none of the components dominates.

For H_2-He mixtures an extension of the experimental parameter range has been made. In Figs. 6-8 E/B is shown for different values of the filling pressure and the discharge current. The current dependence of E/B for pure H_2 and He which has been studied earlier by Eninger (1966) is also found in the mixture experiment i.e. a hydrogen dominated mixture has two modes of E/B - one fast (low current) and one slow (large current) - whereas the current dependence of a helium dominated mixture is comparatively weaker. The pressure dependence of the mixtures seems to be similar to that found earlier for pure gases (Eninger 1966).

The statistical error of the measured values of E/B is typically ±10%. In some cases when the dependence on the composition is very strong, errors in the partial pressures of the gas in the mixing tank could increase the error to a value ±15%.

Ion abundance

For the interpretation of the experimental results it is important to estimate the relative abundance of the ions in the gas mixture plasma and some factors of importance in that context will be discussed here. However, a complete treatment of this problem is very difficult and beyond the scope of this paper. Even experimentally it would be difficult because it requires extraction of ions perpendicular to the magnetic field lines.

The recombination rate could be different for different ions. In the case of volume recombination it is well known that dissociative recombination can be several powers of ten more effective than radiative recombination. This tends to decrease the relative density of molecular ions.

The ions can also be lost through wall recombination and different transport properties for different ions could influence the relative abundance of the ions. Since the particle balance in the current sheet in this experiment is not theoretically fully understood it is not possible to estimate that influence. In the case when even the heavy ions are free orbiting (ion Hall parameter $(\omega\tau)_i > 1$) the heavy ions, because of their larger gyro radii, should have a larger probability to hit the cathode (and thus being lost) than the light ions. The ion gyro radii for different ions at the critical velocity are given in Table 1.

The ions could also be transformed to other kinds of ions by ion-neutral reactions. The cross sections for the possible reactions in the relevant energy range are often insufficiently known as well as plasma properties like the ion velocity distribution and the state of exitation of the ions and the neutrals. Thus it is quite difficult to estimate the influence of such reactions on the relative abundance of the different ions existing in a discharge of the type described here.

Some possible ion-neutral reactions in the first group of mixtures are listed in Table 2 as well as calculated rate coefficients. The rate coefficients have been calculated for $E/B = 5\cdot10^4$ m/s. In some cases where H_2^+-reaction cross sections have not been found the corresponding D_2^+-reaction coefficients have been calculated. For the rate coefficient calculations an ion velocity distribution given by Sherman (1974) has been used. It is applicable in a weakly ionized plasma for ions moving in crossed electric and magnetic fields and where resonant charge transfer is the dominant ion-neutral collision process. The H_2^+-H_2 charge transfer is resonant and H_2^+-N_2, N_2^+-H_2 charge transfer are nearly resonant. However, the ions will also collide elastically (smaller cross sections) which will change the ion velocity distribution. Thus the calculated rates are rather uncertain.

In pure hydrogen most of the initially created H_2^+ ions will very soon (after 3-4 collisions) be converted to H^+ and H_3^+ ions provided the cross sections for reactions that transform the H^+ and H_3^+ ions are small.

Discussion

The theoretical interpretation of the various critical velocity experiments has proved to be very complicated even in the case with only one gas component. A mixture of two components is of course still more complicated and no complete discussion will be attempted here. However, some features of the experimental results will be discussed.

In the gas mixtures of group 1, by introducing 10% of the heavier component the value of E/B will drop to about the mean value of the E/B for the pure components. The heavy component could influence the discharge in several different ways:

1) The Hall and Pedersen conductivities could in a weakly ionized plasma be expressed as functions of the plasma density, the electron and ion Hall parameters (Alfvén-Fälthammar 1963). If the electric field has both radial and axial component the radial current density will depend on both the Pedersen and the Hall conductivities. The heavy ions (which may have small values of the Hall parameter) could change the Pedersen and Hall conductivities as well as the direction of the electric field.

2) In some theories for the critical ionization velocity the electrons are heated through energy transfer from the ions (Lehnert 1967, Sherman 1972, Raadu 1975). The introduction of heavy ions, which are able to gain large energy from the electric field in the discharge could increase such energy transfer. This would give increased ionization (and hence conductivity).

3) Processes (cf. e.g. Table 2) leading to increased heavy ion abundance will amplify both the mechanisms mentioned above.

The tendency of the mixtures belonging to group 2 to adopt the E/B of the component with the lowest ionization potential is somewhat easier to understand. From the ion production curves, Figs. 3-4, it is obvious that even a small amount of the component with low ionization potential will increase the total ionization (and hence the conductivity) appreciably.

The present experiments and earlier limiting velocity experiments indicate that the ionization potential and the atomic (molecular) mass are the most important quantities determining the limiting velocity. In the case of a single gas Alfvén's critical ionization velocity hypothesis could be regarded as one way of combining the influence of these two quantities. For a mixture of two gases, I and II, an analogous way of combining (and also a simple-minded generalization of Alfvén's hypothesis) is to equate the kinetic energy supply associated with the formation of ions moving relative to the plasma with the loss rate through ionization i.e.

$$\alpha\frac{1}{2}\, m_{iI}u_c^2 + (1-\alpha)\frac{1}{2}m_{iII}u_c^2 = \alpha eV_{iI} + (1-\alpha)eV_{iII} \qquad (3)$$

where $\alpha = \nu_{iI}/(\nu_{iI}+\nu_{iII})$ is the fractional ion production rate of component I.

This is also in basic agreement with the modified two stream instability (Sherman 1972, Raadu 1975) due to which the energy source driving the instability is the relative motion between the electrons and the newly formed ions. E/B calculated from eq. 3 is found in Figs. 3-5 (upper diagrams, solid curves). The fractional ion production rate α has been taken from the ion production diagrams (Figs. 3-5, lower diagrams, thermal electrons).
In molecular gases the situation is more complicated. First molecular as well as atomic ions could be formed. Secondly in the case of dissociative ionization the dissociation energy has to be taken into account. However, for molecular gases eq. 3 is shown in Figs. 2-5 only for the case with atomic mass (no dissociation energy). Atomic ionization cross

sections (for the calculations of α) are given by Fite and Brackmann (1958) (H), Fite and Brackmann (1959) (O), Smith et.al (1962) (N). From Figs. 2-5 it is clear that in practically all cases (except in argon dominated mixtures) the experimental values are somewhat larger than the calculated. However, there is a basic similarity regarding composition dependence between the calculated and the measured values of E/B.

In rotating plasma experiments with hydrogen mixtures (Lehnert et al., 1966b) it has been found that H_2 has a dominating effect on the limiting velocity. The reason was assumed to be that the heavier component was centrifuged out from the interaction region. In the coaxial plasma gun there are no centrifugal effects and since no hydrogen dominance is found in mixtures with large mass differences the present results leave support to that assumption.

Acknowledgements

The author wants to thank Professors H. Alfvén and C.-G. Fälthammar for stimulating interest in his work. Discussions with Drs. L. Lindberg and M. Raadu have been of great value. The technical assistance of Mr. R. Landberg is highly appreciated.

The work has been financed by the Swedish Atomic Research Council.

Alfvén, H.: On the Origin of the Solar System. Oxford Univ. Press, Oxford 1954

Alfvén, H. and Wilcox, J.M.: On the origin of satellites and the planets. Astrophys. J., 136, 1016, 1962

Alfvén, H. and Fälthammar, C.-G.: Cosmical Electrodynamics, Fundamental Principles, Clarendon Press, Oxford, 1963

Axnäs, I.: Experimental investigation of an ionizing wave in a coaxial plasma gun. Royal Institute of Technology, report TRITA-EPP-72-31, 1972

Brown, S.C.: Basic Data of Plasma Physics. (2nd revised ed.) M.I.T. Press, 1966

Danielsson, L.: Review of the critical velocity of a gas--plasma interaction, experimental observations. Astrophys. and Space Sience, 24, 459, 1973

von Engel, A.: Ionized Gases, Clarendon Press, Oxford, 1955

Eninger, J.: Experimental investigation of an ionizing wave in crossed electric and magnetic fields. Proc. VII Int. Conf. on Phenomena in Ionized Gases, Belgrade, I, 520, 1966

Fite, W.L. and Brackmann, R.T.: Collisions of electrons with hydrogen atoms. I. Ionization. Phys.Rev., 112, 141, 1958

Fite, W.L. and Brackmann, R.T.: Ionization of atomic oxygen on electron impact. Phys.Rev., 113, 815, 1959

Gustafsson, E. and Lindholm, E.: Ionization and dissociation of H_2, N_2 and CO in charge exchange collisions with positive ions. Arkiv för Fysik, 18, 219, 1960

Lehnert, B.: Ionization process of a plasma. Phys. Fluids, 9, 774, 1966a

Lehnert, B., Bergström, J., and Holmberg, S.: Critical voltage of a rotating plasma, Nucl. Fusion, 6, 231, 1966b

Lehnert, B.: Space charge effects by nonthermal ions in a magnetized plasma. Phys. Fluids, 10, 2216, 1967

Raadu, M.: Critical ionization velocity and electrostatic instabilities. Royal Institute of Technology, report TRITA-EPP-75-28, 1975

Sherman, J.C.: The critical velocity of gas-plasma interaction and its possible hetegonic relevance. Nobel Symposium No 21, 315, 1972. Almqvist & Wiksell, Uppsala.

Sherman, J.C.: Review of the critical velocity of gas-plasma interaction, II: Theory. Astrophys. Space Science, 24, 487, 1973 a.

Sherman, J.C.: The velocities and energies of ions moving in strong electric and arbitrary magnetic crossed fields. J.Phys. B: Atom.Molec.Phys., 7, 244, 1974.

Smith, A.C.H., Caplinger, E., Neynaber, R.H., Rothe, E.W., and Trujillo, S.M.: Electron impact ionizaion of atomic nitrogen. Phys.Rev., 127, 1647, 1962

Vance, D.W. and Bailey, T.L.: Inelastic collisions of H_2^+ and N_2^+ ions with hydrogen molecules. J.Chem.Phys., 44, 486, 1966.

Wilcox, J.M., Pugh, E., Dattner, A. and Eninger, J.: Experimental study of the propagation of an ionizing wave in a coaxial plasma gun. Phys. Fluids, Suppl. 7, S 51, 1964.

Table 1

Gas	Atomic weight	Ionization potential [Volts]	Critical ionization velocity u_c [m/s x 10^{-4}]	Ion gyro radius at u_c [m x 10^3] B = 0.66 T
Hydrogen	1	13.6	5.1	0.8
Helium	4	24.6	3.4	2.2
Nitrogen	14	14.5	1.4	3.1
Oxygen	16	13.6	1.3	3.2
Neon	20	21.6	1.6	4.5
Argon	40	15.8	0.9	5.5

Table 2

Reaction	Rate coeff. $\langle\sigma v\rangle \lvert m^3/s \times 10^{15} \rvert$	Reference
$H_2^+ + H_2 \rightarrow H_2 + H_2^+$	5.3	Brown (1966)
$H_2^+ + H_2 \rightarrow H^+ + H_2 + H$	1.8	"
$H_2^+ + H_2 \rightarrow H_3^+ + H$	1.0	"
$H_2^+ + N_2 \rightarrow H_2 + N_2^+$	4.0	Gustafsson and Lindholm (1960)
$D_2^+ + N_2 \rightarrow N_2D^+ + D$	1.9	Brown (1966)
$N_2^+ + N_2 \rightarrow N_2 + N_2^+$	5.3	"
$N_2^+ + H_2 \rightarrow N_2 + H^+ + H$	0.9	Vance et al. (1966)
$N_2^+ + H_2 \rightarrow N_2 + H_2^+$	3.0	Brown (1966)
$N_2^+ + D_2 \rightarrow N_2D^+ + D$	1.9	"

Figure captions

Fig. 1 A tentative illustration of the particle balance in a critical ionization velocity situation.

Figs. 2-5 Upper diagrams: Measured (circles) and calculated (eq. 3, solid line) values of E/B as functions of the filling gas composition expressed in volume per cent.

Lower diagrams: Calculated values of the electron relative ionization frequencies as functions of the filling gas composition expressed in volume per cent. Dotted line: Thermal electrons giving $\nu_{itot} = 10^6\ s^{-1}$. Solid line: Monoenergetic electrons (40 eV).

Figs. 6-8 Measured values of E/B as functions of the filling gas composition (expressed in volume per cent) for different values of the discharge current and the filling pressure.

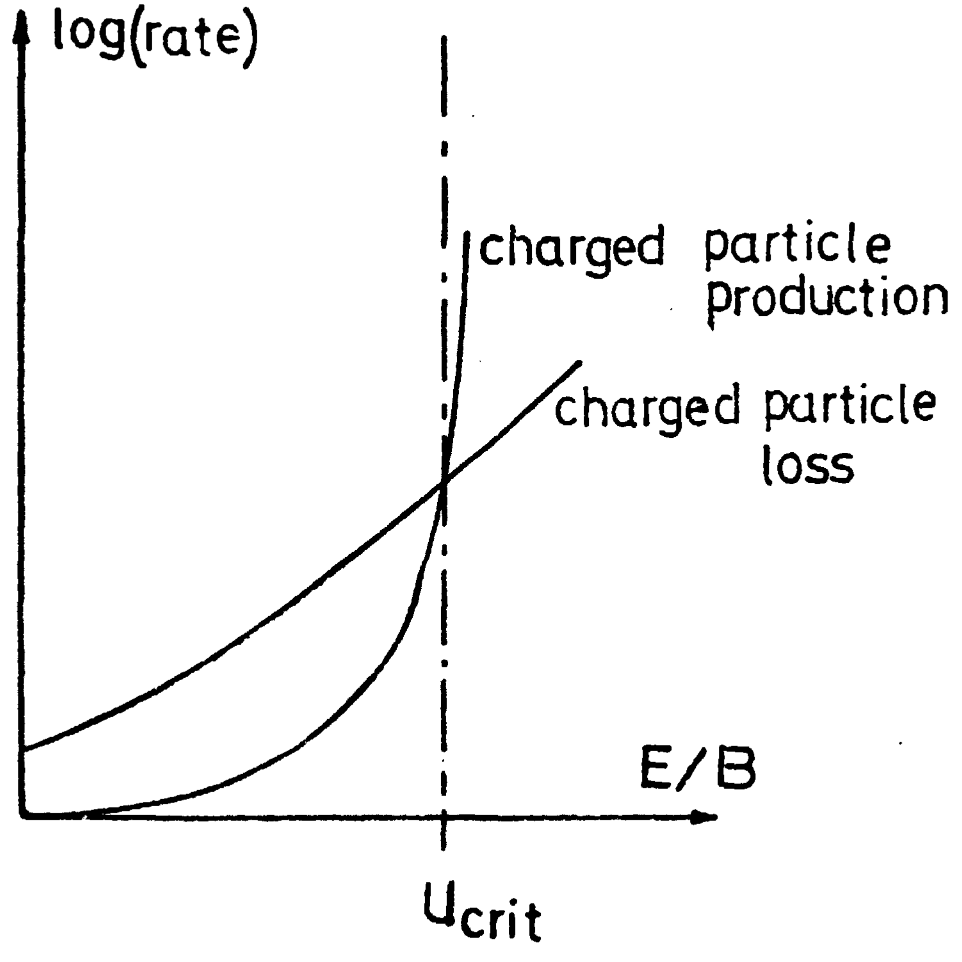
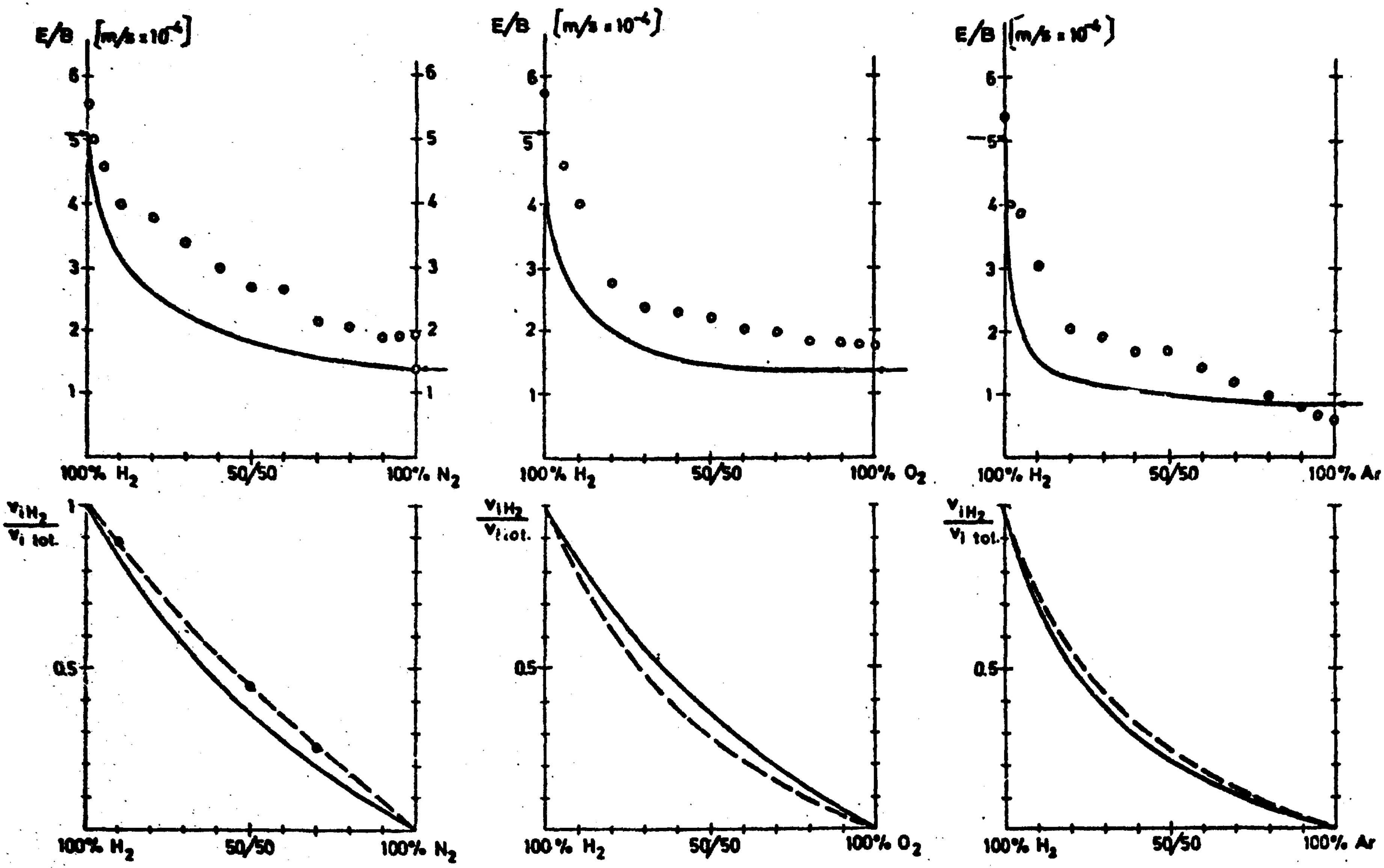
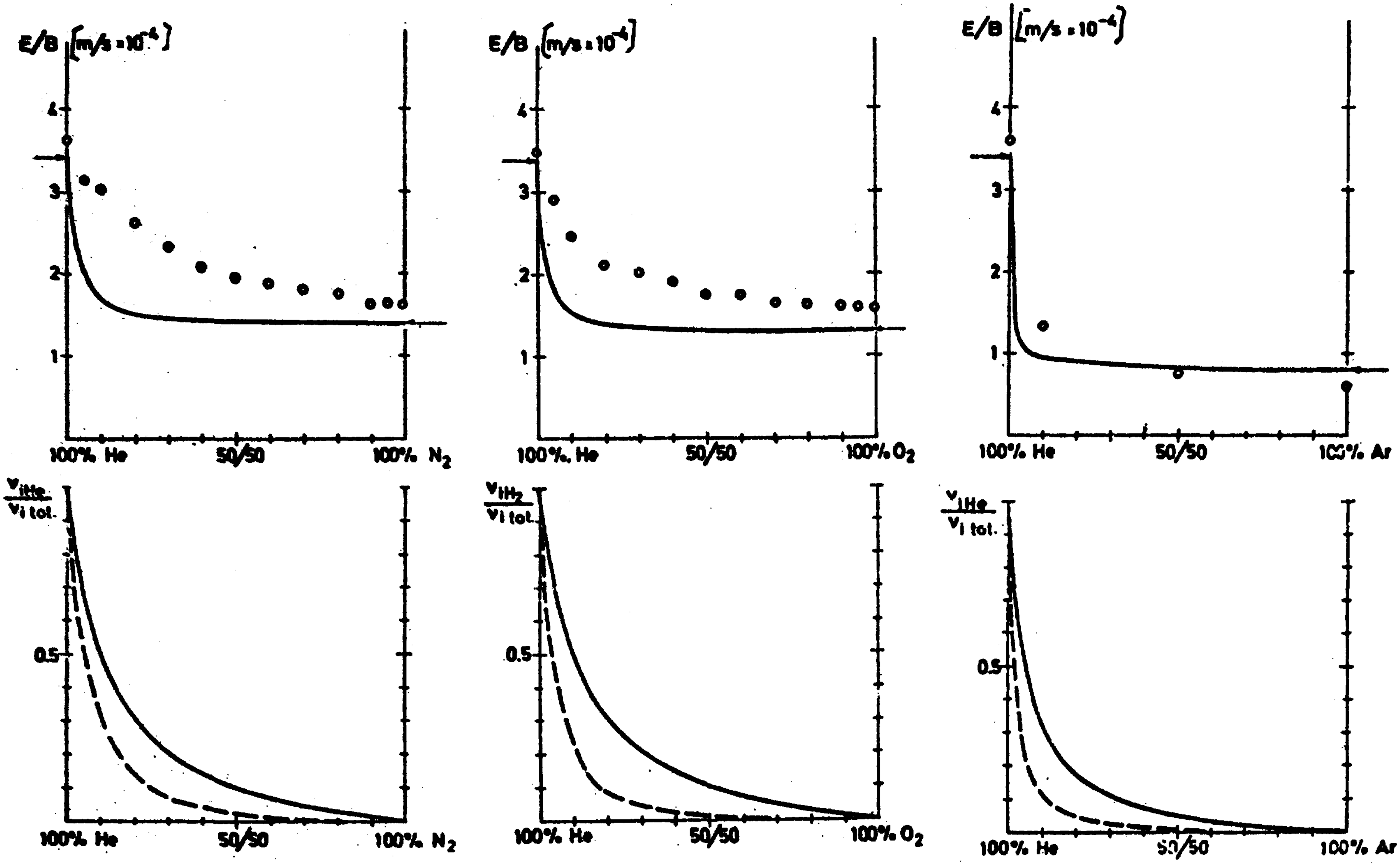

log(rate)
charged particle production
charged particle loss
E/B
u_{crit}

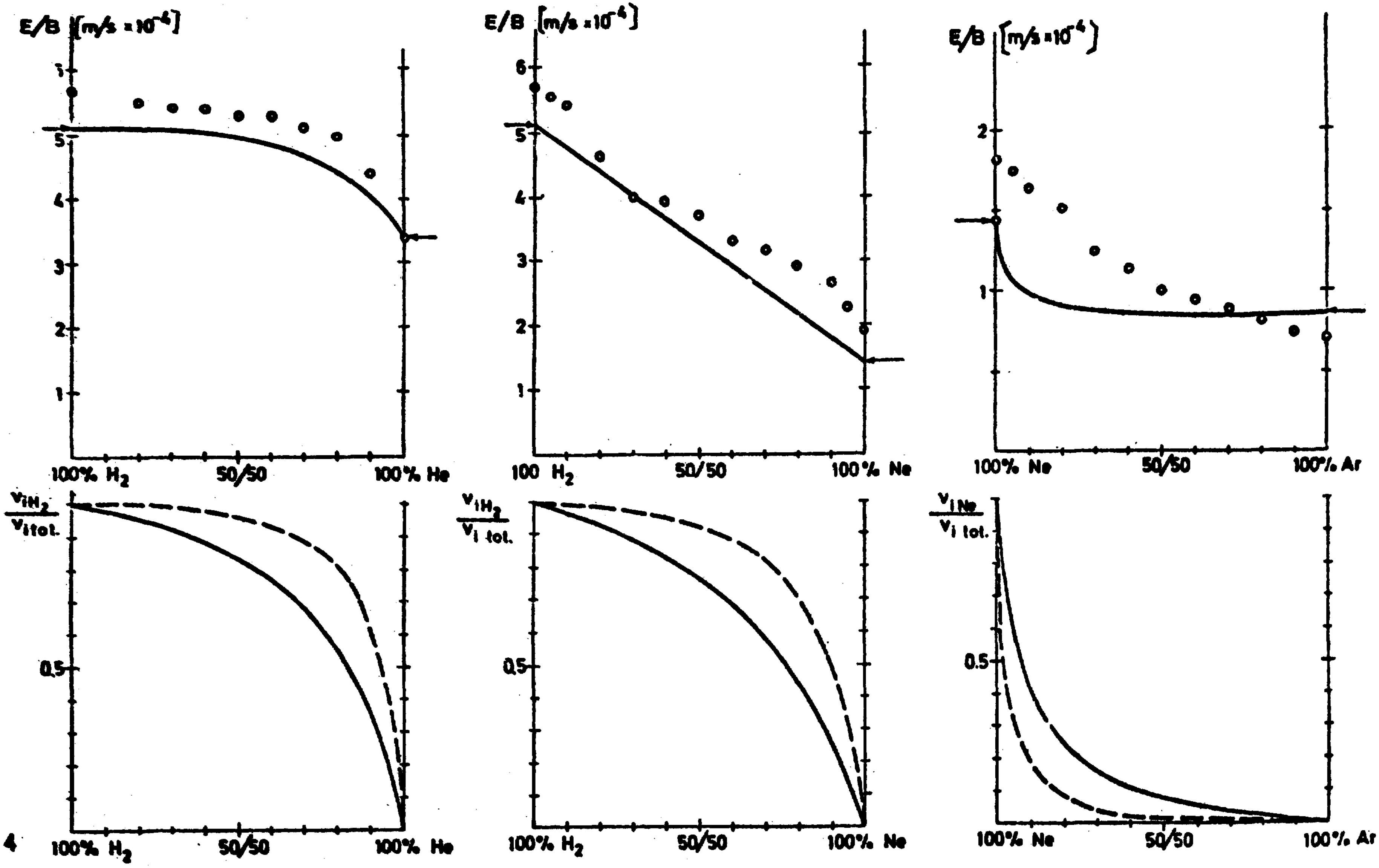
fig. 1



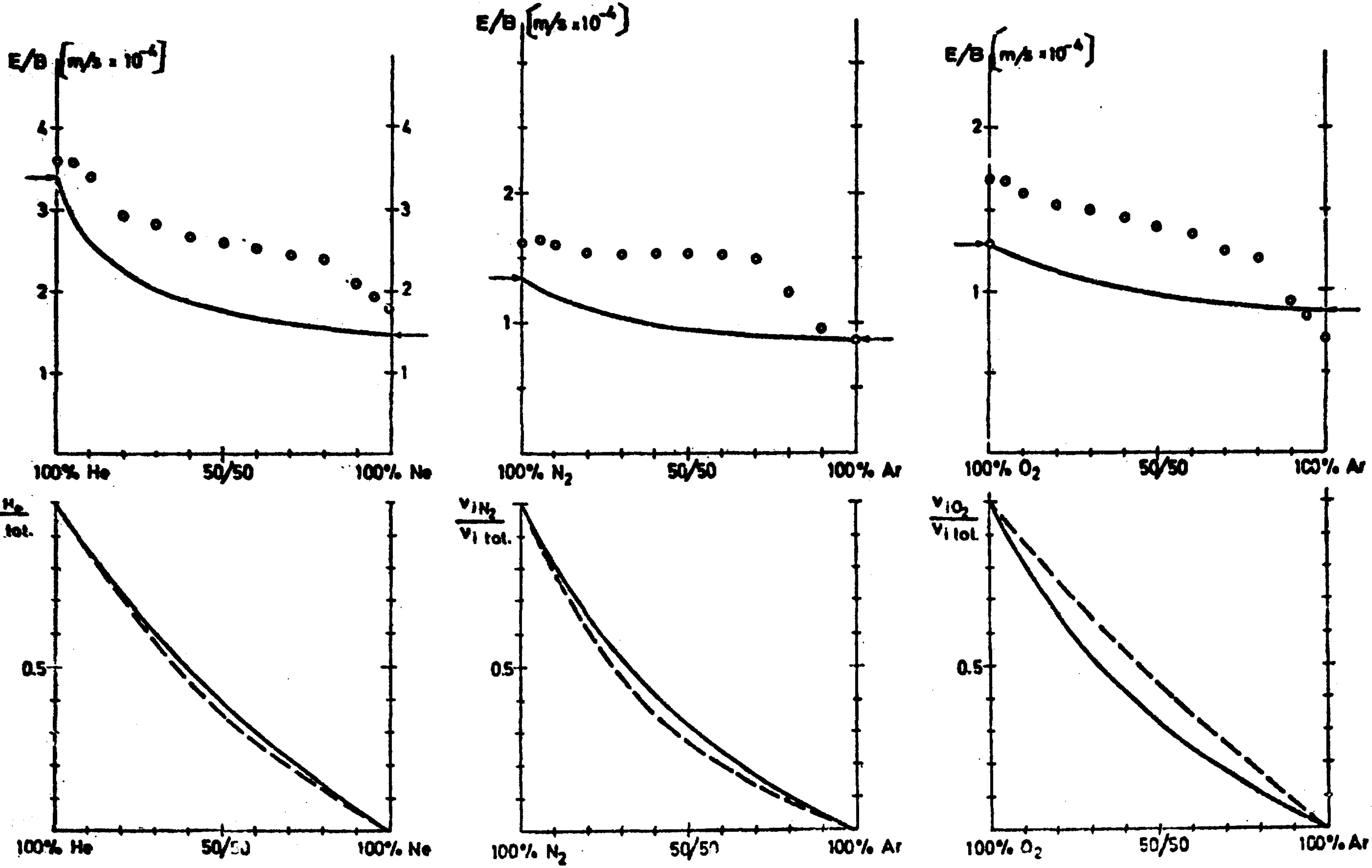
g. 2


E/B [m/s · 10^-4]
4
3
2
1
100% He
50/50
100% N2
100% O2
100% Ar
v_iHe / v_i tot.
v_iH2 / v_i tot.
0.5

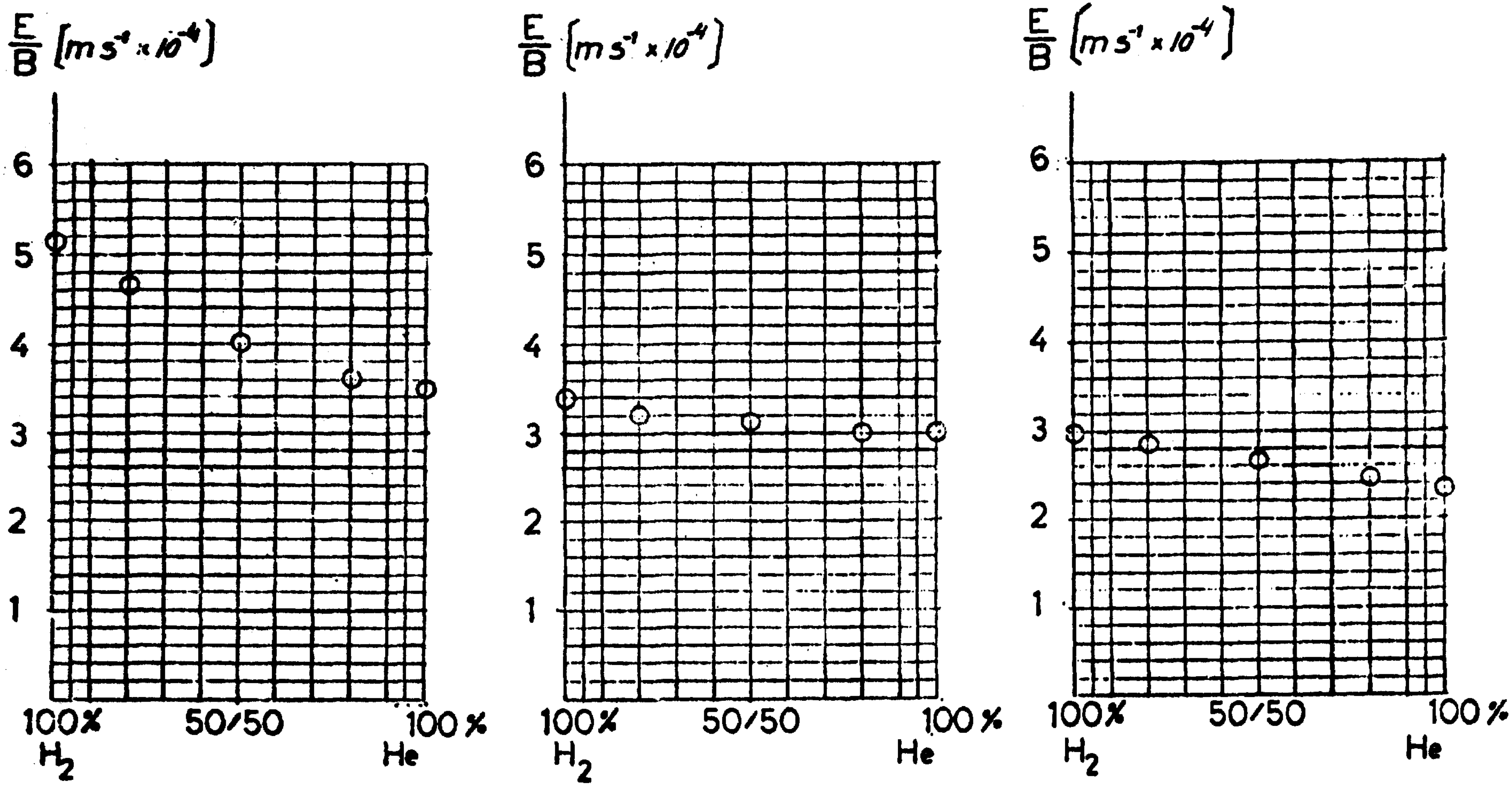
ig. 3


E/B [m/s ×10⁻⁴]
1
2
3
4
5
100% H₂
50/50
100% He
E/B [m/s ×10⁻⁴]
1
2
3
4
5
6
100 H₂
50/50
100% Ne
E/B [m/s ×10⁻⁴]
1
2
100% Ne
50/50
100% Ar
v_iH₂ / v_itot.
0.5
100% H₂
50/50
100% He
v_iH₂ / v_i tot.
0.5
100% H₂
50/50
100% Ne
v_iNe / v_i tot.
0.5
100% Ne
50/50
100% Ar

E- 4


E/B [m/s ×10⁻⁴]
4
3
2
1
100% He
50/50
100% Ne
E/B [m/s ×10⁻⁴]
2
1
100% N₂
50/50
100% Ar
E/B [m/s ×10⁻⁴]
2
1
100% O₂
50/50
100% Ar
v_iHe / v_i tot.
0.5
100% He
50/50
100% Ne
v_iN₂ / v_i tot.
0.5
100% N₂
50/50
100% Ar
v_iO₂ / v_i tot.
0.5
100% O₂
50/50
100% Ar

g. 5



$I_d = 100$ A

$I_d = 600$ A

$I_d = 1400$ A

$p = 0.1$ torr

Fig 6

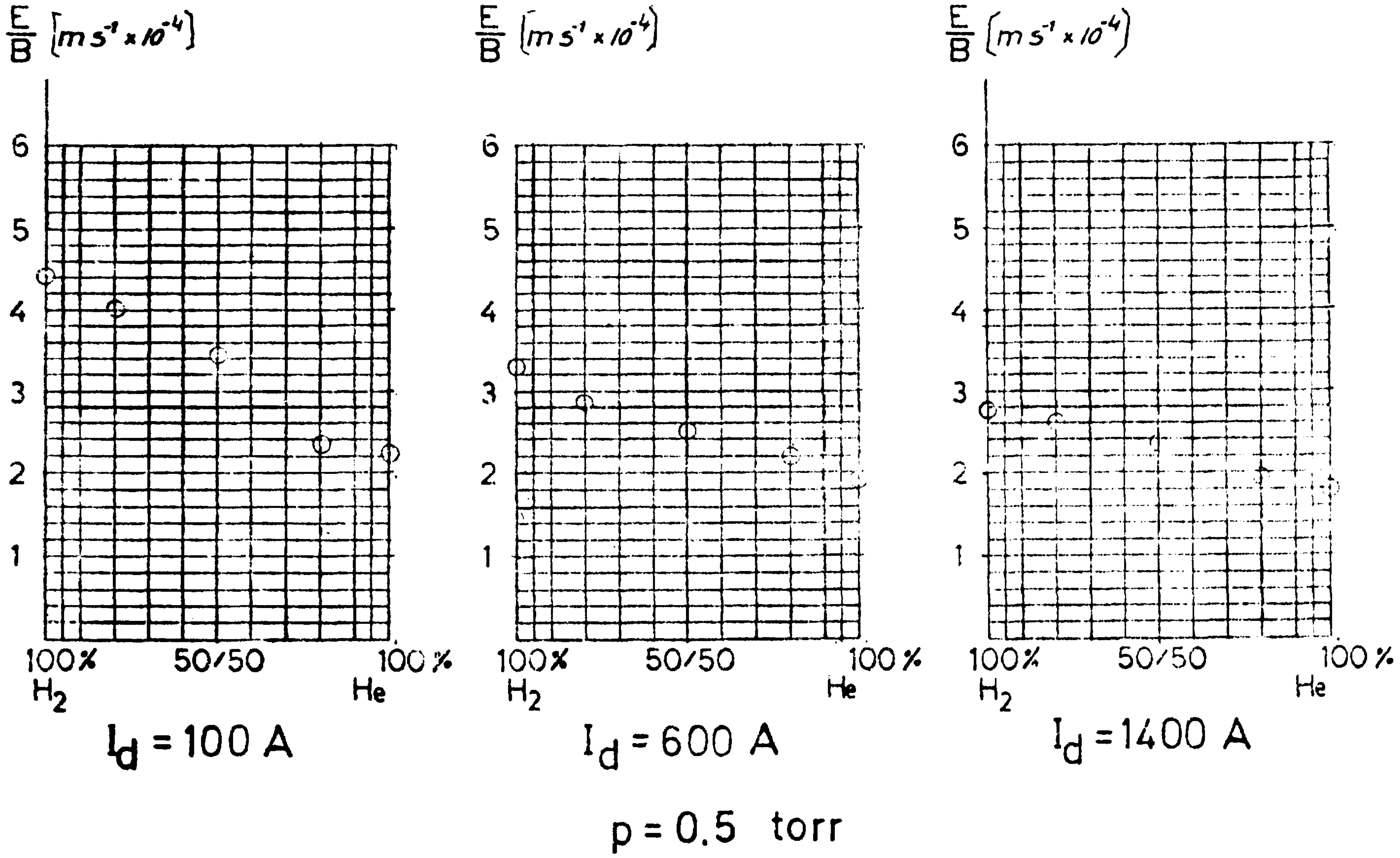
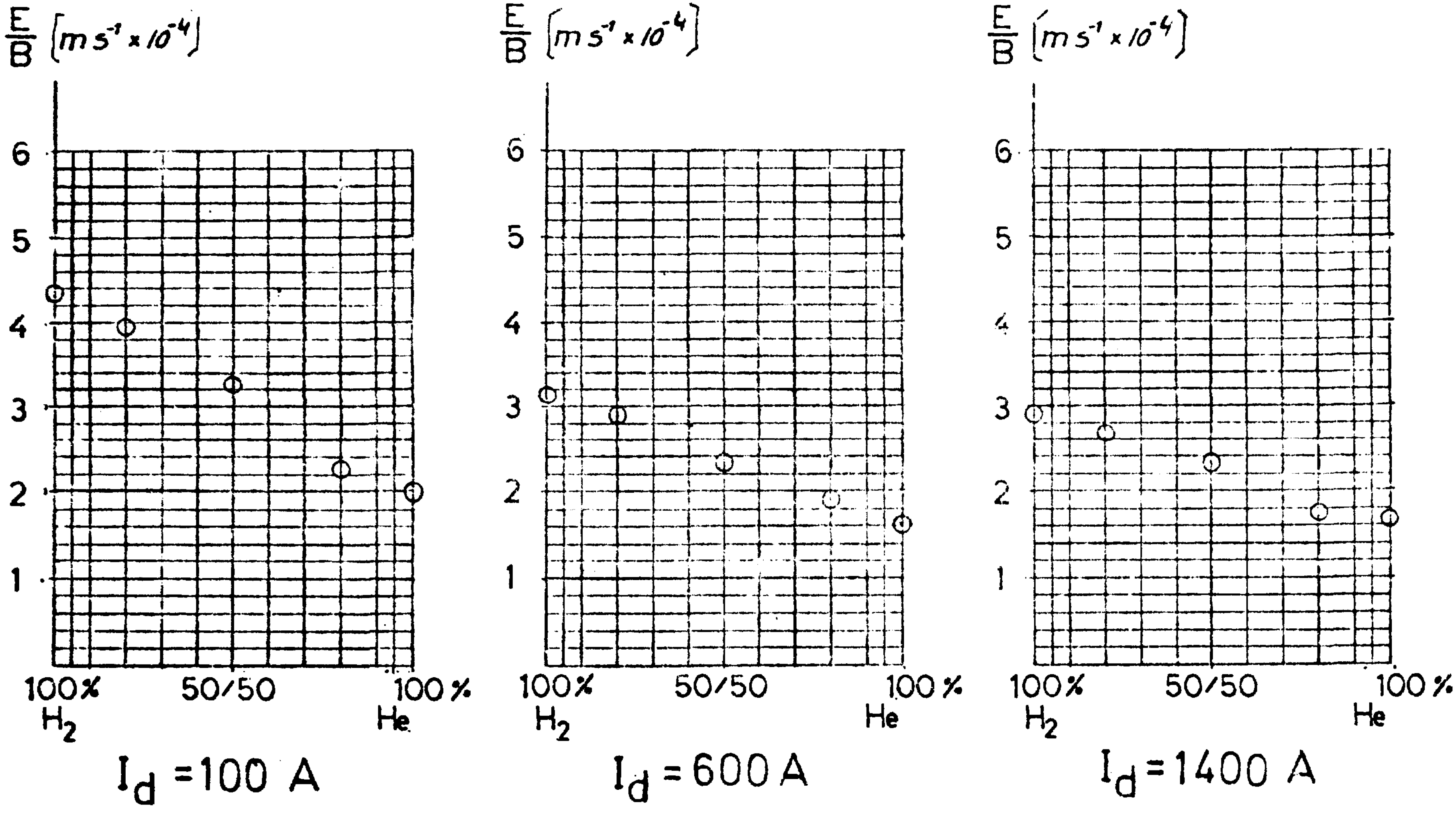

$\frac{E}{B}$ [m s^{-1} x 10^{-4}]
6
5
4
3
2
1
100% H$_2$
50/50
100% He
I$_d$ = 100 A
I$_d$ = 600 A
I$_d$ = 1400 A
p = 0.5 torr

Fig. 7



$I_d = 100$ A

$I_d = 600$ A

$I_d = 1400$ A

$p = 1.0$ torr

Fig. 8

TRITA-EPP-76-02

Royal Institute of Technology, Department of Plasma Physics,
Stockholm, Sweden

VELOCITY LIMITATIONS IN COAXIAL PLASMA GUN EXPERIMENTS WITH GAS MIXTURES

Ingvar Axnäs

April 1976, 23 pp., incl. illus., in English

The velocity limitations found in many crossed field plasma experiments with neutral gas present are studied for binary mixtures of H_2, He, N_2 O_2, Ne and Ar. The apparatus used is a coaxial plasma gun with an azimuthal magnetic bias field. The discharge parameters are chosen so that the plasma is weakly ionized. In some of the mixtures it is found that one of the components tends to dominate in the sense that only a small amount (regarding volume) of that component is needed for the discharge to adopt a limiting velocity close to that for the pure component. Thus in a mixture between a heavy and a light component having nearly equal ionization potentials the heavy component dominates. Also if there is a considerable difference in ionization potential between the components, the component with the lowest ionization potential tends to dominate.

Key words Critical ionization velocity, Critical velocity, Ionization, Plasma-neutral gas interaction, Coaxial plasma gun, Crossed field discharge.

[redacted]