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Abstract

Two methods of measuring the hydrogenic composition of a plasma with an active diagnostic beam are discussed: evaluation at equal energies of the neutrals leaving the plasma and at equal velocities. Evaluation at equal velocity has the advantage that the plasma composition, particle penetration and stripping efficiency of the analyzer do not enter the evaluation. The only plasma parameter that has to be known is the plasma temperature. If measurement at two different velocities is possible, the temperature can also be evaluated from the corresponding four fluxes without any further knowledge of plasma or beam parameters. It is discussed under what circumstances evaluation of the plasma composition is possible for non-Maxwellian distribution functions. As the halo effect may be the main source of error, it is shown that the application of a helium beam may considerably reduce this problem.

Introduction

Not only is the hydrogenic composition of a plasma of importance for the burn rate and power production in a fusion reactor, it also influences the transport of energy and particles in a plasma, influences the interpretation of plasma diagnostics, especially the neutron diagnostic, and has to be controlled inside specific limits for succesful heating, e.g. in the ICRH minority scheme. It would be optimal if the absolute density of the plasma components could be measured time- and space-resolved and if one or all of the components deviated from a Maxwellian distribution, also energy-resolved. In principle, such a measurement is possible with the active charge exchange diagnostic [1]. In practice, the errors in such a measurement are found to be substantial since the local beam density, the penetration of the neutrals from the plasma and the characteristics of the analyzer enter the evaluation of the data. A large variety of different methods of determining the deuteron density absolutely, in addition to the charge exchange diagnostic, have been described and compared for JET discharges [6,7]. In these methods it is generally assumed that the proton density is negligible. The second-best for many experiments will therefore be to measure the relative hydrogenic densities. If impurity concentrations

1

can be measured by other means, the relative hydrogenic composition can then easily be converted into an absolute one.

In this paper, two methods of measuring the relative plasma composition with a diagnostic beam are described. Method I performs the evaluation at equal energy of the neutrals in question, and method II at equal velocity. Each method has its merits. Method I is less restricted with respect to the distribution functions. They need not be Maxwellian, but only equal. It is dicussed under what circumstances the evaluation can be performed if the distribution functions are not equal. The big disadvantage of this method is that the penetration probability of the particles from the measuring volume to the analyzer and the stripping efficiency in the analyzer have to be known and, at least for a hydrogenic beam, also the composition of the beam and the penetration of its components into the measuring column. In general, the plasma and beam compositions, including impurities and beam energies, influence the result. All these problems can be avoided if the evaluation is performed according to method II at equal particle velocities. This method of evaluation is independent of the beam and plasma parameters - except the local ion temperature or distribution function - and of the stripping probability of the analyzer. This second method might therefore be the more favourable one if the plasma is in thermal equilibrium and the temperature is known well enough. It will be shown that even a knowledge of the plasma temperature is not necessary and that it itself can be determined if the fluxes can be measured at more than one velocity.

The first section of this paper gives and explains the general formula for the density ratio as a function of the neutral particle fluxes from active charge exchange. Section II reduces this formula for evaluation at equal energy, and Section III for evaluation at equal velocity. In Section IV it is shown how the temperature and plasma compositions can be obtained simultaneously without any knowledge of the plasma or beam parameters. In Section V it is discussed how the influence of the beam halo effect, which may be a source of considerable error, can be minimized by a suitable choice of beam mass and energy. In the final section the results are summarized and briefly discussed.

I. Outline of the Method

In charge exchange analysis the neutrals arriving at the analyzer are usually ionized in a stripping cell and then analyzed in energy and mass by magnetic and electric fields. If an active doping beam is applied in a pulsed mode, the flux of particles originating from the beam can be discriminated against the passive particle flux that originates from charge exchange on the neutral background in the plasma. The active flux, which is obtained by subtraction of the passive flux from the total flux, comes from a plasma volume that is determined by the common volume of the diagnostic beam and the viewing volume of the analyzer. The measurement is therefore basically a local measurement and allows one to tackle the question whether the density ratio is constant over the plasma radius .

The flux F of ions with energy E at the detector produced by the beam is related to the

2

plasma and beam parameters in the following way:

$$F_i(E) = \sum_j g \cdot n_{oj} \cdot p_j \cdot n_i \cdot f_i(E) \cdot (\Delta E)_i \cdot \sigma(E, E_j) \cdot v(E, E_j) \cdot \eta_i \cdot \beta_i \cdot s_i$$

Here g is a geometrical factor that mainly contains the solid angle of acceptance of the analyzer and the size of the measuring volume. It is the same for all hydrogen isotopes and hence unimportant for this discussion. The index i denotes the plasma components, the index j the beam components (the beam in general may have components with different energy and mass). E is the energy of the neutral particle that is analyzed, n_{oj} the neutral density of the beam components at the plasma volume in question on the assumption of zero plasma density, and p_j is the penetration probability of the beam component j into the measuring volume with plasma. The latter quantity probably depends very little on the hydrogenic plasma composition since the velocity of the beam particles is usually chosen much higher than that of the plasma particles. As only the ratios of the fluxes will enter the evaluation, this quantity is unimportant for single-species beams. Impurities, however, might have a non-negligible influence. n_i is the density of the hydrogenic ions in the plasma, and $f_i(E)$ their energy distribution. $\sigma(E, E_j) \cdot v(E, E_j) = (\sigma \cdot v)_j$ is the charge exchange rate between the particle to be analyzed with energy E and the beam component j with energy E_j. η_i gives the probability of penetration of the produced neutral to the plasma surface. This quantity depends in general on the plasma composition. β_i is the probability of reionization of the neutral in the stripping cell of the analyzer. ΔE_i is the energy resolution of the measuring detector, and s_i its sensitivity. The latter four quantities are functions of E.

If one tried to evaluate the mass composition from passive charge exchange, the corresponding formula would involve integrals along the line of sight of the analyzer over the quantities depending on the plasma radius, such as n_i, the distribution function f_i, the penetration η_i and the charge exchange rate $(\sigma \cdot v)_j$. For such an integral equation it looks quite difficult to obtain even a global value for the density ratio. Even if one restricts the evaluation to the highest energies, which presumably originate in the plasma centre, the evaluation is rather doubtful since the measuring volume of the different components may be different because of their different penetration probabilities. Only for energies at which the plasma is really opaque, this probably being limited to lines of sight of the analyzer through the plasma edge, can passive evaluation give reliable results for the average density ratio if the particle fluxes are integrated over the whole distribution function.

In this paper we shall therefore discuss possibilities of reducing the uncertainties by a special choice of parameters and so be able to make a measurement with tolerable accuracy.

For a given plasma and a given measuring volume $n_{oj} \cdot p_j$ is given and replaced by n_j in the following. From equation 1 the ratio $\alpha_{a/b}$ of the density of the two components $i = a$ and $i = b$ is given by:

$$\alpha_{a/b} = \frac{F_a(E_a) \cdot f_b(E_b) \cdot (\Delta E)_b \cdot \eta_b(E_b) \cdot \beta_b(E_b) \cdot s_b \cdot \sum n_j \cdot (\sigma \cdot v)_{bj}}{F_b(E_b) \cdot f_a(E_a) \cdot (\Delta E)_a \cdot \eta_a(E_a) \cdot \beta_a(E_a) \cdot s_a \cdot \sum n_j \cdot (\sigma \cdot v)_{aj}}.$$

3

II. Evaluation of α at fixed energy E

If the plasma is in thermal equilibrium or more generally, if the distribution functions of the plasma components are equal, and if the velocity of the beam particles v_j is much higher than the velocity v_i of the particles investigated, $v_j \gg v_i$, then $< \sigma \cdot v >_{aj}$ equals $< \sigma \cdot v >_{bj}$ and formula 2 reduces for equal energies ($E_a = E_b$) of the particles to :

$$\alpha_{a/b} = \frac{n_a}{n_b} = \frac{F_a \cdot \eta_b \cdot (\Delta E)_b \cdot \beta_b \cdot s_b}{F_b \cdot \eta_a \cdot (\Delta E)_a \cdot \beta_a \cdot s_a}.$$

For a well-calibrated analyzer the values $(\Delta E)_i$, β_i and s_i are known and the values F_i are measured. If the density profile is known the η_i-values can be sufficiently well calculated on the assumption of pure hydrogen or pure deuterium (tritium) plasma (the temperature does not influence the penetration very much and its effect can therefore be neglected here). $\alpha_{a/b}$ can then be obtained by an iterative method: in a first step the η-values are calculated for a pure a- and a pure b-component; then the α's are determined by using the η-values for one component; now the two η-values obtained for the one-species plasmas are interpolated according to the α-values of the first step and α is then recalculated with these new η-values. Usually the two η-values are not too different and one iteration step should suffice. This is also the reason why a radial change of the composition can be neglected in this evaluation.

If the particle energy can be chosen large enough, so that η_i approaches 1, then the ratio of the measured particle fluxes, corrected by the constants of the analyzer, gives the value of α direct without iteration. One should, however, bear in mind that the above-mentioned condition $v_j \gg v_i$ should be satisfied. If this is not the case, α has additionally to be corrected by $\sum_j n_j(\sigma \cdot v)_{aj} / \sum_j n_j(\sigma \cdot v)_{bj}$.

If the distribution functions are not equal, but known, then there is no extra difficulty in the evaluation of α despite the fact that the distribution functions now have to be included in the formula. But determining a non-Maxwellian distribution function accurately is usually an elaborate matter, especially if α is not known. There are, however, two special cases, not so infrequent, for which evaluation of the distribution function and α seems to be possible.

If one of the components is a minority, then its distribution function can be determined from active charge exchange on the assumption of particle penetration in a plasma consisting of just the other component. α can be determined without iteration.

If any of the components has a non-Maxwellian tail whose contribution to the total density is negligible, one does not have to measure the total distribution function but only the enhancement G(E) at the measuring energy E relative to the thermal distribution. The temperature and enhancement factor can be measured on the assumption of a one-component plasma and both can then be iteratively corrected by the α thus determined.

4

III. Evaluation of α at equal velocity

The greatest uncertainties in the evaluation of α at equal energy of the particles arise in the calculation of η and in the calibration of the analyzer with respect to β. These disadvantages can be avoided if α is evaluated at equal velocity. When the velocity is chosen sufficiently large that scattering is unimportant, then the values of η, β and σv are equal for the three hydrogen components. This is true independently of whether the plasma composition includes impurities. On the other hand, a knowledge of the distribution function and, specifically, of the temperature is more important. For α one finds the following formula for the condition of equal velocity:

$$\alpha_{a/b} = \frac{n_a}{n_b} = \frac{F_a(a \cdot E) \cdot f_b(b \cdot E) \cdot (\Delta E)_b \cdot s_b}{F_b(b \cdot E) \cdot f_a(a \cdot E) \cdot (\Delta E)_a \cdot s_a}.$$

(Here a, b denote the numbers 1, 2 or 3, representing the unit masses of the isotopes.) Besides the measured particle fluxes F_i and the analyzer parameters $(\Delta E)_i$ and s_i, which are relatively easy to measure, the distribution functions of the ionized isotopes f_i are the only quantities that enter the formula . The η_i-values, which are influenced by the isotope composition and also by impurities, and the difficult-to-measure β_i-values of the analyzer are no longer present in the formula. No correction for the charge exchange rates is necessary even if $v_j \ll v_i$.

As in the previous case, a few examples can be discussed where a complete knowledge of the distribution function can be obtained or is not necessary.

When the two components are in thermal equilibrium, the distribution function can be represented by the ion temperature and one gets

$$\alpha_{a/b} = \frac{n_a}{n_b} = \frac{F_a(a \cdot E) \cdot \sqrt{b} \cdot e^{-(b-a) \cdot E/T} \cdot (\Delta E)_b \cdot s_b}{F_b(b \cdot E) \cdot \sqrt{a} \cdot (\Delta E)_a \cdot s_a}.$$

Apart from the well-known analyzer data and the measured fluxes, only the temperature enters the formula. This can be obtained from the charge exchange data, if necessary iteratively as described earlier. In many cases the iteration procedure may not be necessary. For most of the ASDEX conditions the changes in temperature occurring when the measured fluxes are evaluated on the assumption of pure hydrogen or pure deuterium plasmas are only inside the otherwise determined error bars.

To reduce the influence of the error in the temperature measurement, the evaluation should be done at the lowest possible energy. In this respect one should bear in mind that the effect of the halo, which is discussed later, might limit the lowest energy of evaluation. Also scattering must be considered, which might be important at low energies and is different for different isotopes.

If the distribution functions are Maxwellian with enhanced tails and the particle number in the tail is negligible in relation to the total particle number, it is again not necessary to

know the total distribution function, it being sufficient to know the enhancement factor $G_i(i \cdot E)$ relative to the Maxwellian distribution. For this specific case one obtains

$$\alpha_{a/b} = \frac{n_a}{n_b} = \frac{F_a(a \cdot E) \cdot \sqrt{b} \cdot e^{-(b-a)\cdot E/T} \cdot (\Delta E)_b \cdot s_b \cdot G_b(b \cdot E)}{F_b(b \cdot E) \cdot \sqrt{a} \cdot (\Delta E)_a \cdot s_a \cdot G_a(a \cdot E)}.$$

If one of the components is a minority, the iteration procedure for the evaluation of the temperature and of G_i can be omitted.

IV. Simultaneous evaluation of plasma composition and temperature

Evaluation of the plasma composition at equal velocities already avoids a few sources of errors that can occur in evaluation at equal energies and the complicating iteration. Nevertheless, for the evaluation of the temperature one has to go through the full procedure for the conversion of the measured flux to the flux originating in the measuring volume. Method II can be extended to avoid this complication as well. If the fluxes are measured at more than one couple of energies, the temperatures and plasma composition can be measured simultaneously without any additional knowledge of any plasma or beam parameters.

Using the formula for a Maxwellian plasma obtained for method II, one gets

$$\frac{F_{a1}(a \cdot E_1) \cdot \sqrt{b} \cdot e^{-(b-a)\cdot E_1/T}}{F_{b1}(b \cdot E_1) \cdot \sqrt{a}} \cdot \kappa_{1ab} = \alpha_{a/b} = \frac{F_{a2}(a \cdot E_2) \cdot \sqrt{b} \cdot e^{-(b-a)E_2/T}}{F_{b2}(b \cdot E_2) \cdot \sqrt{a}} \cdot \kappa_{2ab}.$$

Here κ_{iab} are the ratios of the analyzer constants for the detectors in question. The above equation holds for a real Maxwellian distribution of the two components. It can be reduced to

$$\frac{F_{a1}(a \cdot E_1) \cdot F_{b2}(b \cdot E_2) \cdot \kappa_{1ab}}{F_{b1}(b \cdot E_1) \cdot F_{a2}(a \cdot E_2) \cdot \kappa_{2ab}} = e^{-(b-a)\frac{E_2 - E_1}{T}}$$

or

$$\frac{T}{(b-a)(E_2 - E_1)} : +[\ \ell n \frac{F_{b1}(b \cdot E_1) \cdot F_{a2}(a \cdot E_2) \cdot \kappa_{2ab}}{F_{a1}(a \cdot E_1) \cdot F_{b2}(b \cdot E_2) \cdot \kappa_{1ab}}]^{-1}.$$

The temperature can be obtained by measuring four fluxes and the energies and calibration constants for the respective detectors.

For α one gets:

$$\alpha_{a/b} = \frac{\sqrt{b}}{\sqrt{a}} \cdot \frac{F_{a1}^2 \cdot F_{b2} \cdot \kappa_{1ab}}{F_{b1}^2 \cdot F_{a2} \cdot \kappa_{2ab}}$$

This method then allows one to make a local quasi-real-time measurement of the ion temperature and the plasma composition, which can be obtained as described in method II. The time resolution is limited by the pulse length of the diagnostic beam, which must be finite to measure the fluxes with tolerable statistical errors.

6

It is easy in this case to calculate the error ΔT in the temperature measurement as a function of the errors in the flux and energy measurement (neglecting the calibration errors):

$$\frac{\Delta T}{T} : \left[\frac{(\Delta E_1)^2 + (\Delta E_2)^2}{(E_2 - E_1)^2} + \frac{1}{K^2}\sum_{i,m}(\frac{\Delta F_{im}}{F_{im}})^2\right]^{1/2}$$

with

$$K = \ell n \frac{F_{a1} \cdot F_{b2} \cdot \kappa_{1ab}}{F_{b1} \cdot F_{a2} \cdot \kappa_{2ab}}$$

and

$$F_{im} = F_{im}(i \cdot E_m).$$

For a good measurement it is desirable to have a large separation of the two energies and a large value of K, which means a small ratio of, for example the hydrogen fluxes, and a large ratio of the deuterium fluxes. This can be obtained if the low energy level for hydrogen could be placed at or even below an energy equal to the temperature, and the second energy level twice as high as the first.

In any case it is clear that the statistical errors in the flux measurements should be in the range of a few per cent only to determine the temperature and, later, the plasma composition with tolerable errors.

V. Influence of the halo effect and of scattering

The application of a diagnostic beam has the advantage not only that local values can be measured, but - even more important - also that the volume where the neutrals come from is well defined and equal for all components. One of the main reasons why the evaluation of α from passive charge exchange is not possible is the unknown origin of the neutrals.

The main drawback for active evaluation is the halo effect. Passive fluxes can be subtracted from the total fluxes to give the active fluxes if the diagnostic beam is run in a modulated mode. However, the halo particles, which result from higher generations of exchanging neutrals, have the same time structure as the neutrals from active charge exchange and therefore cannot be subtracted from the signal. This can lead to erroneous results because the origin of the halo particle is unknown and can be quite different from that of the active neutrals, with the consequence that in method I η cannot be correctly determined for the halo particles and in method II the temperature is different for different radial origins of the neutrals. Calculations show - see, for example, ref. 2 - that the halo effect can be substantial, especially at low energies.

As the halo effect cannot be avoided, its influence should be minimized. Plasmas with low density and poorly recycling walls seem to be advantageous. The halo effect can probably best be minimized by replacing the commonly used hydrogen diagnostic beam by a helium beam with the proper energy. The charge exchange cross-section between helium and protons has a maximum at a relative velocity that corresponds to a proton energy of about 25 keV and is negligible at low energy. Figure 1 shows the product of the charge

exchange rate $\sigma \cdot v$ and the penetration probability η for the beam as a function of the energy E of the analyzed hydrogen atom for different energies and masses of the beam and different line densities for the penetration of the beam into the measuring volume [3]. For the hydrogen beams the curves have a maximum for the lowest energies of the analyzed particles, that is for particles that have nearly no chance of penetrating the plasma and reaching the analyzer and which therefore only contribute to the halo. On the contrary, the helium beams produce a maximal charge exchange rate at energies of the analyzed particles between 20 and 40 keV with a particularly low rate at low energies, especially for low-energy beams. For low plasma densities and hence good beam penetration the total charge exchange rate is substantially higher for hydrogen than for helium beams. But owing to this very effect the penetration of hydrogen beams is much poorer than that of helium beams at higher line densities. At penetration line densities of $2.5 \cdot 10^{15} cm^{-2}$ helium beams with the same unattenuated density as hydrogen beams already produce more neutrals - because of their better penetration - than hydrogen beams in the full energy range of analyzed particles, except the very low energy ones, which again would contribute to the halo only. The ratio of particles in the "useful" energy range (E larger than a few times T) to the energy range where particles mainly contribute to the halo can probably be made 2 - 5 times higher for helium beams than for hydrogen beams, a factor that in many cases suffices to render the halo effect negligible.

In addition to the halo effect, scattering of the neutrals in the plasma and in the stripping cell (or the foil) in the analyzer is a factor that restricts the evaluation of the data to higher energies. With the data given in ref. 4, the loss of particles due to scattering in a stripping cell (here hydrogen on hydrogen) will be less than a few per cent for energies above 1 keV if the line densities in the stripping cell can be chosen below 10^{14} m^{-2} (linear mode of the stripping cell).

As far as scattering of the neutrals on their way through the plasma is concerned, the scattering cross-section seems to be much smaller than the charge exchange cross-section for energies above 100 eV [5]. This effect should therefore have a negligible influence if the energy for the evaluation is chosen above 1 keV.

VI. Summary

Application of an active beam allows measurement of the relative composition of the hydrogen components in the plasma. Two methods of evaluation have been proposed. One measures the neutral fluxes that result from charge exchange with the active beam, in a neutral particle analyzer at equal energies of the different species, and, to determine the density ratio, requires a knowledge of the penetration probabilities of the particles in question from the measuring volume to the analyzer. In addition, the stripping probability of the analyzer and the energy resolution and sensitivity of the analyzer channels in question have to be known. The main errors - besides the effect of the beam halo - probably result from uncertainties in the penetration and stripping probabilities. On the other hand, the method does not depend on a one-point evaluation: as this method applies the same procedure to the raw data as is used for the evaluation of the temper-

8

ature, a measure of any error can be estimated from how parallel the straight lines are for the two isotopes that result for the temperature in the semilog plot of the fluxes.

The other method makes use of the fact that the penetration and stripping probabilities are equal for equal velocities of the analyzed hydrogen particles. For evaluation at equal velocities these quantities therefore do not have to be known; instead, the temperature is the important quantity, the uncertainty of which mainly affects the accuracy of the measurement. In many cases it may be possible to measure the particle fluxes at more than one pair of energies with sufficiently small statistical errors. It is then possible to evaluate the temperature and the plasma composition simultaneously. In this case no iteration is necessary and no parameter of the plasma or the beam has to be known. Both quantities, temperature and composition, can basically be measured in real time, limited by the pulse length of the beam that is necessary to obtain small statistical errors.

The halo effect has been dicussed and it has been shown that helium diagnostic beams probably produce a halo effect that is small enough not to influence the measurement considerably if the energy of the beam is appropriately chosen. As a result of scattering the lowest energy of evaluation should probably be higher than 1 keV, at least as long as this effect cannot be properly taken into account.

Acknowledgement

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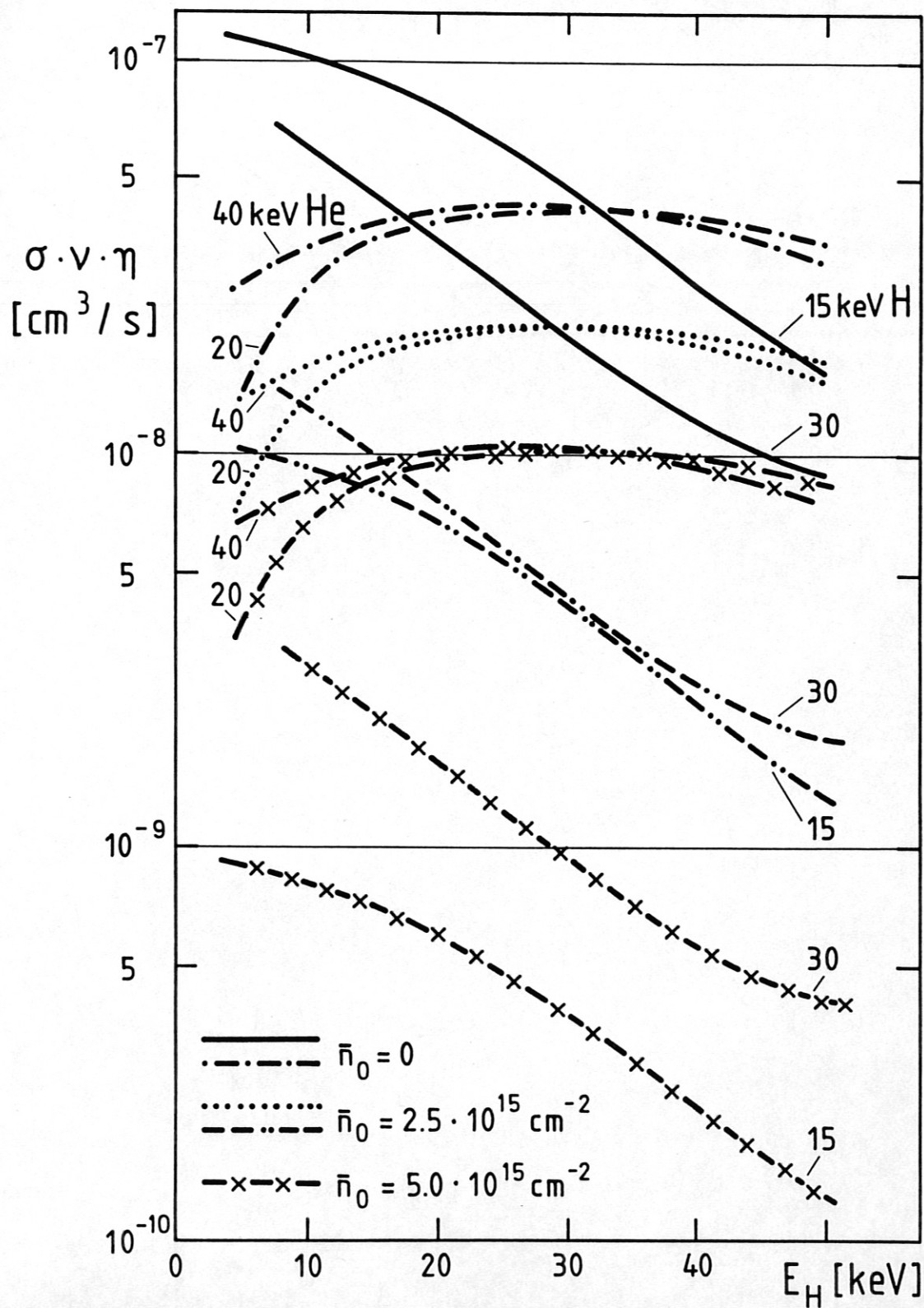
Fig. 1 Product of the charge exchange rate $\sigma \cdot v$ and the penetration probability of the beam η as a function of the energy of the analyzed neutral (here hydrogen atoms) for beams with different energies and masses and for different line densities.