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Reflection of Ionized Hydrogen Clusters at Polished Stainless Steel

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Ionized hydrogen clusters of either charge polarity containing some 10^5 molecules of hydrogen can be reflected at a polished stainless steel surface, for purposes of fusion fuel injection, very similarly to neutral clusters. The effective charge of positive cluster ions increases by a factor of about 1.5 during the reflection.

Fuelling or heating of nuclear fusion plasmas may possibly be accomplished by injection of clusters of fuel material originating from partly condensing nozzle flows [1]. Screening out the core of such a nozzle jet and transferring it via intermediate pressure stages into high vacuum leads to beams of high mass flux and speed ratio [2], containing primarily clusters and only a small amount of residual uncondensed gas [3].

Aiming at mechanical cluster beam focusing, the conditions for optimum reflection of clusters at polished surfaces have been investigated rather thoroughly [4–7]. For reasons of sufficient penetration into the plasma, or as a means of plasma heating, the clusters have to be speeded up considerably, which requires ionization to allow acceleration by electric fields [8]. Then, the problem of space charge induced beam spreading arises, especially before, or at the very beginning of, the electrical acceleration. Considering mechanical focusing of cluster ion beams as a possible counter-measure the reflection of ionized hydrogen clusters at polished stainless steel is investigated.

For that purpose, the experimental arrangement formerly used to study the reflector temperature dependence of the reflection of neutral clusters [7] is supplemented by an electron impact ionizer in front of the reflector. A schematic view of the experimental set-up is given in Figure 1. The hydrogen clusters are generated by means of the cluster beam source already described using, however, liquid neon as nozzle coolant and a source pressure of the hydrogen feed gas of 1300 torr. The clusters are ionized by electrons of 200 eV energy for reflection experiments with positive cluster ions, and of 50 eV for experiments with negative cluster ions [9]. Switching off the ionizer in front of the reflector allows to

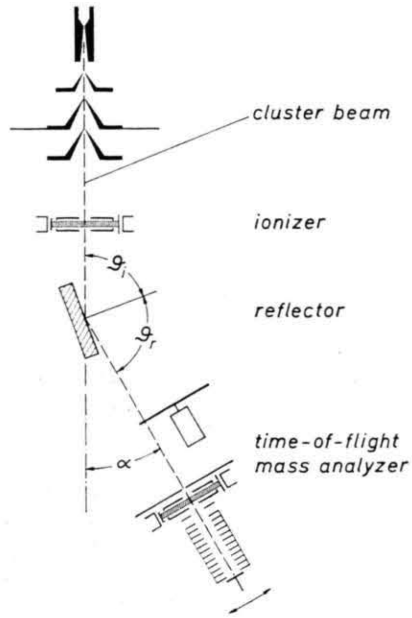

Fig. 1. Schematic view of the experimental set-up.

measure again the reflection of neutral clusters. The inclination of the reflector is the same for all measurements, yielding an incidence angle ϑ_i of the neutral beam of 85°, measured from the surface normal. The reflector temperature is kept at 220 K which seems to be not far from the optimum reflector temperature for the chosen conditions. The reflector is surrounded by a cooled baffle to reduce contamination by diffusion pump oil. In order to allow measurements of the incident beam the reflector is retracted from the beam path. When investigating cluster ion beams no use is made of the built-in electron impact ionizer of the analysing system, while for studying neutral cluster beams this ionizer is used with 200 eV electron energy. The analysing system is a time-of-flight mass spectrometer especially developed for cluster beam measurements [9]. It can be rotated in the plane of incidence on an axis through the point of intersection of the neutral beam center line with the reflector surface.

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Figure 2 shows the experimental results obtained with positive and negative cluster ions, and with neutral clusters for comparison, under otherwise identical conditions. Here, the intensity i is determined as the time integral of the measured time-of-flight signal of the cluster ions. It is normalized to

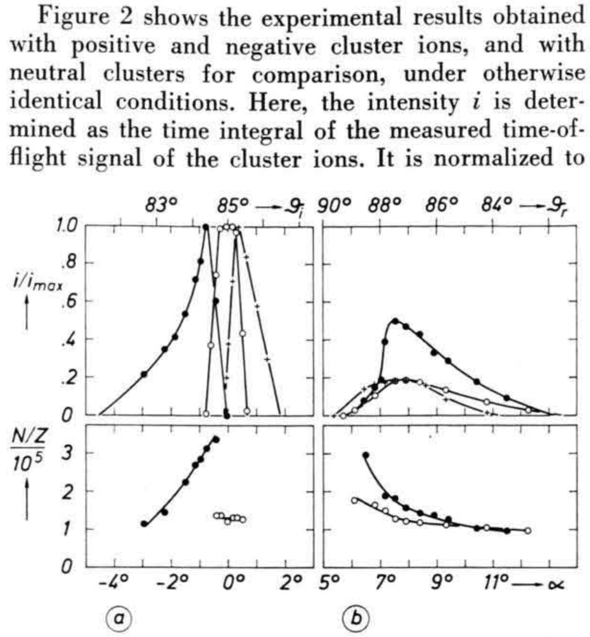

Fig. 2. Angular profiles of the normalized intensity i/i_{max} and of the effective cluster size N/Z in molecules per elementary charge for (a) the incident and (b) the reflected beams of hydrogen clusters. Black dots: positive cluster ions; empty circles: neutral clusters; crosses: negative cluster ions.

the maximum value of the respective incident beam, i_{max}, which for positive cluster ions amounts to 3%, for negative cluster ions to 2%, of the maximum value measured with the neutral clusters after ionization in the analysing system. N/Z is the approximate mean specific cluster size, as measured by the accelerating-field time-of-flight technique [9], with N denoting the number of molecules and Z the number of elementary charges per cluster. The angle α measures the rotation of the analysing system from the center line of the incident neutral beam.

The experimental data show that in fact cluster ions can be reflected at polished stainless steel just as well as neutral clusters. The measured angular profiles of the normalized intensity and of the mean cluster size are quite similar for the reflected beams of charged or neutral clusters. For negative cluster ions, no N/Z data are presented because the intensities are too low for reasonable size evaluations. However, the order of magnitude of the size of the negative cluster ions is the same as that of the positively charged or of the neutral clusters.

The observed differences of the incidence angles, depending on the polarity of the cluster charge and on the cluster size, can be reduced to the existence of an unwanted electric field in the ionizer arising from surface coating and subsequent charging, which is largely due to the only weak magnetic guidance of the ionizing electrons, used in order to avoid magnetic deflection of the cluster ions. The ϑ_i-scale of Fig. 2 a refers to directions of incidence originating from the ionizer. For the neutral beam, this scale has to be replaced by $\vartheta_i = 0.58\,\alpha$ as its divergence originates from the nozzle.

The observed decrease of the mean size of the reflected neutral clusters with decreasing angle of reflection ϑ_r has already been explained earlier as a separation of incident clusters of different sizes due to the reflection process [7]. The enhanced separation observed with the positive cluster ions seems plausible in view of the increasingly steeper incidence of cluster ions of decreasing size which results from the mentioned electrical mass separation of the incident cluster ions.

Most unexpectedly, the normalized reflected intensity is markedly higher for positive cluster ions than for neutral clusters. The ratio of the angular intensity integrals of the reflected and of the incident beam is 0.93 for positive cluster ions, 0.68 for neutral clusters, and 0.60 for negative cluster ions. As the intensity is actually the electric current carried by the clusters after ionization, the higher reflected intensity of positive cluster ions could be due to ionization at the reflector of electronically excited metastable clusters. This process can be disregarded, however, because no ion signal is found if the ionized clusters are electrically deflected out of the beam in front of the reflector.

On the other hand, the effective cluster size N/Z of the positive cluster ions decreases much stronger during the reflection than that of the neutral clussters. Weighting the measured effective cluster size by the appropriate intensity, one can determine an average effective cluster size for the different angular beam profiles. It amounts to 1.3×10^5 molecules per elementary charge for the incident, and to 1.2×10^5 for the reflected, neutral cluster beam after ionization in the analysing unit. The slight decrease of the average N/Z is thought to be due to a reflection induced decrease of the average number of molecules per cluster, N, and has already been reported earlier for reflector temperatures somewhat higher than the optimum reflector temperature [7].

The average effective cluster size of the positive cluster ions, however, decreases during the reflection from 2.4×10^5 to 1.5×10^5 molecules per elementary charge. If the average N decreases only as much as observed with neutral clusters an increase of the average Z by a factor of about 1.5 has to be assumed. This additional ionization provides just somewhat more ion current than necessary to explain the factor of 1.4 by which the normalized reflected intensity of the positive cluster ions exceeds that of the neutral clusters. We therefore conclude that cluster ions can be reflected at polished stainless steel practically like neutral clusters but tend to get higher positively charged, presumably by losing electrons which have been previously excited during the electron impact ionization.

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