Diagnostics of effusing plasmas

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DIAGNOSTICS OF EFFUSING PLASMAS

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INTRODUCTION

The most important part of an apparatus for plasma etching or deposition is the plasma source that is being used. For optimalization with respect to etch rate, deposition rate and energy or gas consumption, we have to know the source characteristics. An experimental determination of densities, fluxes and temperatures of ions and radicals is needed. A model for these quantities, verified with experimental data, is most useful.

An example of a plasma used for the deposition of titanium nitride is a hollow cathode arc [1]. In this paper a number of diagnostics is presented, sufficient to measure all wanted quantities in such an arc. A model for the axial momentum balance is given. Using the experimental data this model has been verified.

THE HOLLOW CATHODE ARC

The investigations were made in a large size hollow cathode arc (HCA) in argon. The HCA is a type of arc that is operated at relatively low gas pressures and high currents. The voltage between anode and cathode is low. The most important features of the HCA are a hot hollow cathode made of tantalum with a large thermionic emission, a continuous gas feed through the hollow cathode, a continuous pumping of the gas and confinement of the plasma column by an external static magnetic field. The independent variables of the HCA are the plasma current, the confining magnetic field, the gas flow, the pressure outside the arc, the cathode diameter and the length of the arc. Cathode and anode can be moved both axial and lateral. Scans in all measurements can be done by displacement of the plasma column in order to keep the optical paths unchanged. In table 1 relevant data are given for independent and dependent variables.

DIAGNOSTICS

To characterize the hollow cathode as a plasma source, we have to know the density, the temperatures and the flow speeds of the different particles (atoms, ions and electrons). Here a number of optical diagnostics is presented that gives experimental data of all the desired quantities. The measurements have been performed in the first 10 cm from the cathode.

a) Thomson scattering

The electron density ne and the electron temperature Te are measured with the aid of a Thomson scattering experiment [2]. A pulsed laser beam is focused into the plasma. The light scattering on free electrons is measured under an angle of 90°. The intensity of the scattered light is proportional to the electron density whereas its Doppler broadening gives the electron temperature. The main advantages of Thomson scattering are that the plasma is not disturbed, the measurement is local and the desired quantities can be calculated from the measurements without uncertainties in the interpretation. The scattered radiation is measured at five different wavelength channels between 690 nm and 694 nm where only very weak argon lines are present. An absolute electron density measurement is possible by calibrating a channel at the laser wavelenght (694.3 nm) with Rayleigh scattering on neutral argon gas at 2700 Pa. The relative sensitivity of the side band channels are calibrated with a tungsten ribbon lamp. Corrections are made for stray light, dark currents and plasma background radiation. Usually the laser measurements are averaged over 10 shots. With a weighted least squares method a Gaussian function of the wavelenght shift is fitted to the measurements, giving directly electron density and temperature. The noise in the plasma background radiation is the main source of errors and limits the applicability of Thomson scattering to electron densities up to 10^{20} m^{-3}.

b) line intensity measurements

Combined with a collisional radiative model, the experimental values of the absolute emissivities of some spectral lines in the plasma give the neutral particle density and the electron temperature [3]. The measured light intensity gives the plasma emissivity integrated over the line of sight and by Abel inversion the local emissivity is determined. This method is also applicable close to the cathode where the plasma radiation is to high to use Thomson scattering for the determination of electron density and temperature.

c) continuum radiation measurements

The continuum intensity of the plasma is formed by free-free and by free-free radiation and is measured in one of the Thomson channels. To get local values Abel inversion has been used. The emissivity is proportional to n_e^2 with no significant influence of T_e [2]. To get absolute densities, this measurement is calibrated with Thomson scattering at low densities.

d) line width measurements

Temperatures of ions and neutrals are derived from the Doppler braodening of spectral lines. Lines are selected by a 0.25 m grating monochromator and scanned by a Fabry-Perot interferometer [4]. The measured intensity profiles are fitted with a Voigt function by means of a least squares method. The ion temperature can be derived from the Gaussian part of the Voigt profile. For a neutral line a fit with two Gaussian contributions has to be done. This corresponds to the existence of two groups of neutral particles with different temperatures. The hot group of neutral particles is caused by ion-neutral charge exchange collisions. The cold particles come from the gas surrounding the arc [6].

e) line shift measurements

The drift velocities of ions and atoms are measured from the Doppler shift of spectral lines. The wavelength shift involved is 10^{-4} nm for a velocity of 45 m/s measuring the 668.4 nm ArI line. The same set-up as for line width measurements has been used. An absolute wavelenght shift is obtained by using a reference beam that emerges from the plasma opposite to the primary beam. This reference beam is chopped and imaged back into the plasma. A spectral red shift of the primary beam occurs together with a blue shift of equal magnitude in the secondary one. The signals of the direct and of the indirect light are measured simultaneously. The primary beam gives a DC signal and the secondary beam an AC signal that is seperated with a lock-in amplifier. For the velocity measurement only the middle of the line profile is needed.

The drift velocity consists of an axial and an azimuthal component. The axial drift velocity is caused by longitudinal pressure gradients. The azimuthal drift velocity (rotation) is composed of an E/B dominated drift and a smaller oppositely directed diamagnetic drift [4]. By measuring under an angle with the axis of the arc, we see both the axial and the azimuthal component of the drift velocity. These can be seperated by a lateral scan in which the axial component gives an even function of the distance to the axis and the azimuthal component an uneven function. In seperating both components also the effect of the higher intensity in the middle of the arc is taken into account [7].

EXPERIMENTAL RESULTS

A complete set of measured quantities at the axis of the arc is given for the standard condition of table 1. The electron density is given in fig. 1. An extrapolation towards z=0 indicates a value for ne of 10@21 m-3 at the cathode tip. Fig. 1 indicates a radial expansion of the plasma with at least a factor of 2 towards z=2 cm. This corresponds to the plasma radius of 5.5 mm that has been measured at z=2.5 cm. The temperatures of the different particle species is given in fig. 2. One has to realise that the neutral density decreases very fast outside the cathode (see fig. 3). Up to 5 cm from the cathode the neutrals are mainly coming from the cathode and have a high temperature. For distances larger than 5 cm from the cathode the neutrals are coming from the beckground gas. Their density is constant and their temperature is low. This effect is also visible in the axial drift velocities of ions and neutrals (fig. 4). The hot neutrals emerging from the cathode have more or less the same velocity as the ions. The cold neutrals coming from the background gas have no axial velocity. Note that at the cathode the heavy particles are moving at a very high (supersonic) velocity.

THE MOMENTUM BALANCE

For the description of the axial momentum balance we use Braginskii's model [5]. We assume rotational symmetry and stationary conditions. An equation for the longitudinal momentum balance for the ions and the electrons will be used. A term for ionizing and elastic collisions with neutrals is included. This is allowed because collisions among ions and electrons are much more frequent than collisions that involve atoms. The mutual momentum interactions between ions and electrons will cancel. Also the electric field disappears out of the momentum balance of the mixture because of its electrical neutrality. Electron inertia, electron viscosity and collisions of electrons with neutrals are negligible because of the small mass of the electrons compared to that of the heavy particles. All this results in a momentum balance in which ion inertia, pressure gradient of ions and electrons, ion viscosity and collisions of ions with neutrals are taken into account.

The experimentally determined values of the plasma quantities are used to calculate the different contributions to the momentum balance. Because the gradients of these quantities are needed, analytical expressions are used that fit the measured data. This avoids large errors due to scattering of experimental data. The main terms are the ion and electron pressure gradient and ion viscosity while neutral friction has a minor influence. These balance within a factor two. It is possible that viscosity term is too small because turbulence is not taken into account.

Far from the axis viscosity vanishes because the mean free path for ions becomes larger than the plasma radius. The neutral friction is expected to take over the decelerating force there because the neutral density is larger than at the axis of the arc [7].

SOURCE PROPERTIES

With the diagnostics described above, enough experimental data are known to determine the source properties of a hollow cathode. In fig. 5 the ionization fraction is given as a function of the gas flow at different currents. For low values of the gas flow the ionization fraction goes to one. Especially at high currents the ion flux almost equals the gas flux. At high gas flows the ion flux saturates. The ion saturation production is 5 % of the charge carrier flux I_a/e. So a high ion production rate with a low gas waste can be obtained by drawing a strong current with limited gas flux.

CONCLUSIONS

A number of diagnostics to measure all plasma properties in the vicinity of the hollow cathode is described. With the experimental data the momentum balance in the plasma and the source properties of the hollow cathode are determined. The main driving term in the momentum balance is the pressure gradient of ions and electrons. The decelaration of the ions is mainly caused by ion viscosity and to some extent by friction with neutrals. At high currents the ion flux almost equals the gas flux. At high gas flows the ion flux saturates.

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I_{pl}	plasma current	10 - 100 A	50 A
B_z	magnetic field	< 0.5 T	0.2 T
Q	gas flow	$5\ 10^{19}$ - $5\ 10^{20}$ s^{-1}	$3\ 10^{20}$ s^{-1}
p	pressure	10^{-2} - 1 Pa	0.27 Pa
d_c	cathode inner diameter	6 - 8 mm	6 mm
L	length plasma column	0 - 2 m	1.3 m
n_e	electron density	10^{18} - 10^{21} m^{-3}	
$\bar{n}_a$	neutral particle density	10^{18} - 10^{21} m^{-3}	
T_e	electron temperature	2 - 10 eV	
T_i,T_a	heavy particle temperature	0.2 - 5 eV	
R_{pl}	radius plasma column	1 - 2 cm	

Table 1. A review of the relevant data of the HCA.

(Right column: standard condition)

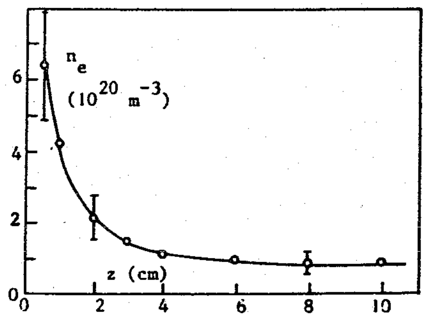

Fig. 1. The electron density at the axis (cathode at z = 0).

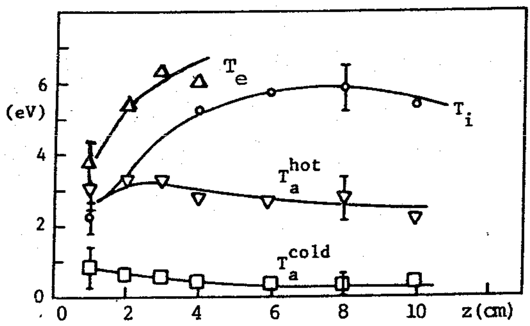

Fig. 2. Temperatures of electrons, ions and hot and cold neutrals.

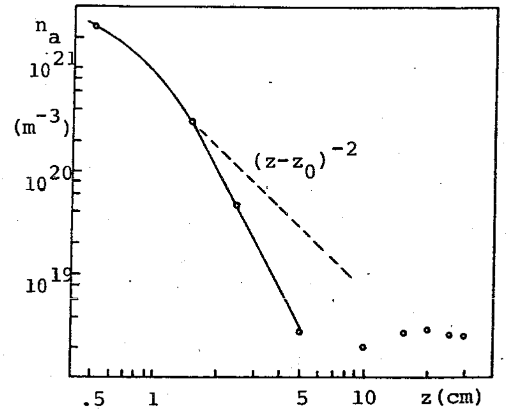

Fig 3. Neutral particle density. Dashed curve: the decrease in the case of free expansion.

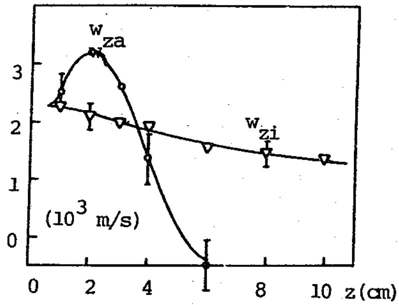

Fig. 4. Drift velocities of ions (w_{zi}) and neutrals (w_{za}).

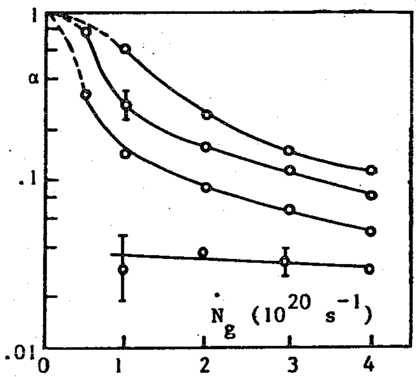

Fig. 5. The ionization fraction α as a function of the gas flow at different currents (from above downward 150, 100, 50 and 20 A resp.). Other parameters according to the standard condition.