On the possibility of measuring the q-profile
in dense plasmas by means of molecular beams

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**Abstract:**
A method of measuring the q-profile (slightly off the centre) in a plasma is described in detail. Radially injected molecular neutrals are ionized in the plasma and rotate according to the local magnetic field. After dissociation the neutral atom carries the information on the velocity of the molecular ion at the time of dissociation to a neutral particle analyzer. In this paper it is shown how this information can be used to calculate the local field. The production and penetration of molecular beams are discussed as well as the requirements to be met by the beam and analyzer. Also discussed are the possibility and influence of neutral atom beams and their possible relevance to the same type of measurement. It is shown that the Shafranov shift can be determined by suitable choices of the injection and detection geometries. The method seems to be especially suited to measuring the time variation of local q-values with a time resolution of about 1 ms. Although the penetration of the particles depends on the plasma conditions, the quantity measured by the method discussed only depends on the local field ratio. It is shown that the method could also be applied in large plasma experiments the size of JET, and that an accuracy in measuring $q$ of better than or about 10 % may be achieved.

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# 1. Introduction

The q-profile is one of the physical quantities in the plasma that, on the one hand, are important for understanding many plasma processes in transport and confinement, and that, on the other, are still difficult to measure, especially in dense plasmas. A few methods have been devised during recent years[1] and progress has been made. It nevertheless seems that many results are not very direct and not unambiguous and that further new methods might help to clarify open problems. The method now described here in more detail has already been proposed[2]. It has also been considered for application in PLT at Princeton after an unpublished study had shown its applicability[3].

The present paper discusses many aspects of the proposed method in the most general form possible. These include the optimum production of molecular beams, their penetration in the plasma and the choice of the beam energy. Plasma parameters enter via the discussion of particle penetration. Beam parameters such as the beam width and divergence are investigated with respect to their influence on the measurement. The unavoidable Frank-Condon effect is taken into account. It is also discussed how the necessarily large amounts of neutral atoms in the beam could affect the measurement and whether under special circumstances the double charge exchange of these particles could also be used for measuring the q-value[4,5].

The first part of this paper describes the principles and the basic limitations of the method. The optimum geometry is found and a measuring arrangement is described that allows one to measure the value and directions of the poloidal field. The second part contains all the information necesary to estimate whether such a method could be successfully applied in a certain fusion experiment. Section 4 discusses some limitations resulting from the unavoidable Frank-Condon effect or relating to the physical properties of the molecular beam. Section 5 demonstrates that the system allows in situ calibration and an easy discrimination of the signal against the usual charge exchange and background signals. In Section 6 it is attempted to obtain a good estimate of the possible influence of atoms in the beam, which are usually abundant in relation to molecules. Section 7 shows the results of some calculations for ASDEX as an illustration of a possible application and Sec. 8 sketches a possible analyzer geometry. The paper concludes with a summarizing discussion and it is attempted to show for what beam conditions and plasma parameters the desired q-value could be obtained with acceptable accuracy.

## 2. Principle of the method

The proposed method makes use of the fact that a radially injected molecule after ionization in the plasma will gain toroidal velocity on its orbital path in the toroidal field owing to the Lorentz force in the poloidal field. If the molecule dissociates, the neutral atom carries the information of this velocity at the time of dissociation, which can be measured by a neutral particle analyzer. The toroidal angle of the particle velocity only depends on the direction of injection and the poloidal direction of the analyzer which are known, and on the direction and strength of the field. The following discussion shows how one or the other or both can be obtained from the measurement.

For the calculation of the particle motion in the field it is assumed that the magnetic fields are constant over the Larmor orbit of the ionized molecule, that the fields can be split into a poloidal $B_{pol}$ and a toroidal $B_{tor}$ component with $B_{pol} \ll B_{tor}$, and that the motion can therefore be described in a cylindrical system of the toroidal field. The purpose of the calculation is to establish a relation between the ratio $\beta$ of the local poloidal and toroidal field and the toroidal angle $\alpha = \frac{v_{tor}}{v_{pol}} \approx \frac{v_{tor}}{v}$ of the orbiting molecule. In a locally cylindrical system (see Fig. 1), with $\rho$ and $\varphi$ phase coordinates of the Lamor orbit, projected in the poloidal plane, and z the axial (toroidal) component, the equation of motion in the axial direction can be written with the approximation $B_{pol} \ll B_{tor}$:

$$m \cdot \dot{v}_z \approx m \cdot \omega_L \cdot \frac{dv_z}{d\varphi} \approx e \cdot v_\varphi \cdot B_\rho. \tag{1}$$

Here $m$ and $e$ are the mass and charge of the molecule, $v_\varphi, v_\rho$ and $v_z$ are the velocity components with $v_\rho \ll v_\varphi$, $\omega_L$ is the Larmor frequency and $B_\rho$ is the component of $B_{pol}$ that is perpendicular to the motion of the particle.

$B_\rho$ can be expressed in terms of the here likewise cylindrical plasma frame with components $r, \vartheta, z$ (see Fig. 1):

$$B_\rho = |B_{pol}| \cdot cos(\vartheta_1 - \varphi). \tag{2}$$

Here $\vartheta_1$ is the direction of the poloidal field in the plasma frame.

After inserting eq. 2 in eq. 1 integration of the latter gives

$$v_z - v_{zo} = \frac{e \cdot v_\varphi}{m \cdot \omega_L} \cdot |B_{pol}| \int_\gamma^\epsilon cos(\vartheta_1 - \varphi) \cdot d\varphi \tag{3}$$

and

$$\alpha = \frac{v_z - v_{zo}}{v_\varphi} \approx \frac{|B_{pol}|}{B_{tor}} \cdot G(\vartheta_1, \gamma, \epsilon), \tag{4}$$

where $\epsilon$ and $\gamma$ are the ionization and dissociation points, respectively, on the molecular orbit and are known from the arrangement of the beam and analyzer; $\alpha$ is a function only of the field ratio and the direction of the poloidal field $\vartheta_1$ (and of a possible but known initial velocity $v_{zo}$ in the axial direction).

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The direction of the poloidal field is known.

The topology of the flux surfaces and hence the direction of the poloidal field are known or can be reasonably assumed in many cases. In other cases the direction is at least known in special areas, e.g. in planes of symmetry. Then $G(\vartheta_1, \gamma, \epsilon)$ can be calculated and the measurement of $|\alpha|$ gives the ratio of the fields, which is needed for evaluating $q$. Optimizing the geometry of the beam and analyzer for maximum $\alpha$ and hence for the smallest influence of uncertainties in $\gamma$ and $\epsilon$, one finds

$$\epsilon_{opt} = \vartheta_1 \pm 90°,$$

$$\gamma_{opt} = \vartheta_1 \mp 90°.$$

The optimum configuration is an arrangement with the ion source (beam) and analyzer at the same poloidal position and the direction of the beam and line of sight of the analyzer parallel or antiparallel to the direction of the poloidal field. In the toroidal direction, the ion source and analyzer could be separated according to the angle $\alpha$, which for the optimum case is

$$|G_{opt}(\vartheta_1, \gamma, \epsilon)| = 2,$$

$$|\alpha_{opt}| = 2 \cdot \frac{|B_{pol}|}{|B_{tor}|}.$$

In many cases this optimum geometry will not be technically possible. For other than the optimum geometry one finds $-2\beta \leq \alpha \leq 2\beta$, with $\beta = |\frac{B_{pol}}{B_{tor}}|$. In general, the geometry factor $G(\vartheta_1, \gamma, \epsilon)$ has to be calculated for each geometry. This can be done in a simple code for the equation of motion on the assumption of an arbitrary poloidal field strength and known field direction. An example of such a calculation is given in Sec. 7. It should be mentioned here that the statement[2,5] that the toroidal angle of the escaping atom is the pitch angle of the field is only true under the special condition when the beam and line of sight are perpendicular to one another and beam or line of sight are parallel to the field direction. Generally the statement is wrong.

The direction of the poloidal field is not known:

If neither the direction nor the strength of the field is known, full information on the field can be obtained from two independent measurements. At least the one of the angles $\gamma$ and $\epsilon$ has to be changed in the two experiments. Measuring the two toroidal angles $\alpha_1$ and $\alpha_2$, which are given by

$$\alpha_1 = \frac{|B_{pol}|}{B_{tor}} \cdot \int_{\gamma_1}^{\epsilon_1} \cos(\vartheta_1 - \varphi)d\varphi,$$

$$\alpha_2 = \frac{|B_{pol}|}{B_{tor}} \cdot \int_{\gamma_2}^{\epsilon_2} \cos(\vartheta_1 - \varphi)d\varphi,$$

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one finds for the angle $\vartheta_1$

$$\vartheta_1 = -\frac{\alpha_2(\sin\gamma_1 + \sin\epsilon_1) - \alpha_1(\sin\gamma_2 + \sin\epsilon_2)}{\alpha_2(\cos\gamma_1 - \cos\epsilon_1) - \alpha_1(\cos\gamma_2 - \cos\epsilon_2)}.$$

With $\vartheta_1$ known, the field ratio can be calculated in the usual manner and can be checked for consistency in the two independent measurements.

If only the field direction is not known, this can be obtained from a single measurement with an uncertainty about the sign, which in most cases can probably be found from other considerations.

## 3. The realizability of the proposed method

### a) Production of molecular beams

From Ref. 6 it can be seen, that with optimum setting of the neutralizer parameters a considerable fraction of a molecular ion beam can be neutralized without dissociation. This fraction depends on the beam energy. Figure 2a shows the ratios of full-energy molecules to accelerated molecular ions (before the neutralizer) in curve 1. Curve 2 gives the ratio of the neutral molecules to the total number of neutrals after the neutralizer for the accelerated $H_2^+$ component, and curve 3 the ratio of full-energy neutral molecules to half-energy neutral atoms. Figure 2b gives the same ratios for the two-thirds energy neutral molecules, resulting in the neutralizing process from the original $H_3^+$ component. In curve 1 these molecules are related to full-energy $H_3^+$ ions, in curve 2 to the total number of neutrals in the neutralized $H_3^+$ beam, and in curve 3 to the neutral atoms with one-third energy. Curve 1 is the efficiency of the neutral molecule production as a function of the energy. Curve 3 compares the number of neutral molecules with the number of neutral atoms with the same energy as those atoms that are ejected from the dissociative process. The effect of these atoms, which could also produce a signal on the neutral particle detector after double charge exchange, will be discussed later. All curves of Fig. 2 are taken at a line density of $2 \times 10^{16}$ $cm^{-2}$ in the neutralizer, which is close to the optimum for neutral molecule production for all energies. The figures show that reasonable fractions of the neutralized beams consist of molecules. These fractions are the larger, the lower the energy is. The optimal energy for the measurement is, however, influenced by many other parameters, such as the dependence of the beam current on the extraction voltage, beam penetration, size of Larmor orbit etc., some of which are discussed later.

### b) Penetration of the molecular beam and ejected atom

The penetration $\eta$ of the molecular beam and the ejected neutral atom determines the range of plasma parameters for which the proposed method might be applicable for a given beam current or defines the necessary beam current for given plasma parameters.

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In evaluating

$$\eta = e^{\int \frac{d\ell}{\lambda(\ell)}} \quad \text{with} \quad \lambda(\ell) = \frac{1}{n(\ell) \cdot \sigma_{eff}(\ell)}$$

the following processes were taken into account:

$$\sigma_{eff} = \underbrace{\frac{<\sigma v>_{cx}}{v_b}}_{\substack{\text{charge} \\ \text{exchange}}} + \underbrace{\frac{<\sigma v>_I}{v_b}}_{\substack{\text{ionization} \\ \text{by ions}}} + \underbrace{\frac{<\sigma v>_{iD}}{v_b}}_{\substack{\text{dissociation} \\ \text{by ions}}} + \underbrace{\frac{<\sigma v>_e}{v_b}}_{\substack{\text{ionization} \\ \text{by electrons}}} + \underbrace{\frac{<\sigma v>_{eD}}{v_b}}_{\substack{\text{dissociation} \\ \text{by electrons}}}$$

$$\sigma_{eff} \sim \sigma_{cx} + \sigma_i + \sigma_{iD} + \frac{<\sigma v>_e}{v_b} + \frac{<\sigma v>_{eD}}{v_b}$$

The temperature variation and hence the spatial dependence of the cross-sections are neglected to allow a rough estimate:

$$\eta = e^{-\sigma_{eff}(E) \cdot \int n d\ell}.$$

Figure 3 gives effective cross-sections for neutral molecules and atoms in the energy range of interest. The electron data are given for temperatures of 0.1, 1.0 and 10 keV. The data for this figure were taken from Ref. 7 for charge exchange and ionization and from Ref. 8 for dissociation by electron impact. The cross-section for dissociation by protons was taken as $1 \times 10^{-16}$ $cm^2$, a value slightly larger than the summarized values of the corresponding electron processes. For this estimate the penetration $\eta$ is displayed in Fig. 4 as a function of the line density for different effective cross-sections. In Fig. 5 the penetration is plotted as a function of the line density for different energies of atoms and molecules and for a plasma temperature of 1 keV. These values will soon be used to estimate the molecular current density of a probing beam necessary for a measurable signal.

c) Necessary molecular beam current density

The range of line densities for which this method can be applied strongly depends on the density of the neutralized molecular beam current that is available. To estimate this, we use the following procedure: It is assumed that the neutral particles from dissociation will impinge on $N$ channels of an analyzer, and that the average pulse rate of the channels should be $P$. The particles come from the measuring volume $V$, which is determined by the common volume of the injected molecular beam and the line of sight of the analyzer. $\eta_1$ and $\eta_2$ are, respectively, the penetration probabilities of the molecule to the measuring volume and of the atoms after dissociation from the measuring volume to the analyzer. $\eta_3$ is the ionization probability of the neutral atom in a foil in front of the analyzer. $\epsilon/360$ is the ratio of the viewing angle of the analyzer to the full angle of 360°, into which the atoms are ejected. $e$ is the charge of the electron, $n_e$ the density of electrons and ions in the measuring volume and $\bar{\sigma}_i$ is the ionization cross-section of the molecule in $V$ ($\bar{\sigma}_i = \sigma_{eff} - \sigma_{iD} - \frac{<\sigma v>_{eD}}{v_b}$).

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We then find for the current density

$$j = \frac{e \cdot N \cdot P \cdot 360}{\bar{\sigma}_i \cdot n_e \cdot V \cdot \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \epsilon}.$$

If the values

$$
\begin{aligned}
N &= 10, \\
P &= 10^4 \ s^{-1}, \\
V &= 4 \ cm^3, \\
\epsilon &= 0.2°. \\
\eta_3 &= 0.2
\end{aligned}
$$

are assumed, this reduces to

$$j = \frac{3.6 \cdot 10^{-11}}{\bar{\sigma}_i \cdot n_e \cdot \eta_1 \cdot \eta_2}.$$

If, for simplicity and to get an upper limit for the estimate, it is assumed, that the measuring volume is in the centre of the plasma and the line density is the same for the molecular beam and the escaping atom, the central electron temperature is 1 keV and the central density is

$$n_o = \frac{2 \cdot \int_a^o n_e d\ell}{a},$$

$a$ being the minor radius of the plasma, then we find the dependence of $j/a$ on the line density as shown in Fig. 6. It is obvious that a slight increase in beam energy brings a large reduction in beam current density which by far overcompensates the deterioration of the molecular beam production as shown in Fig. 2. As large line densities are usually obtained in high-field or large-minor-radius experiments, good spatial resolution, which is given by the size of the Larmor orbit, can be obtained even with large beam energies.

Figure 6 also indicates the operation ranges of a few experiments. For JET with a minor radius of 125 cm the necessary current densities at $\int n d\ell = 0.8 \times 10^{16} \ cm^{-2}$ range from 0.29 mA/cm² at a beam energy of 50 keV and 20 mA/cm² at a beam energy of 30 keV to 0.275 A/cm² at a beam energy of 20 keV. It should be possible to produce beams with molecular current densities of a few mA/cm² at a beam energy of about 40 keV, which should yield good results on JET. The necessary current densities for smaller experiments become rather small and should not pose any technical problem.

d) Lifetime of the ionized molecule

For optimum measurement of the local q-value the lifetime of the ionized molecule should be less than or of the order of the orbit time of the molecule. If the lifetime were much longer, the motion of the molecule along trapped particle orbits as well as scattering might influence the angular information. On the other hand, the dissociation time should not be much shorter than the time the molecule needs to rotate from the

point of injection to the line of sight of the analyzer, because under this condition the necessary current, estimated in the last Section, would increase accordingly. Again, taking from Ref. 8 the cross-sections of dissociation of ionized hydrogen molecules by electron and proton impact (neglecting ionizing collisions, which contribute only about 3 % to the effect), we can plot the electron density divided by the magnetic field strength for the condition that the dissociation time is equal to the Larmor time of the molecule as a function of the electron temperature. In Fig. 7 these values are given for three energies of the molecules. Only in low-density, high-field, high-temperature plasmas might the dissociation time reach a few Larmor times. For high density but low field and low temperature the dissociation time becomes rather short. In such a case it is worthwhile to have a small angle of molecular rotation between the beam injection and line of sight of the analyzer.

## 4. Effects that influence the width of the measuring angle

The width of the toroidal measuring angle is not zero, the reason for this being briefly discussed in the following. The first effect is based on the Frank Condon-effect, which is unavoidable and cannot be reduced. The two other effects are connected with the quality of the beam and can in principle be made negligibly small.

### a) Frank-Condon effect

Dissociation of the ionized molecule occurs via excitation of vibrational states that decay into the states of the separated atom and ion, where part of the energy of the excited state is imparted to the separating particles in the form of kinetic energy. The mean kinetic energy of each particle[8] is 4.3 eV with a homogeneous angular distribution. This leads to a half-width of energy in the toroidal direction of $\pm 2.15$ eV and to an angular spread $\Delta \alpha$, which is given in Fig. 8 as a function of the energy of the escaping atoms (which equals half the beam energy). In the range of interest the angular half-width caused by the Frank-Condon effect is less than 0.6° and seems to be tolerable, especially since the effect is symmetric in angle and the maximum of the distribution, which is used to determine the toroidal angle, is not influenced by this effect.

### b) Beam divergence

The beam divergence in the toroidal direction causes a proportional effect on the spread of the toroidal angle. It seems a plausible requirement to reduce the beam divergence to about the angular spread that is caused by the Frank-Condon effect. Care should be taken to ensure that the divergence is symmetric in order not to influence the maximum of the distribution of the escaping atoms.

### c) Beam width

The viewing angle of the analyzer determines the extent of that part of the beam part is seen by the analyzer. This part should be small enough to make sure that the fields

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do not appreciably change along the analyzed part of the beam. The same argument also applies to the lateral width. The beam width in the toroidal direction affects the resolution of the measurement of the angular spread. The tolerable toroidal width therefore depends on the specific design of the analyzer. As a rough guess, a width of $\pm 1$ to 2 cm might be tolerable. The same should be true of the third direction.

These requirements on the beam, namely divergence of less or about $0.6°$ and a beam radius in the measuring volume of 1 to 2 cm, may be important for evaluating the beam current density that could be obtained in the measuring volume.

## 5. Possibilities of calibrating the analyzer and discriminating against background

Absolute measurement of the toroidal angle of the escaping atoms requires an exact knowledge of the angle with no poloidal field. This angle can be found by using the double charge exchange process of half-energy protons, injected into the gas-filled chamber with toroidal field only. As will be seen later, the double charge exchange process is rather effective when the gas pressure is high enough. This method provides in situ calibration for zero poloidal field.

Discrimination against passive charge exchange background can be accomplished by suitable pulse shaping of the beam. Discrimination against particles from active charge exchange can be done by using the fact that active charge exchange atoms have a weak toroidal dependence only. If the analyzer has a larger than necessary toroidal extent, a few channels can be used to measure and then subtract the active charge exchange signal. The background signal from light, x-rays or neutrons can be subtracted in the manner described in Ref. 9 and successfully applied in ASDEX.

## 6. Effect of protons in the beam

It has been proposed [4,5] that proton beams and the double charge exchange process be used to determine the poloidal magnetic field. Preliminary experiments have even been performed, but with doubtful results [4,10]. The reason that protons will fail to give good results in high-density plasmas is the long lifetime of the protons against charge exchange in the background neutral gas or even in the neutral beam. Even with a charge exchange rate of $10^7 \ cm^3/s$ and neutral densities of $10^{10} \ cm^{-3}$ the lifetime against charge exchange is 1 ms and therefore much longer than typical diffusion times of ripple-trapped particles. In medium-dense plasmas with reduced neutral density the charge exchange lifetime easily exceeds also the $90°$ scattering time and the energy slowing-down time.

If protons are therefore not suited to measuring the poloidal field, they might, nevertheless, make some undesired contribution to the signal. This might not be negligible because the number of atoms in the beam is already larger than the number of neutral molecules and because all protons that are ionized during penetration may

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cross the line of sight of the analyzer during their lifetime. This at least is then true when the beam is radially injected in such a way that all ionized particles are on ripple-trapped orbits, and the line of sight of the analyzer is in the direction of the drift motion of the protons. The effect of the protons will be illustrated under the conditions of the ASDEX experiment. Figure 9 shows the minor cross-section of ASDEX with the beam, line of sight of the analyzer, direction of the drift, and dimensions. We assume that in the optimized system $z$ times more protons of half-energy are present in the beam than molecules with full energy. We further assume that the fraction $\eta$ of the molecules penetrates to the centre, and that the fraction $(1 - \eta)$ of the atoms has already been ionized and trapped. (Here we assume for simplicity the same $\eta$ for atoms and molecules.) All ionized atoms are assumed to be on ripple-trapped orbits. The drift velocity of the ripple-trapped protons in ASDEX is of the order of 100 $\mu s/40$ cm. If the line of sight has a height of 2 cm the protons then spend $t_s = 5$ $\mu s$ in the line of sight of the analyzer. In the measuring volume with a length $\Delta x$ along the beam the fraction $p$ of the remaining molecules will be ionized.

One finds for the ratio of atoms from dissociation to atoms from charge exchange protons :

$$f = \frac{\eta \cdot p \cdot T_{cx}}{z \cdot t_s (1 - \eta)}.$$

For the centre of the plasma a reasonable estimate for $p$ is $p = 1 - \eta^{\frac{2 \cdot \Delta x}{a}}$. The lifetime $T_{cx}$ of the protons against charge exchange is

$$T_{cx} = 1/(n_o \cdot < \sigma v >_{cx}).$$

As the product $\eta \cdot p/(1 - \eta)$ gets smaller when $\eta$ decreases, the worst case will be for small $\eta$. If we assume $\eta = 0.01$, and if one takes the maximum of $< \sigma v >_{cx} = 1.5 \times 10^{-7}$ $cm^2/s$, one finds with $z = 5$:

$$f \geq \frac{10^9}{n_o}.$$

In the usual ASDEX plasmas and actually in all cases where $\eta$ is small, the neutral density is much smaller than $10^9$ $cm^{-3}$ and hence the protons will not play an important role. This is also seen experimentally on ASDEX. There the half and one-third energy components in the beam which may result from the dissociation of neutral molecules with full or two-third energy play an important role and lead to very strong signals in the energy spectrum of the charge exchange neutrals, whereas the full-energy component, which can only result from double-charge exchange full-energy atoms, cannot be seen on the spectrum. The full-energy component, for example, can only be seen if the beam is injected in the plasma after a disruption, when the plasma density is low and the neutral density high.

If a pure proton beam were used for the experiment, it would be possible to detect a signal from the double charge exchange atoms. But again, because of the long lifetime against charge exchange, the protons may be subject to drift motions and scattering and the toroidal angle might be smeared out and no longer uniquely detectable.

If the signal from protons is considered as a source of misinformation in special cases, injection should be done from the side to which the drift velocity is directed. At least for the central part of the plasma the proton contribution will then be diminished by a large factor.

In experiments with very low field ripple, the protons formed from the injected atoms may be on banana orbits, have a long lifetime in the plasma and may cross the line of sight of the analyzer a few times. The estimate of the proton effect in this case is more complicated.

## 7. Sample calculation of an experiment

A few calculations of the resulting toroidal angle were performed for ASDEX type plasmas. In the example given in Fig. 10a beam is injected from above (see insert in Fig. 10) and is scanned over the plasma cross-section. The line of sight of the analyzer is fixed along the vertical midplane. Circular flux surfaces and different Shafranov shifts were assumed for the different cases. In these model calculations the toroidal field has a 1/R dependence and the poloidal field is proportional to the minor radius of the flux surface. The energy of the hydrogen molecules is 30 keV and the toroidal field at R = 1.65 m is 2 T. The ionized molecules make an approximately 90° turn before they are dissociated and the atom travels to the analyzer. Effects of divergence or Frank-Condon are neglected. According to the calculations in the first section the toroidal angle for this geometry should correspond to the angle of the field lines, i.e. the geometry factor is about 1.

Plotted in Fig. 10 is the toroidal angle $\alpha$ and the field angle $\bar{\beta}$, averaged over the path of the ionized molecule. The width in the $\alpha$-curve is caused by the fact that the analyzer views an area 1 cm above and below the midplane, and, depending on the position, the rotation angle of the ionized molecule slightly changes. The $\bar{\beta}$-value certainly does not show such an effect. For the interpretation of an experiment one would determine the geometry factor from these graphs and multiply the measured angle by this geometry factor to obtain the actual local field ratio.

Figure 10 also shows, that the Shafranov shift can be measured in this geometry with an accuracy of about ±1 cm. The geometry factor, here defined as $\alpha/\bar{\beta}$, is close to +1 or -1 in large areas and only becomes small in the range of the Shafranov shift.

## 8. Example of an analyzer geometry

Although the analyzer is in principle a neutral particle analyzer, a practical solution will differ quite a bit from the usual arrangement. In order to get the q-value at

one position in one shot (as a function of time), the arrangement of the detectors in the analyzer should be in the toroidal direction. As the energy of the particles to be measured is known, one energy channel suffices for the analyzer. Mass separation is not necessary. This results in a rather simple arrangement with a system of diaphragms and a stripping foil in front of the analyzing electric field followed by, for example, a channel plate detector. Figure 11 gives a sketch of a possible analyzer arrangement. With a sufficiently large number of separate detectors the accuracy of the angular measurement might be 0.2°.

## 9. Summary and conclusions

Atoms from dissociation of injected and ionized hydrogen molecules carry information on the (quasi-) local value of the ratio of the poloidal to the toroidal field that can be gained with the help of a special neutral particle analyzer. Estimates of this paper show that molecular beams can be produced with sufficiently high current density. The penetration of the particles was calculated and it was shown that the proposed method might be applicable for rather large values of $\int n d\ell$ corresponding to normal values of the JET experiment. It might be surprising that this method should be applicable for conditions where the usual active charge exchange diagnostic is known to be inapplicable. There are two plausible reasons for this: 1) active charge exchange takes place with plasma particles of all energies, especially with the low-energy ones that do not leave a dense plasma. The flux of high-energy neutrals with an energy a few times the ion temperature onto a detector with about 10 % energy resolution is already orders of magnitude lower than the total flux of charge exchange particles. In contrast, the atoms of the dissociated molecules all have a rather high energy, half the acceleration energy in a very small energy range; 2) particles resulting from active charge exchange are distributed over all directions. The atoms from dissociation, in contrast, are all ejected into a very narrow angle in the toroidal direction, which, taking into account beam divergence and the Frank-Condon effect, may only be about 1.8°, i.e. again 2 orders of magnitude smaller then the angle from active charge exchange. This gives the molecular beam method an advantage of about four orders of magnitude over active charge exchange and is the reason why this method is applicable to very high line densities.

The purpose of the method is to measure the q-profile and the Shafranov shift. It has to be borne in mind that the method in its simple form requires a knowledge of the field topology. But if this is the case, a q-value can be determined. The important question now is how accurately this can be done. If in ASDEX geometry $q$ equals 1 at the flux surface radius of r = 10 cm, then the local field ratio is 3.47°. If the toroidal angle could be measured with the estimated accuracy of ±0.2° and the radius of the flux surface with ±0.5 cm, the measured value of $q$ would be evaluated in the

limits $0.9 \leq q \leq 1.1$ with about equal contributions being made to the error by the inaccuracy in radius and the toroidal angle.

The method is not well suited to measure the central value of $q$, because there the relative error in the knowledge of the minor radius will be too large. The accuracy improves with larger values of $r$. In addition, the method can be used to follow the time evolution of the local $q$. As the signal level can be very high - the necessary current density in many cases will be much smaller than the possible current density - time resolution of ms may be feasable. This would allow to study the redistribution of the plasma current during sawteeth or internal disruptions.

None of the methods used hitherto to measure the q-profile can be applied under very general plasma conditions. The method proposed here seems to be applicable in a very wide range of line densities and plasma temperatures and could therefore be very suitable for use as a standard method.

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## Figure captions

Fig. 1: Geometry of field and motion of a molecule.

Fig. 2a: Optimum molecular fractions with full energy, relating to different ion and neutral fractions of a $H_2^+$ beam.

Fig. 2b: Optimum molecular fraction with two-thirds energy, relating to different ion and neutral fractions of a $H_3^+$ beam.

Fig. 3: Effective cross-sections for atoms and molecules for three different electron temperatures.

Fig. 4: Penetration $\eta$ as a function of line density for different effective cross-sections.

Fig. 5: Penetration $\eta$ as a function of accelerating voltage for different line densities for molecules and atoms for $T_e = 1$ keV.

Fig. 6: Current density over minor radius as a function of line density for beam accelerations of 20/30/50 keV. Operational range of experiments.

Fig. 7: $n_e/B$ as a function of $T_e$ for a gyration time of a molecule equal to the dissociation time.

Fig. 8: Angular spread due to Frank-Condon effect.

Fig. 9: ASDEX geometry.

Fig. 10: Toroidal angle to radius for ASDEX geometries.

Fig. 11: Sketch of a possible neutral particle analyzer, suited to measurement of the toroidal angle.
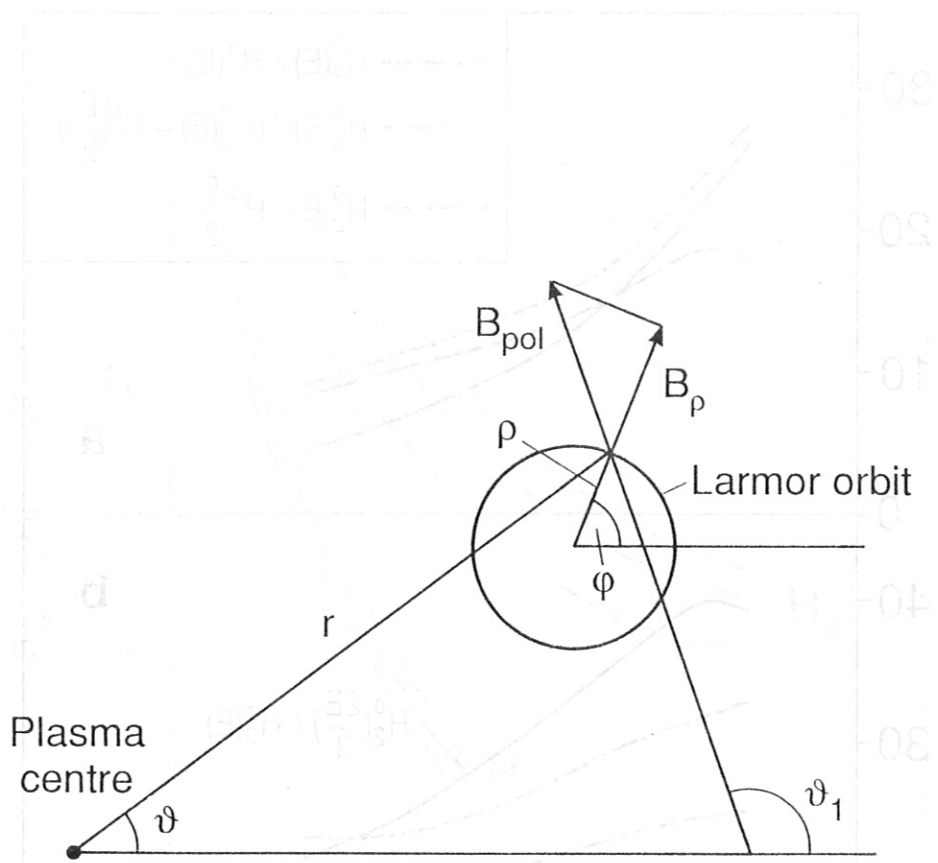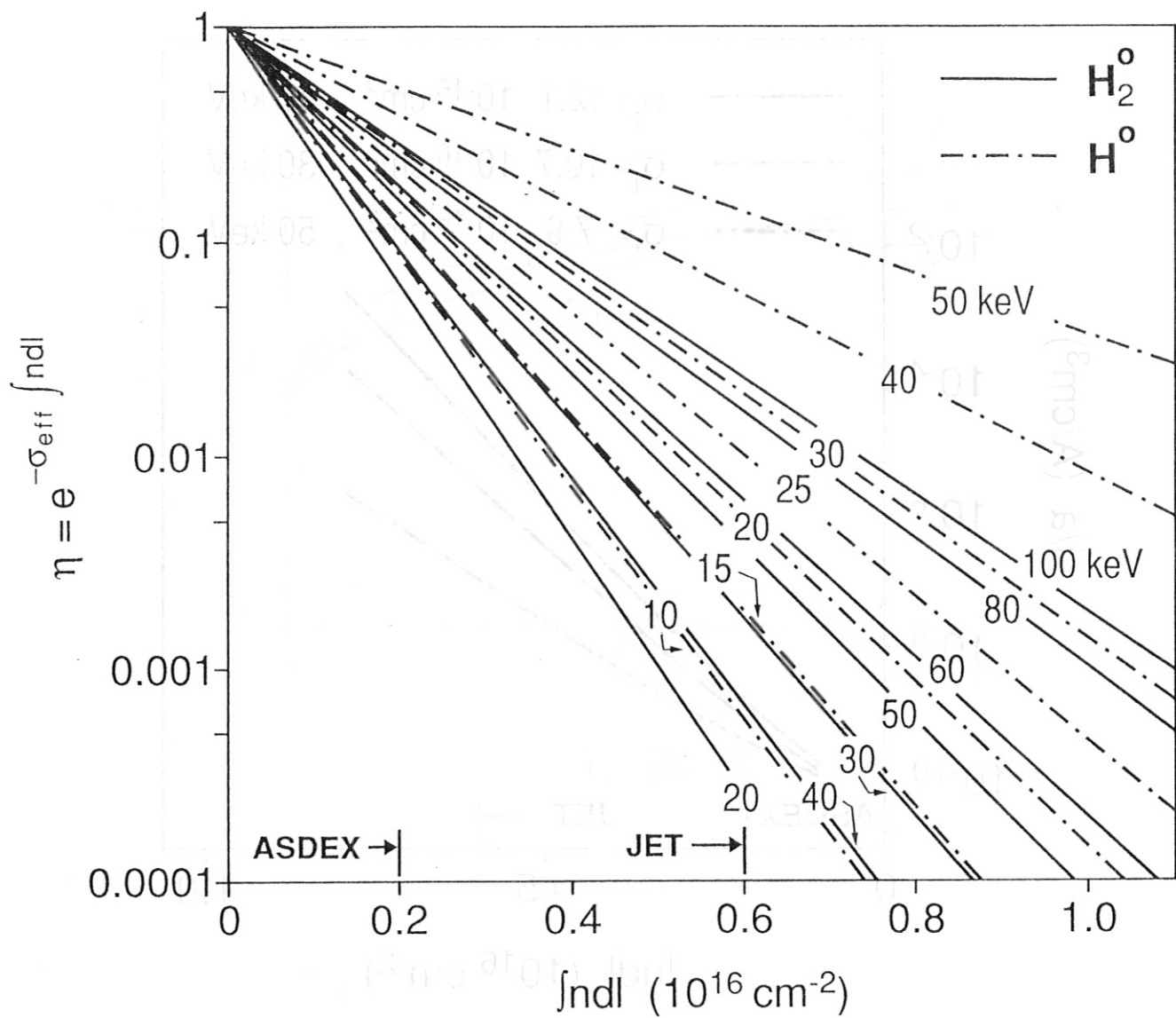
Fig. 1
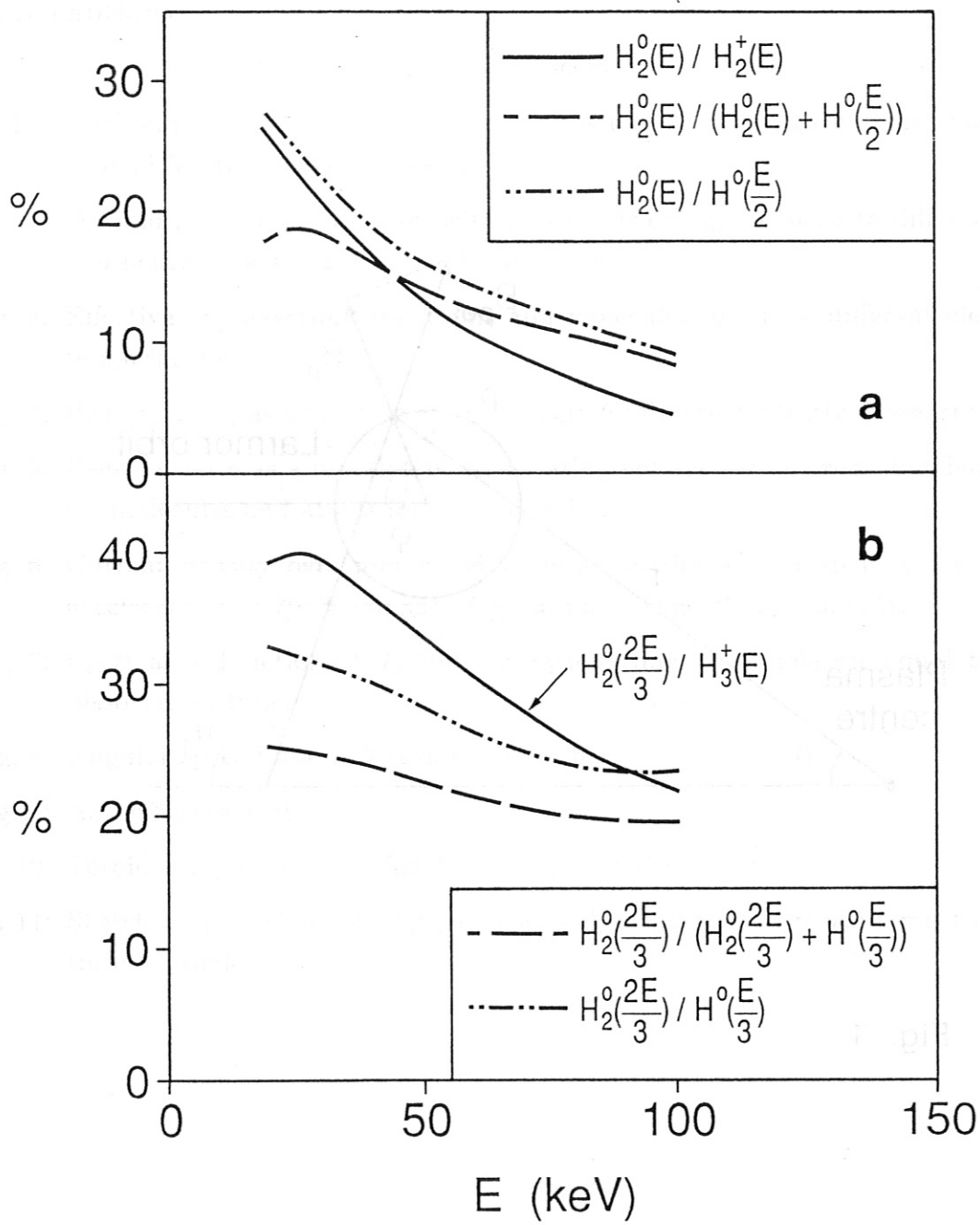
Fig. 2

Fig. 3

Fig. 4

Fig. 5

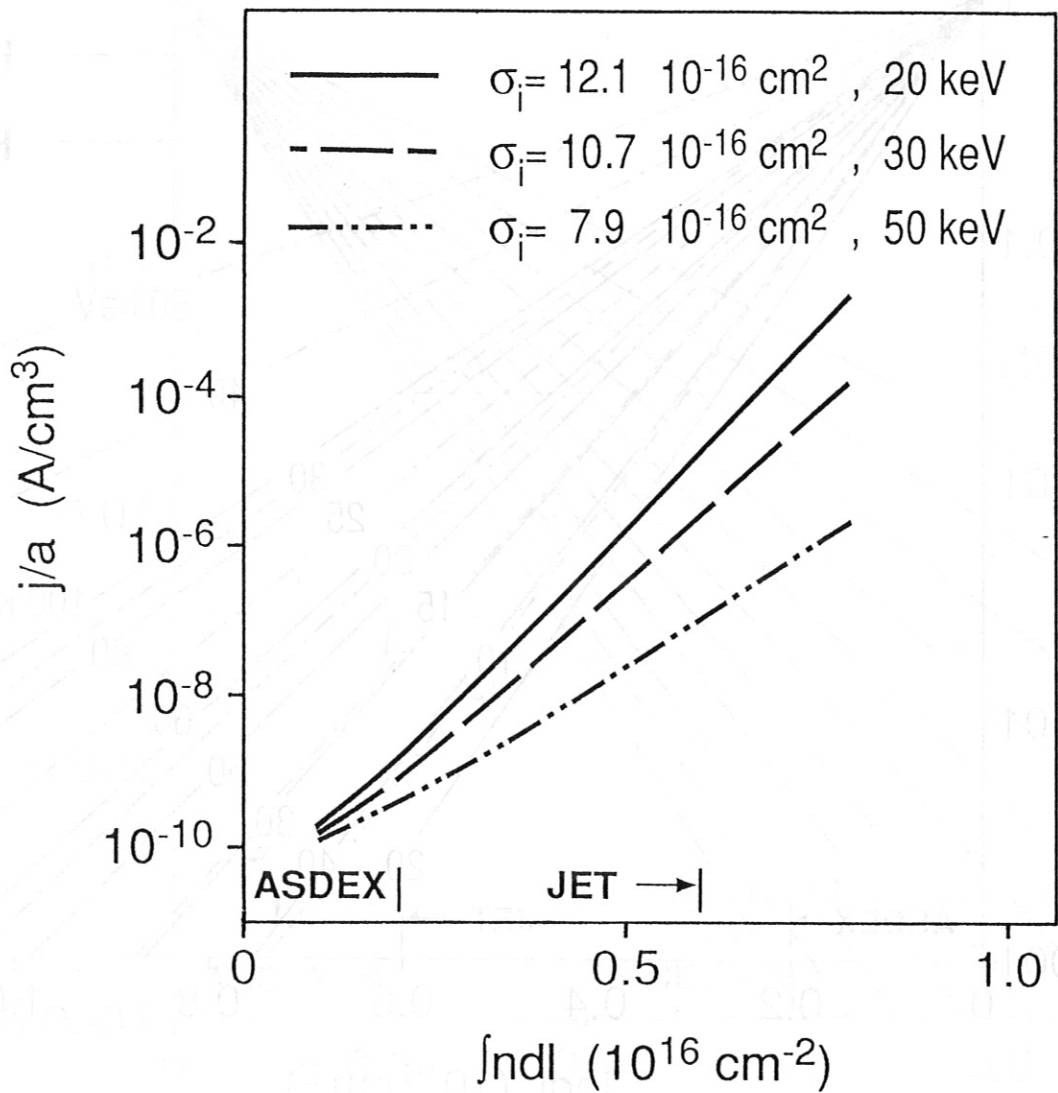Fig. 6

Fig. 7

Fig. 8

drift

to analyzer

R=165 cm

Δx

pivot point

a=40 cm

v

30°

molecular beam

Δx

**Fig. 9**

Fig. 10

beam

plasma

side view

aperture

aperture
foil

condensor plates

array of detectors

beam

plasma

top view

**Fig. 11**