The role of collisions for beam formation in a plasma potential gradient.

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The formation of a beam in the expanding region of inductively coupled helicon type plasma was first observed by Charles and Boswell [1]. Such beams have later been actively investigated and are generally understood as being formed by a so-called current-free double layer (CFDL) [2, and references therein]. Most theoretical works, e.g. [3] have focused on explaining the formation of the CFDL.

In this report, we study the formation of an ion beam in the expanding plasma of the Njord device [4]. We investigate how energy-dependent collisional cross-section may form a beam in the downstream plasma, by calculating the development of the initial ion energy distribution from a semi-empirical model of the total and charge-exchange cross-sections given by [5].

The Njord device has a plasma source similar to that of Chi Kung, used in [1], with a Boswell type saddle antenna coupling the 13.56 MHz, 1000 W RF power through a 30 cm long and 13.5 cm wide Pyrex tube, to an argon gas at 2.8 mTorr pressure. Two magnetic field coils, 10 cm wide are placed 10 cm apart outside the antenna, providing a maximum of 20 mTesla in the source. A third coil placed at z= 60 cm (with origo at the outer edge of source coils, provides a small magnetic field of abut 5 mTesla at z = 50 cm. In this experiment, we used a retarding field energy analyser (RFEA), as described earlier [4], with the modification that for axial measurements the analyser was modified to point forward along the axis of the probe rod. Also, switching the position of the retarding and discriminator grids proved favourable with respect to the probe resolution. Plasma potentials from emissive probe (EP) measurements were obtained as the floating potential of the probe at a filament current where the emissive current was comparable to the electron saturation current.

Shown in Figure 1 are axial potential profiles within and immediately downstream of, the inductively coupled helicon source of the Njord device, as obtained by both emissive probes and a retarding field energy analyser. Measurements with the EP could be obtained nearly 2/3 into the source due to lightweight probe and rod, while RFEA measurement could be obtained only from the entrance of the source and outwards into the downstream plasma. From the EP potential profile, it is seen that an inhomogeneous plasma potential in the production region inside the source may give rise to the wide energy distribution emerging from the end of the source, as measured with the RFEA. This is in agreement with similar behaviour reported elsewhere [6]. It is also seen that the beam is formed from within the boundaries of this distribution, which has been reported earlier [7].

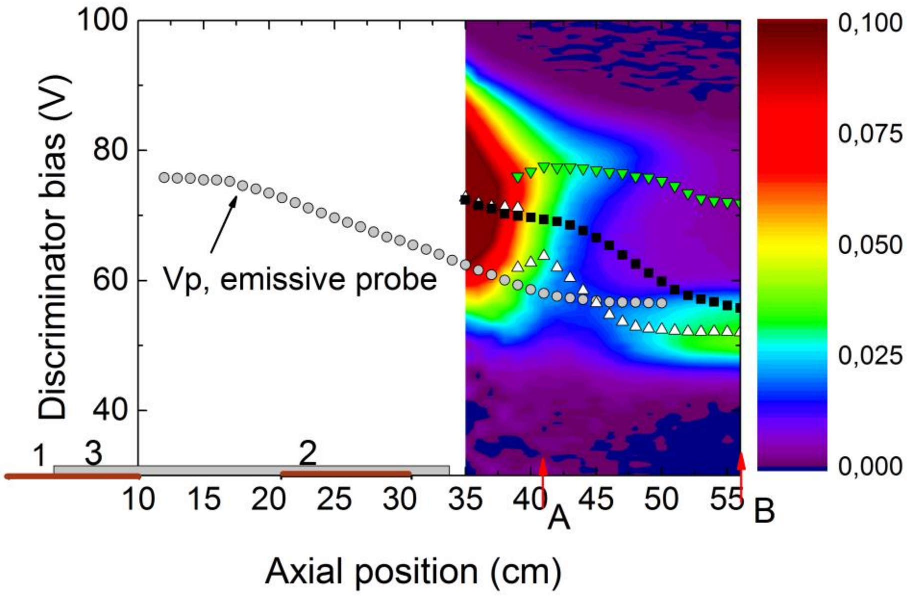

Figure 1. Axial potential structure, as measured with the emissive probes (grey circles), and from the centre of mass (CM) of the RFEA distribution (black squares). Beam potentials (green inverted triangles) and background potentials (white triangles) from Gaussian fits are also shown. Colour contour plot shows the ion energy distributions obtained by the RFEA. 'A' indicates the axial position of the port-dome intersection and 'B' indicates the position of radial probe ports. The brown thick lines on the x-axis labelled '1' and '2' mark the positions of the source field coils, and the grey thick line labelled '3' marks the position of the Pyrex source tube.

Position of beam appearance depends on energy resolution of the RFEA and fitting procedure. In our case, the beam appears only near the end of the V_p drop measured by the emissive probe. The potential drop in CM of the distribution occurs after the appearance of the beam in the fitted data, possibly because the RFEA measures flux from the source, while the EP potential is not directional. The potential drop of the fitted cold distribution coincides better with the formation of the beam and has a larger gradient. Thus, within the plasma flow from the source, a rather large discrepancy between the different potential measurements is apparent. On the other hand, the potentials converge in the non-flowing cold plasma created by charge exchange.

The ion energy distribution emerging from the source at z = 35 cm, forms the starting distribution for an experimentally based model to investigate how this distribution is affected by downstream momentum and charge-exchange collisions in order to investigate their role in forming an ion beam further downstream. A simple model of collision cross-sections as a function of energy difference between ions and neutrals is obtained by a nonlinear fit to experimental momentum and charge-exchange collisional cross-sections for argon given by [5]. At smaller energy differences, the momentum collision cross-section increases such that collisions between particles of similar energy lead to larger loss of ions from the source plasma and to more effective production of downstream plasma by charge-exchange collisions. From the data sets reproduced in [8], we obtained for the sum of charge-exchange and momentum collision cross-sections, which result in loss of ions from the plasma originating from the source, a power-law function $\sigma_t = 91.9 \cdot V^{-0.141}$. For charge exchange collisions only, resulting in production of downstream, low-temperature plasma, the polynomial

$$\sigma_{cx} = 40.88 - 1.42285V + 0,05458V^2 - 0.00101V^3 + 8,66797e-6V^4 - 2,79539e-8V^5$$

provided a good fit to the data set. Here V is the energy (in eV) taken from the origo in the CM of the distribution.

The remaining ion flux after a distance z, considering only particle loss, is given as $\Gamma(z,V) = \Gamma_0 \cdot \exp(-z/\lambda_{mfp}(V))$, where $\lambda_{mfp}(V) = (n_g \sigma(V))^{-1}$, and Γ_0 is the initial, measured ion energy flux from the source at z = 35 cm. Ion flux transformed into neutrals is $\Gamma_{chx}(z,V) = \Gamma_0 \cdot [1 - \exp(-z/\lambda_{cx}(V))]$. Total number of particles in this flux is the same as the total number of ions created as a Gaussian distribution of cold ions. Downstream ion-flux to the probe, created by charge-exchange collisions, is thus modelled as $\Gamma_c(z,V) = \frac{\Gamma_{chx0}(z)}{2w\sqrt{2\pi}} \cdot \exp(-2(\Delta V)^2 / w^2) \exp(-z/\lambda_{cx}(V)) \cdot 0.146$,

where $\Gamma_{chx0}(z) = \int_{V_{min}}^{V_{max}} \Gamma_{chx}(z,V)\,dV$ and $\Delta V = V - V_p$ (z = 0.56 m). The resulting, total distribution is then given as $\Gamma_{tot}(z,V) = \Gamma(z,V) + \Gamma_{chx}(z,V)$. One should note that to compensate for the energy resolution of the RFEE [9] versus the actual thermal energy of the ions measured by Laser Induce Fluorescence diagnostics of the cold ion distribution, the energy axis was multiplied by a factor 0.02. Furthermore, to compensate for the fact that charge-exchange collisions produce ions moving in arbitrary directions and that the RFEA samples a partial flux constrained by an opening angle of 90^o, the total number of ion produced was multiplied by the factor of 0.146, the resulting ratio between the unit area covered by the opening angle and a full view over the 4π solid angle. Figure 2 displays the axial development of the resulting modelled distribution. The calculated normalised ion distributions with loss only, shown in figure 2 a), display how the asymmetric loss develops in the model. The dip in the middle develops where the potential of the CM is nearly constant. This is not seen in the axial development of the experimental distributions. Nevertheless, the qualitative features of the total distribution show similarities with the experimental, both in the development of a weak downstream beam structure and the cold downstream plasma.

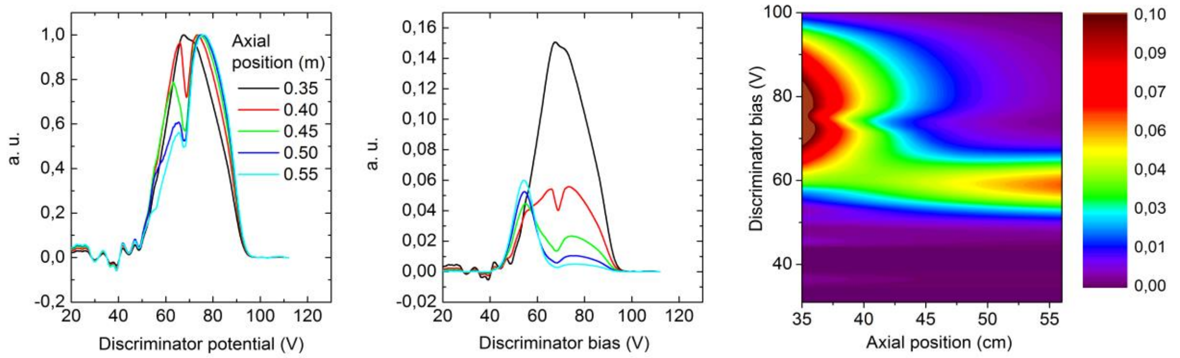

Figure 2. a) Modelled normalized ion distribution with loss only and b) total modelled distribution at different axial position, and c) colour-contour plot of modelled total distribution.

In conclusion, we find indications that collisions between particles of nearly the same energy within the bulk of the distribution may result in a non-symmetric bite-out of the distribution. Hence the high-energy part can survive as a beam and the less energetic part of the distribution undergoes a faster loss and participates in the formation of downstream plasma by charge-exchange collisions. With better energy resolution of the measurements of the ion distributions and more accurate model, the quantitative agreement is likely to improve.

References.

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