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Spectroscopic Determination of the Species Distribution and the Divergence of the ASDEX Upgrade Neutral Beam Injection System

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ABSTRACT. The species and power distributions and the divergence of the ASDEX Upgrade neutral beam injection system have been measured with H_α Doppler shift spectroscopy. The species distribution of both the RF and the arc sources depend mainly on the source input power and the gas flow into the source. For the same injected current, the new RF sources deliver a higher full energy fraction than the arc sources. This might be explained by the higher degree of dissociation of hydrogen molecules in the source. However, in the case of the same ion extraction geometry, the divergence of the RF sources is slightly higher than the divergence of the arc sources, possibly due to higher ion/electron temperatures in the source plasma.

1. Introduction

The neutral beam injection system of ASDEX Upgrade consists of two almost identical beam lines with four beam sources each. Each beam line delivers 10 MW of D^0 for up to 8 s. Conventional arc sources are used for the first beam line, whereas the second beam line is equipped with new RF sources. Both types of sources deliver a mixture of hydrogenic atomic and molecular ions. Hence the injected neutral beam consists not only of full energy neutral atoms, but also of atoms with half and third energy. The RF sources have been recently upgraded from 60 kV to 100 kV maximum extraction voltage, by increasing the gap between the plasma and the acceleration grid[1]. This changes the focusing properties of the extraction system and reduces the optimum perveance (see below), leading to a lower beam current at the maximum power of 2.5 MW per source.

In this paper we report on measurements of the species and power distribution and the divergence of the ASDEX Upgrade neutral beam sources by means of H_α Doppler shift spectroscopy. The fractions of the different ions in the extracted ion beam is described by the *species distribution*, whereas the *power distribution* gives the fractions of the neutral atoms with the different energies in the injected neutral beam. The knowledge of these parameters is important for the upcoming neutral beam current drive (NBCD) experiments at ASDEX Upgrade.

[1]Due to limitations of the power supplies, the actual maximum possible extraction voltage is 95 kV.

2. H_α Doppler Shift Spectroscopy

The extracted ion beam from the plasma sources consists of D^+, D_2^+, and D_3^+ ions. All these particles interact with the neutralizer gas leading to neutralization and, for the molecular ions, to dissociation as well as to excitation of the resulting neutral atoms. The spectroscopic analysis of the Doppler shifted H_α light [1] emitted by the excited fast neutral atoms in the beam gives the species distribution of the ion source and the power distribution of the neutral beam injected into the torus as well as the divergence of the neutral beam.

The experimental setup and the evalua-

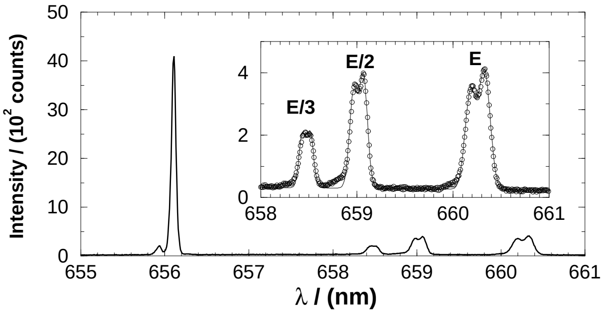

Figure 1: Typical H_α spectrum, obtained in the neutralizer for a 93 kV, 63 A deuterium beam from a RF source. The solid line in the insert is a fit with two Gaussians per peak.

tion of the species and power distribution from the H_α spectra is described elsewhere [2]. Shortly, spectra are routinely obtained in the neutralizers. Under certain conditions — injection in the torus without plasma and magnetic fields —, the H_α emission can also be measured in the duct between the beam line and the torus vessel.

Figure 1 shows a typical spectrum obtained in the neutralizer of the second beam line for a 93 kV deuterium beam. Each of the three Doppler shifted peaks shows a sub-structure with two peaks which can be well described by a sum of two Gaussians. The sub-structure indicates the two sub-beams of each source, generated by a small angle tilting (±0.9°) of the grid halves for beam focusing reasons.

The **species distribution** can be obtained by weighting the ratio of the peak integrals with the respective cross sections of H_α excitation, molecule dissociation, and neutralization for the involved neutral and ionized hydrogenic particles. The situation in the neutralizers is rather complicated: the excitation of the fast neutral atoms occurs by charge exchange collisions of fast ions as well as by excitation collisions of fast neutrals with the hydrogen background gas. Furthermore, the knowledge of the gas density profile in the neutralizers is limited. Hence, we assume that the target thickness, i.e. the product of gas density and the length of the interaction path in the neutralizer, is high enough, so that the species distribution has reached equilibrium in the excitation region.

The species distribution characterizes the ion source. However, the final neutral beam injected into the plasma is characterized — apart from others — by the **power distribution**, obtained by weighting the species distribution with the neutralization cross section for an infinitely thick target.

The infinitely thick target assumption has been validated with measurements of the power distribution in the duct, where the conditions are much less complex because H_α light is created by collisions of fast neutral atoms with the low-density background gas only. Hence, the power distribution can be calculated by simply weighting the peak ratios with the H_α excitation cross sections.

The **divergence** of the injected neutral beam is calculated from the widths of the Gaussians fitted to the Doppler shifted subpeaks (see Figure 1). The extracted current $I_{\rm ex}$ is determined by the space-charge-limited flow of ions and is given by

$$I_{\rm ex} = C\,\sqrt{Z/M}\;(a/d)^2\;U_{\rm ex}^{3/2}, \qquad (1)$$

where Z and M are the charge state and the mass of the extracted ion, respectively. a is the aperture radius, d the distance between the plasma and the acceleration grid and $U_{\rm ex}$ the extraction voltage. The ratio

$$P = I_{\rm ex}/U_{\rm ex}^{3/2} \qquad (2)$$

is called perveance.

For a given extraction geometry, there is an optimum match between the ion flux density and the electrostatical potential — i.e. the *optimum perveance* —, so that the resulting plasma curvature would lead to a zero beam divergence. However, other effects, like optical aberrations of the beam focusing or ion drifts in the source perpendicular to the beam extraction direction due to non-zero ion temperatures, lead to (small) energy deviations and angular distributions of the extracted ions and, hence, to a non-zero divergence of the injected neutral beam.

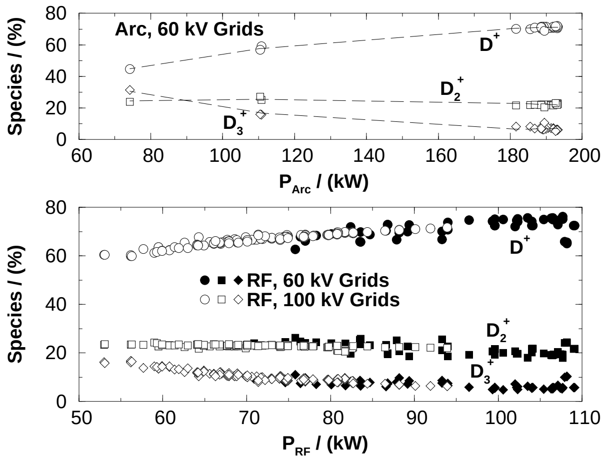

Figure 2: Species Distribution vs. arc power (top) and vs. RF power (bottom).

3. Results and Discussion

3.1. Species and Power Distribution

Figure 2 shows the species distribution for the arc sources as well as for the RF sources with the 60 kV and 100 kV grids[2]. Generally, the fraction of deuterons in the extracted ion beam increases with increasing input power and — not shown here — with increasing gas pressure in the ion source. Due to the $U_{\rm ex}^{3/2}$ dependence of the extracted current and, hence, of the source input power (see Eq. 1), an increase of the input power is tantamount to an increase of the extraction voltage. As can be seen in the lower part of Figure 2, the species distribution does not depend on the extraction voltage: e.g. the deuteron fraction is about 68% at 80 kW input power, regardless of 50 kV extraction voltage for the 60 kV grids or 93 kV extraction voltage for the 100 kV grids. The increase of the deuteron fraction is associated with a decrease of the amount of D_3^+ molecules. However, the fraction of D_2^+ molecules does not change. This is consistent with model calculations [3].

Figure 3 shows the dependence of the power distributions on the extraction voltage for the three different cases. The RF sources are more efficient than the arc sources: for the same injected power at equal

[2]In the following, the 'different' RF sources are denoted by the maximum extraction voltage for the grid; the actual extraction voltage may be lower.

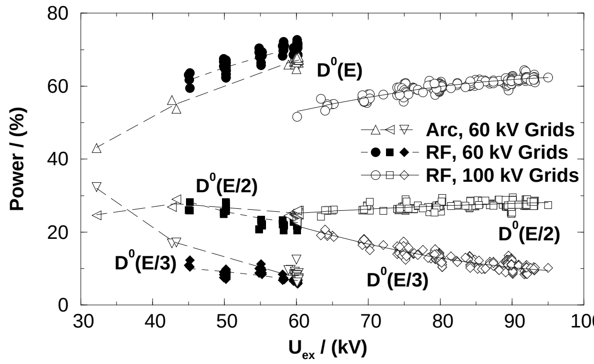

Figure 3: Power distributions vs. extraction voltage for deuterium beams.

energy, hence for the same extracted current, the amount of full energy deuterons is higher (see also Table 1). Due to the decreasing neutralization probability with increasing beam energy — and due to the lower source input power — the amount of full energy neutrals is reduced in the case of the 100 kV RF sources: these sources deliver at 95 kV still less full energy deuterium atoms then the arc sources at 60 kV.

The increase of the deuteron fraction with increasing source input power is mainly due to an increasing electron density; according to probe measurements at the testbed [4], the electron temperature remains constant with increasing RF power for constant pressure. The higher deuteron efficiency of the RF sources might be related to the differences of the plasma generation and in the resulting electron energy distributions. In arc sources, there are two kinds of electrons [3]: mono-energetic *primary electrons* are emitted from the filaments with energies of several 10 eV to 100 eV, interact with the hydrogen background gas and the already generated ions and molecule ions, and create *secondary electrons* with a maxwellian energy distribution. These electrons have mean energies of some eV. Due to the large number of filaments (here 24), the plasma is very uniform in an arc source.

In RF sources, however, fast primary electrons do not exist and the electron energy distribution is more maxwellian-like. Furthermore, the RF power is coupled to the

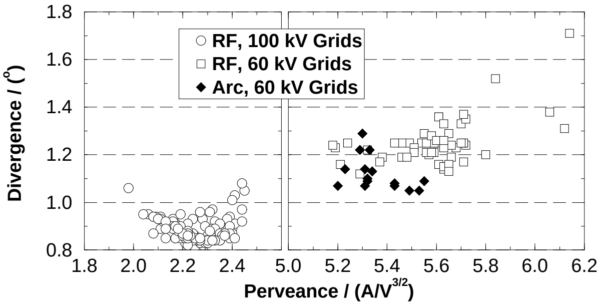

Figure 4: Divergence vs. perveance. Shown is the mean divergence of the two sub-peaks of the full energy peak (see Figure 1). Both sub-peaks have nearly the same divergence.

plasma only at the edge (within the skin depth of a few cm), leading to an non-uniform electron energy distribution with the electron temperature increasing towards the edge. Typical mean energies are 5 eV to 10 eV at the plasma center, and more than 25 eV at the edge in the RF coupling region [4]. These temperatures are higher than the temperature of the secondary electrons in arc sources and are around the maximum of the cross section for the dissociation of the deuterium background gas ($D_2 + e \rightarrow D^0 + D^0 + e$) at 16 eV [3]. Hence, the degree of dissociation might be higher in RF sources and more D^+ ions can be extracted than from arc sources for the same extracted total current.

With the power distribution given in Table 1, the current drive efficiency of the 100 kV RF sources is reduced by about 10% compared to a beam with full energy neutrals only (from 52 kA/MW to 47 kA/MW at $T_e = 2$ keV at half minor radius).

3.2. Divergence

Figure 4 shows the dependence of the divergence of the different sources on the perveance. The minimum divergences are listed in Table 1. For the same extraction geometry (60 kV grids), the divergence minimum — defining the perveance optimum — of the RF sources is slightly higher than that of the arc sources, whereas the RF sources with the 100 kV grid geometry have a much lower divergence minimum.

Table 1: Power distribution and minimum beam divergence, $\epsilon_{\rm min}$, for 2.5 MW D^0 injection.

	Arc, 60 kV	RF, 60 kV	RF, 93 kV
E	65%	74%	63%
$E/2$	25%	19%	27%
$E/3$	10%	7%	10%
$\epsilon_{\rm min}$	1.0°	1.1°	0.8°

If the ion temperature T_i does not depend on the RF power, as it is the case for the electron temperature (see above), the lower divergence of the 100 kV grids can be mainly related to a decrease of the ratio of the perpendicular to the parallel velocity components of the extracted ions ($\epsilon \propto (T_i/U_{\rm ex})^{1/2} \Rightarrow \Delta\epsilon_{60\ {\rm kV}\rightarrow 93\ {\rm kV}} = -0.2°$). Also, the smaller aberrations of the ion optic system due to the higher aspect ratio d/a of the 100 kV sources decreases the minimum divergence further.

The reasons for the slightly higher divergence of the RF sources are not clear. In-homogeneities of the electron density in the sources across the plasma grid can be ruled out: the plasma density profiles of our RF sources have been optimized [5]. Probably, the larger divergence can be related to the in-homogeneous electron temperature distribution in the RF sources (see above). This will lead also to an increased ion temperature in the regions where the RF couples to the plasma (at the edges), increasing the ion velocity components perpendicular to the ion beam. However, fast beam modulations due the RF coupling cannot be ruled out. A spatially resolved spectroscopic system at the testbed measuring the divergence at the beam edges is under construction.

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