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TIME-OF-FLIGHT ANALYSIS OF NEUTRALS FROM A PLASMA AS A DIAGNOSTIC FOR THE ION VELOCITY DISTRIBUTION

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Introduction :

In a plasma energy is transfered from ions to neutrals by elastic collisions and charge exchange. By measuring the velocity distribution of the fast neutrals with a time-of-flight spectrometer, we get very detailed information on the ion velocity distribution.

Experimental set up :

All measurements have been done with our time-of-flight spectrometer /1,2/. A four stage differentially pumped vacuum system is used with a fifth stage as a beam trap. In the experiments described the first stage is used as the source chamber for the H.C.D. The end anode is the separation between the first and the second stage. The chopper is located at 24 cm from the end anode, i.e. the effective source. The first disc has two narrow slits opposite to each other with an open time of 1.8%. A second disc with two broader slits cuts off low velocity molecules to avoid overlap between two succeeding periods. Beyond the cut-off the background is measured simultaneously with the signal due to the molecular beam. The flight path from chopper to detector is 1.36 m. A typical chopper period is 9.1 ms, resulting in an open time of 160 μs. At 2000 m/s the velocity resolution is then 6.8% (rms spread). The detector is a residual gas analyser, fitted with a cross-beam ioniser, a quadrupole mass filter and an electron multiplier. Single ion counting is used and the ion pulses are recorded in time channels, according to their flight-time. The total pressure in the source chamber is of the order of $5\ 10^{-11}$ torr. The beam is collimated before entering the detector. Typical beam diameter is 1 mm.

Time-of-flight analysis of neutrals from a plasma has been tested for a Hollow Cathode Discharge /3/. A schematic view is given in Fig. 1. The diameter of the orifice in the end anode is 1.0 mm. For the measurements described, two configurations have been used : a long discharge with a cathode to end anode distance l_o=200 mm and a short discharge where the end anode is placed in front of the magnet resulting in l_o=15 mm. All our measurements have been done with Argon. The flow rate through the cathode is varied between 0.1-0.5 torr l s^{-1}. A typical value of the magnetic induction is 680 Gauss. Power is supplied between cathode and ring anode while the end anode is at a floating potential. A typical diameter for the plasma core is 4 mm. The arc current is varied between 5 and 20 A resulting in maximum current densities of 10^6 A/m^2.

Theory :

Fast neutrals are created in collisions between neutrals and ions. The forward intensity I(o)($s^{-1}sterad^{-1}$) and the normalised velocity distribution P(v)dv of fast neutrals effusing from the orifice in the end anode with cross section A is given by /3/

$$I(o)P(v)d^2\omega dv = [\int_0^{\ell_o} \dot{n}(z,v)\ T(z,v)\ Adz]d^2\omega dv \qquad (1)$$

with $\dot{n}(z,v)$ the production rate of fast neutrals per volume, per velocity and per solid angle. T(z,v) is the transmission probability through the plasma of a fast neutral created at z with velocity v.

We first discuss the various terms in Eq. 1 in the case of a homogeneous arc, i.e. constant densities and temperatures. The production rate is then given by

$$\dot{n}(z,v)dzdv=({}^1/4\pi)n_n n_i \bar{v}_i\ \{Q_{exch}P_{exch}(v)+Q_{el}P_{el}(v)\}dzdv \qquad (2)$$

$$P_{exch}(v)dv=({}^2/\alpha_i)({}^v/\alpha_i)^3 \exp -({}^v/\alpha_i)^2\ dv \qquad (2a)$$

$$P_{el}(v)dv=({}^2/\alpha_i)({}^v/\alpha_i) \exp -({}^v/\alpha_i)^2\ dv \qquad (2b)$$

with $\int_0^\infty P(v)dv=1$, $\alpha_i=(2kT_i/m)^{\frac{1}{2}}$, $\bar{v}_i=({}^2/\sqrt{\pi})\alpha_i$, and n_n and n_i are the neutral and ion density, respectively. $P_{el}(v)$ is the velocity distribution of the flux of fast neutrals created by elastic collisions and Q_{el} is the corresponding total cross section. For calculation of the momentum transfer we assume for this process a hard sphere differential cross section. $P_{exch}(v)$ is the velocity distribution of the flux of fast neutrals created by charge exchange and Q_{exch} is the corresponding total cross section. For charge exchange the differential cross section is strongly peaked in forward direction and the velocity distribution $P_{exch}(v)$ of the resulting neutrals is the Maxwell Boltzmann (MB) flux distribution of the ions. The transmission probability is given by

$$T(z,v) = \exp -[n_i Q_i\left(\frac{g_i}{v}\right) + n_e \langle Qg_e \rangle_{ion} \frac{1}{v} + n_n Q_n \left(\frac{g_n}{v}\right)]z \qquad (3)$$

describing the attenuation of the molecular beam by collisions with ions, electrons (ionisation) and slow neutrals, respectively; g is the corresponding relative velocity. The transmission probability decreases exponentially with increasing z. The inverse of the sum of the three products (nQ(g/v))(m^{-1}) is the measure for the view depth in the plasma, i.e. the length of the plasma slice which effectively contributes to the molecular beam.

The velocity factor (g_i/v) for ion-fast neutral collisions (Eq. 3) decreases from 1.30 for v=$\alpha_i\sqrt{2}$ to 1.04 for v=4α_i, and the maximum deformation of the velocity distribution due to fast neutral-ion collision is 30% for v>$\alpha_i\sqrt{2}$. Assuming T_i=4 T_n the velocity factor (g_n/v) decreases from 1.07 at v=$\alpha_i\sqrt{2}$ to 1.01 at v=4α_i. We can conclude that the velocity dependence of the transmission probability only slightly influences the shape of the velocity distribution for high velocity fast neutrals. For low electron temperatures ionisation can be neglected in Eq. 3.

In the real arc we have to take into account the axial dependence of the neutral density due to the wall recombination on the end anode and we have to replace n_n in Eq. 2 by $n_n(z)$ and $n_n z$ in Eq. 3 by

$$(n_n z)' = \int_0^z n_n(z')dz'.$$

Results :

Evaluation of the data is done by least squares analysis of the time-of-flight spectra, using appropriate model functions. In fig. 2 a typical time-of-flight (TOF) spectrum is given in the case of the long discharge(intermediate ion densities $n_i \sim 10^{19} (m^{-3})$) The view depth is then of the order of 2.5 cm. The spectrum is well described by the sum of two M.B. distributions (1,3) and P_{exch} + (Q_{el}/Q_{exch}) P_{el}(2),using the experimental values Q_{exch} = 47 Å^2 /4/ and Q_{el} = 17 Å^2 /5/, at a reduced energy of 1 eV. We neglect the slight velocity dependence of these cross sections. For a TOF spectrum of a M.B. distribution the count rate at the maximum (located at $v = \alpha_i \sqrt{2}$) is a direct measure for the intensity I(o). For P_{exch} + (Q_{el}/Q_{exch}) P_{el} the equivalent measure for intensity is the maximum count rate multiplied by an extra factor 1.23. The maximum of this distribution is only slightly shifted from $v = \alpha_i \sqrt{2}$. The temperatures for the three distributions (1,2,3) are of the order of 800K, 3500K and 15000K, respectively.

The hot distribution (2) is due to the bulk of the ions. This is supported by ion temperatures, calculated by solution of the ion energy balance. The superhot distribution (3) is attributed to an overpopulation of the high energy tail of the ion velocity distribution. This overpopulation of the tail of the ion velocity distribution increases with decreasing neutral density in the discharge chamber and increasing arc current, i.e. with increasing drift parameter (Fig. 3), which is defined as the ratio of the electron drift velocity and the electron thermal velocity. The ratio between the two highest temperatures is constant within 25% over the whole range of parameters. Therefore this tail formation and associated anomalous ion heating may be attributed to current driven instabilities e.g. anomalous ion acoustic turbulence /6/. The cold distribution is attributed to low energy ions, due to the increase of the neutral density towards the end anode, caused by wall recombination on the end anode.

In the case of the short discharge the view depth is <1 mm. Measurements with the short discharge are well described with the same model function as used for the long discharge. The measured temperatures are 15000K for the bulk of the ions and 50000K for the superhot distribution. The intensity is a factor 100 higher, i.e. ion densities in the order of $10^{21} (m^{-3})$.

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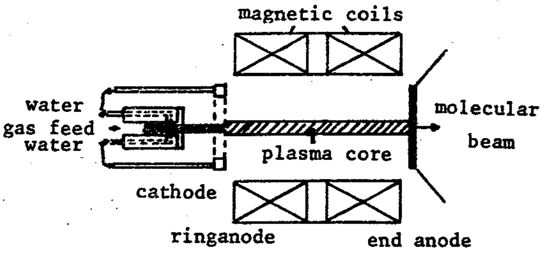

Fig. 1 Schematic view of the Hollow Cathode Discharge (H.C.D.), as situated in the source chamber.

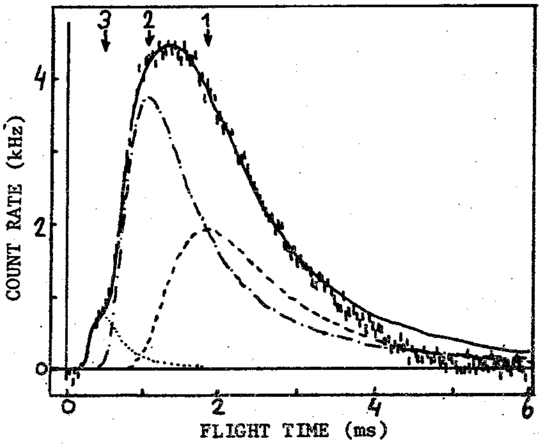

Fig. 2 A measured TOF spectrum curve fitted by least squares analysis with the model functions given. The measured spectrum is represented by the bars, indicating the error bar due to the statistical noise. Temperatures are 679 K (1), 2178 K (2),and 11283 K (3), respectively. Experimental conditions : arc current, 10A; magnetic induction, 6.8 10^{-2}T; neutral density in the source chamber, n_{source}, 4.8 $10^{20} (m^{-3})$.

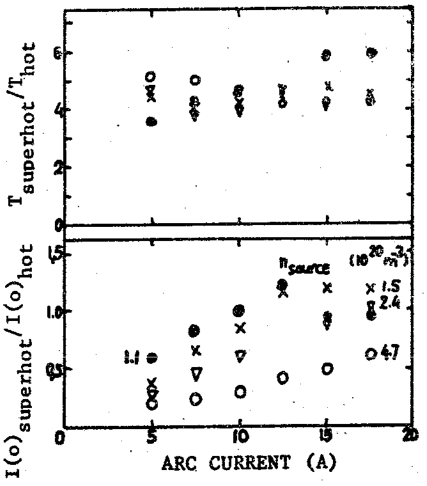

Fig. 3 The ratio of the intensity and temperatures of the superhot and hot distribution as a function of the arc current, at a magnetic induction of 6.8 10^{-2}T, with the neutral density in the source chamber as a parameter.