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Analysis of dielectric properties of atmospheric-pressure negative ion plasmas
大気圧負イオンプラズマ現象の誘電特性解析

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In the ambient air around us, collective phenomea mainly composed of positive and negative ions may exist, and we refer to it as "atmospheric-pressure negative ion plasma" hereafter. Unlike collisonless negative ion plasmas and ionic plasmas, the charged particles in an atmospheric-pressure negative ion plasma suffers heavy collisions against neutral particles in the air, and its collective properties might much different from classical understandings of the plasmas. Dielectric properties as well as transport parameters are derived theoretically and numerically, and new findings on its behaviors are addressed.

1. Introduction

Plasma sources in non-thermal states at atmospheric pressure in the ambient air have attracted much attention since they do not require huge vacuum systems for conventional fabrication processes in the semiconductor industry. Recently, in addition to this point, reaction fields induced by such plasmas in or on liquids are a new emerging area of plasma engineering. Also plasma-biomaterial interaction is a very promising research target since plasmas have not been able to access it when they are generated at low pressure.

In our recent report [1], we measured lifetime of electrons in the non-thermal atmospheric pressure. In the similar condition to the ambient air, they survive, at most, for 1 μs. Addition of oxygen to nitrogen lessens their lifetime, partly because electrons attach oxygen molecules, resulting in negative ion formation. However, after that, negative ions and remaining positive ions have much longer lifetime when we assume that their losses are attributed to recombination. As we will mention later, although their densities are not so high, they can survive for seconds or more, and we refer to such a state as "atmospheric negative ion plasma" or "atmospheric ionic plasma."

When we consider their governing equations, we will notice that their transport properties are much different from those of the classical plasmas, since they are collisional and they have a number of mass spectra. In this report, we demonstrate their significant features stressed in their unusual conditions that have not been investigated so far.

2. Theoretical Prediction

Starting point of theoretical analysis on the atmospheric-pressure negative ion plasmas are momentum balance equation, given as

$$\begin{aligned} &M_{\alpha=\mathrm{p,m},\, i=1,2,3,\ldots} n_{\alpha i} \frac{\partial \boldsymbol{v}_{\alpha i}}{\partial t} \\ &= n_{\alpha i} q_{\alpha i} \boldsymbol{E} - \nabla p_{\alpha i} - M_{\alpha i} n_{\alpha i} \boldsymbol{v}_{\alpha i} \nu_{\alpha i \mathrm{g}} \end{aligned} \qquad (1)$$

where M is the mass of an ion, n is its density, $\boldsymbol{v}$ is its fluid velocity, q is its electric charge, p is its pressure, ν_{g} is its elastic collision frequency, n is the electric field, and t is the time. The subscript α denotes positive ion ("p") or negative ("n") ion, and the subscript i is the sequential number of ions with different mass numbers. That is, we have to solve a number of equations, expressed in Eq. (1), for each ion species.

At the first glance, the set of equations based on Eq. (1) are not summarized in the Drude model, although there is certainly frequency dependence. The second point we will notice that the dielectric constant deduced from the set of the equations are not linear. These two points indicate that the dielectric properties are much different from the conventional dielectric functions for usual plasmas composed of electrons and positive ions.

3. Numerical Results

We performed numerical analysis based on the fluid model; from the original numerical code [2], we replace electrons by negative ions, and we assumed that negative ions have similar mass to positive ions (Xe^+) with negative charge. We also set suitable recombination coefficient between positive and negative ions at atmospheric pressure [3].

Assuming certain initial density profiles, we obtain their decaying properties. First of all, when we assume that negative ions are only present, the lifetime of the ions is quite short; no ions are detected after 0.1 s. On the other hand, when we assume that uniform and equal density profiles for both ions as initial states, we observed quite long lifetime; for atmospheric–pressure negative ions with densities ranging from 10^5-10^6 cm^{-3}, the lifetime is several seconds. During such a long lifetime, the ions can drift outwards to get touch with other boundaries, such as solids, liquids, and biomaterial surfaces. Some modification of the numerical results indicates that this losses of ions are mainly attributed to recombination in the space, not to transport to the wall boundary.

4. Conclusion

A regime of the collective motions by negative ions and positive ions is described theoretically. The features will lead to new understandings of the plasma-related phenomena, and may reveal unknown effects induced by atmospheric-pressure plasmas.

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