J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 163–166

A Computational Model for He^+ Ions in a Magnetized Sheet Plasma: Comparative Analysis between Model and Experimental Data

BLANTOCAS Gene Q.[1], RAMOS Henry J. and WADA Motoi[2]

National Institute of Physics, College of Science, University of the Philippines, Diliman Quezon City 1101, Philippines

[1] West Visayas State University, Lapaz, Iloilo City 5000, Philippines

[2] Department of Engineering, Doshisha University, Kyoto 610-0321, Japan

(Received: 11 December 2001 / Accepted: 12 July 2002)

Abstract

An E×B probe was used to extract He^+ ions from a magnetized steady state sheet plasma. Plasma parameters T_e, n_e and extracted He^+ ion current were analyzed vis-à-vis a modified Saha population density equation of the collisional-radiative model. Numerical calculations show that at low discharge currents and in the hot electron region of the sheet plasma, relative densities of He^+ ions show some degree of correlation with ion current profiles established experimentally using the E×B probe. Both experimental and computational results indicate a division of the plasma into two distinct regions each with different formation mechanisms of He^+ ions.

Keywords:

sheet plasma, E×B probe, collisional-radiative model, MSPDE - modified Saha population density equation

1. Introduction

The collision and capture processes of He^+ ions with other charged particles play vital roles in the study of astrophysical phenomena and in fusion and beam transport research [1]. In this work, He^+ ions were extracted using an E×B probe from a magnetized sheet plasma ion source (MSPIS). In most researches He^+ ions were extracted from multicusp sources. This report furnishes new insights to He^+ ions produced in sheet plasmas. Experimental data were analyzed vis-à-vis a modified Saha population density equation (MSPDE) of the collisional-radiative (CR) model, providing an alternative physical representation of He^+ particle distribution in the sheet plasma. In contrast with direct measurements of the E×B probe, the MSPDE method offers a choice of numerical and diagnostic simplicity.

2. Experimental Set-Up and Principles of the Method

A schematic diagram of the MSPIS facility is shown in Fig. 1, while that of the E×B probe is shown in Fig. 2(a). A representative He^+ peak detected by the probe is shown in Fig. 2(b). Detailed descriptions of the ion source and the E×B device are found in refs. [2,3]. Base pressure was typically in the order of 1×10^{-6} Torr. Helium gas at 0.02 Torr fed into the production chamber diffused into the extraction chamber via a small aperture between limiters E_1 and E_2. The existence of a pressure gradient between these two regions facilitated the diffusion process. The initial gas filling pressure in the extraction chamber before discharge was 0.002 Torr. A potential of 20 V (V_4) was applied across the hot cathode assembly, with corresponding filament current

Corresponding author's e-mail: plasma@nip.upd.edu.ph

ranging from 20 to 25 A. Energetic electrons emitted from the filament are further accelerated by the fields of V_1 (90–120 V) and V_2 (100V), ionizing helium neutrals thereby generating helium plasma in the extraction region. The cylindrical plasma initially formed is compressed into a sheet configuration by a pair of strong Sm-Co dipole magnets (~1.5 kG). The plasma discharge current I_d in the extraction region was varied from 1.5 to 4.5 A by increasing V_1 from 90 to 120 V. Experimental parameters such as electron temperature T_e, density n_e and He^+ ion current were measured by the Langmuir and E×B probes at locations orthogonal to the sheet plasma. These data were investigated using the MSPDE of the CR model. It is a model for optically thin plasmas of moderate density where the loss mechanism results from the combination of interacting collisional

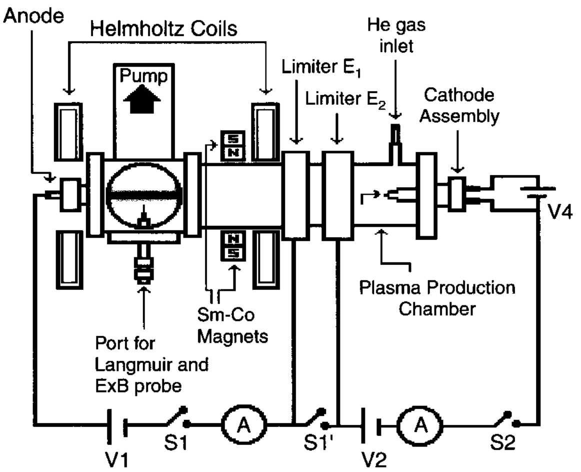

Fig. 1 Schematic diagram of the Magnetized Sheet Plasma Ion Source

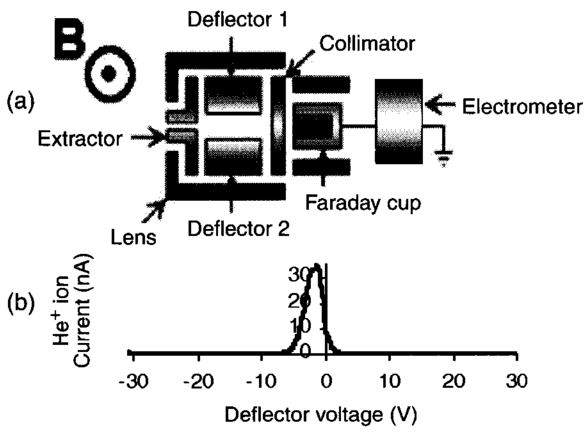

Fig. 2 (a) Schematic diagram of the E×B probe. (b) Typical signal peak of He^+ detected by the probe.

and radiative processes. One of the salient features of the model is that for hydrogenic ions at levels above the ground state, the probability of collisional processes becomes greater while that of radiative processes becomes smaller. Hence there is always some level above which the effect of radiative processes is negligible. Under these circumstances a modified form of the Saha equation can be used to evaluate the population densities of upper level hydrogenic ions. [4]. The equation in its generalized form is given by $N_{Z-1}(p) = 1/2\omega_{Z-1}(p)/\omega_Z(g)N_Z(g)n_e[h^2/(2\pi mKT_e)]^{3/2}$ exp $[E_p(p)/KT_e]$, where $N_{Z-1}(p)$, $N_Z(g)$ are the number densities of hydrogenic ions in the quantum level p and bare nuclei in the ground state, $\omega_{Z-1}(p)$, $\omega_Z(g)$ are the statistical weights of hydrogenic ions and bare nuclei in their designated levels, $E_p(p)$ is the ionization potential of a hydrogenic ion in its quantum level p, K is Boltzmann Constant, m, T_e and n_e are electron mass, temperature and density, respectively. For hydrogenic ions, the energies depend only on the principal quantum number hence the statistical weight can be substituted by $2p^2$. Bare helium nuclei, because of the absence of valence electrons, are considered to have single quantum states hence the weight factor is taken as unity. Imposing the condition of macroscopic neutrality such that $n_e \approx zN_z$ and replacing E_p(p) by E_H/p^2 where E_H is the ionization potential of hydrogen; the final expression for the MSPDE takes the approximate form: $N_{Z-1}(p) = p^2n_e^2/z[h^2/(2\pi mKT_e)]^{3/2}$ exp $[E_H/(p^2KT_e)]$. Substituting plasma parameters T_e, n_e in the MSPDE at each data point for each discharge current used and numerically varying the values of p in a stepwise permutation from 1 to 30, yields density plots of He^+ ions as functions of distance from the sheet plasma core. The density plots (MSPDE curves) are then compared with the experimental curves of extracted He^+ ions (E×B probe curves) to see whether or not some degree of correspondence exists between them.

3. Results and Discussion

Investigations were conducted to establish the spatial distributions of T_e and n_e (Figs. 3(a) and (b)) and current profiles of He^+ ions (Fig. 4(a)) by successively positioning both Langmuir and E×B probes at various distances from the sheet plasma core using three different plasma discharge currents (I_d), viz, I_d = 1.5 A, 3 A and 4.5 A. The probe's extraction voltage was set at 65 V; this is the calibrated potential that limits the extraction of He^+ ions only. The calibration of the probe was reported in ref. 3. Values of p from 1 to 30 were permuted 3 at a time. Each value of p for all possible sequence, together with T_e and n_e values corresponding to each discharge current used were substituted into the MSPDE to calculate the density profiles of He^+ ions, Fig. 4(b). However, calculations were discontinued at p values above 30 since beyond this limit, pronounced differences with the spatial curves of Fig. 4(a) are seen, as shown in one of the density plots for excited He^+ ions, Fig. 5. At the p value of 2 for I_d current 1.5 A, experimental and calculated curves showed unequal but correlated values except at the periphery (7 cm) where slight dissimilarities are manifested (Figs. 4(a) and (b)). This could be ascribed to some wall effects. At p values of 3 and 4 for I_d currents 3 and 4.5 A respectively, slight disagreements are seen. These differences are likely caused by the presence of doubly excited metastable states of helium atoms (He^{**}) which decay through radiationless transition into ground state He^+ ions through: $He^{**} \rightarrow He^+(1s) + e$. The probe detects $He^+(1s)$ ions but they are not captured in the MSPDE curves because of the built-in constraint that it is only applicable to upper level He^+ ions. Experimental and calculated curves show that ion concentration increases steadily from the center reaching an optimum value, and then gradually tapers off at the peripheral region of the plasma, where cold electrons are predominant. These low energy electrons with low thermal velocities have a higher probability of being captured in the recombination process involving He^{++} to form He^+: $He^{++} + 2e \rightarrow He^+ + e$. Hence a higher concentration of He^+ is observed within this vicinity. The set of coupled differential equations linking both collisional and radiative processes in the CR model need not be actually solved, since only a representative plot of ion concentrations in the direction transverse to the sheet plasma core is desired. It is necessary only to note that the MSPDE can be applied to states above the ground level where radiative processes become quite insignificant. The MSPDE is an exponential function of the ionization potential $E_p(p)$ which in turn is inversely proportional to p^2. Hence, implicit in the equation, the

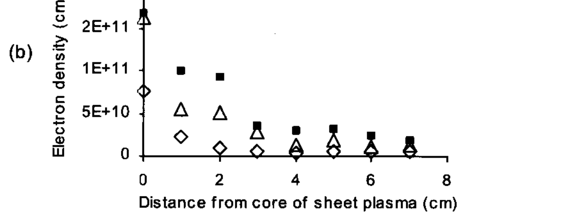

Fig. 3 Spatial configurations of electron (a) temperatures and (b) densities of the sheet plasma at discharge currents I_d = 1.5, 3 and 4.5A.

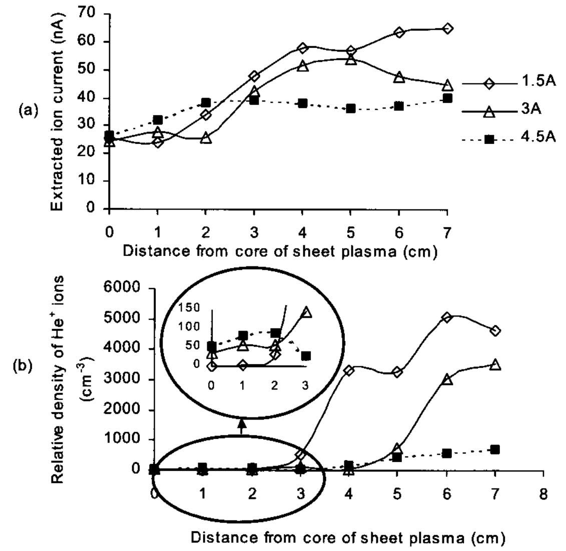

Fig. 4 (a) He^+ ion current profile in the sheet plasma as detected by the E×B probe using the three plasma discharge currents I_d = 1.5A, 3A and 4.5A. (b) Relative density profile of He^+ corresponding to the three I_d's calculated using the MSPDE of the CR model. (Inset) He^+ density profile in the hot electron region i.e., from the center (plasma core) up to 2cm away perpendicular to the sheet.

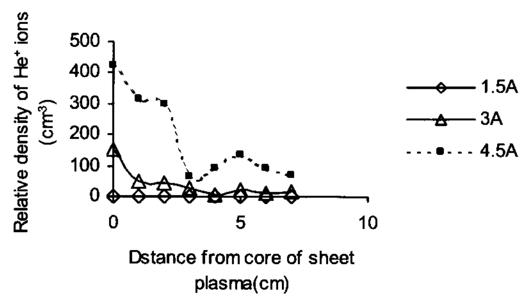

Fig. 5 Relative densities of He^+ ions calculated using the MSPDE at large values of p (i.e., p = 10, 20 and 30 for I_d = 1.5, 3 and 4.5 A respectively). The same plasma parameters were used as in Fig. 4(b).

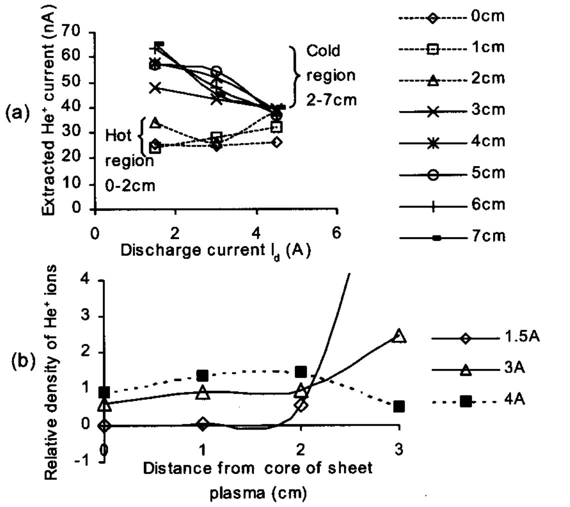

Fig. 6 (a) He^{+} yield as a function of the discharge current I_d, the plots represent the position of the probe with respect to the plasma core. (b) Relative density profile of He^{+} ions in the hot electron region (0–2 cm away orthogonal to the plasma core) at the same discharge currents. The plots were calculated using the MSPDE.

density of He^{+} is a decreasing function of the quantum level (p level) it occupies. He^{+} ions produced at high plasma discharge currents are more energetic, thus they occupy relatively higher quantum levels than those produced at lower discharges. The production of He^{+} from He^{++} at high discharge currents proceeds at a slower rate. Hence, a much lower flux of He^{+} ions is detected at high discharge conditions. The relationship between He^{+} yield and discharge current shown in Fig. 6(a) indicates a division of the sheet plasma system into two distinct regions each with different formation mechanisms of He^{+} ions. In the region comprising cold (slow) electrons from 2 to 7cm, the production of He^{+} is done more effectively through low discharge currents. In this region, the main formation mechanism of He^{+} ions is through the electron-ion recombination channel: $He^{++} + 2e \rightarrow He^{+} + e$. On the other hand, the opposite applies to the hot (fast) electron region, i.e., from the center up to 2 cm away, it is seen that, to affect a significant increase in He^{+} yield, high discharge currents are necessary. In this region, the main formation mechanism of He^{+} is through electron impact collisions: $e + He \rightarrow He^{+} + 2e$. In this particular region, higher discharges are essential to strip helium neutrals of their bound electrons. This in turn translates to a modest increase in He^{+} yield. This assertion is further substantiated by the density curves in the hot electron region using the MSPDE (Fig. 6(b) and inset of Fig. 4(b)). The plot supports the fact that indeed high discharges are needed here to increase He^{+} ion concentration.

4. Conclusions

The MSPDE is valid at very low discharge currents, numerical calculations of the density curve (plot of $I_d = 1.5$ A in Fig. 4(b)), albeit crude, bear a certain degree of correlation with the experimentally measured spatial distributions of He^{+} ions (plot of $I_d = 1.5$ A in Fig. 4(a)). This is actually the condition for a quiescent steady state sheet plasma at optimum He^{+} extraction. Secondly, the MSPDE has also captured the hot electron region of the sheet plasma; there is strong correspondence here between experimental observation (hot electron region of Fig. 6(a)) and numerical calculations (Fig. 6(b)). Thirdly, MSPDE curves show that the number density of He^{+} ions is much smaller than the number densities of free electrons and bare nuclei He^{++}; the predominance of He^{++} species has been experimentally demonstrated in ref. 3. Subsequently, a theory for He^{+} formation mechanism in the sheet plasma was formulated. These findings have established the set parameters as bases for future enhancement and beam conversion of extracted He^{+} from the sheet plasma source. Modifications of the facility for this purpose are now ongoing.

References

[1] D.E. Post *et al.*, Fusion Technol. **1**, 355 (1987); M. Sasao *et al.*, ibid **10**, 236 (1986).
[2] Y. Abate and H. Ramos, Rev. Sci. Instrum. **71**, 3689 (2000).
[3] G. Blantocas, H. Ramos and M. Wada, Rev. Sci. Instrum. **73**, 976 (2002).
[4] Huddlestone *et al.*, *Plasma Diagnostic Techniques*, (Academic Press, New York, 1965).