

# PLASMA-STRUCTURE FORMATION DUE TO A LOCAL PRODUCTION OF HUGE NEGATIVE IONS

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## Abstract

A Q-machine experiment and a particle simulation show that a novel plasma structure is formed due to a local production of huge negative ions. The local production triggers the generation of a two-stream instability of positive and negative ions, which leads to a double-layer formation around the center of the production region. This double layer intermittently generates propagating solitary waves with negative potentials.

## 1. Introduction

In recent years there has been growing attention in phenomena in space, fusion-oriented, and materials-processing plasmas [1] with fine particles (particle diameter  $\leq 10 \mu\text{m}$ ) and dust ( $\leq 100 \mu\text{m}$ ). As these huge particles are often negatively charged in a plasma, it is of considerable interest to investigate effects of the negative ion production on microscopic and macroscopic plasma structures.

So far most of the investigations using basic laboratory plasmas have been concerned with clarification of characteristics of low-frequency plasma waves and instabilities in plasmas including negative ions. They have mainly been carried out by using a gas of  $\text{SF}_6$  (sulphurhexafluoride gas, mass number  $\simeq 146$ ) particles as a negative ion source in the experiments [2] where production regions of negative ions are widely distributed over the devices because of the neutral gas diffusion. In this work,  $\text{C}_{60}$  (fullerene, mass number  $\simeq 720$ ) particles, which are large cage-like molecules composed of 60 carbon atoms, are used as a negative ion source.  $\text{C}_{60}$  particles (particle diameter  $\simeq 7 \times 10^{-4} \mu\text{m}$ ) belonging to ultrafine particles are much smaller than usual fine particles, but are much larger than positive ions  $\text{K}^+$  (potassium, mass number  $\simeq 39$ ) in our plasma [3]. Huge negative ions  $\text{C}_{60}^-$  are locally produced in the plasma column as a result of sublimation characteristic and large electron affinity (2.65 eV) of the  $\text{C}_{60}$  particles. Resultant plasma structures have been investigated by a laboratory experiment and a particle simulation [4].

## 2. Experimental apparatus and simulation model

The experiment is performed in a single-ended Q machine with a vacuum chamber of 15.7 cm in diameter and 400 cm long, as shown in Fig. 1(a). A plasma consisting of electrons and positive ions  $\text{K}^+$  is produced by contact ionization of K atoms on a hot tungsten plate (4 cm in diameter) under the electron-rich condition. The plasma of density  $n_p \simeq 5 \times 10^9 \text{ cm}^{-3}$  and electron temperature  $T_e \simeq 0.2 \text{ eV} \geq T_+$  (positive-ion temperature) is confined radially by a magnetic field (3kG), being terminated by an endplate situated at a distance of  $z = 175 \text{ cm}$  from the hot plate. The hot plate is grounded and the endplate is kept at a floating potential.  $\text{C}_{60}$  particles are injected from the sidewall in the direction toward the plasma and locally distributed in  $45 \leq z \leq 55 \text{ cm}$ . Thus huge negative ions  $\text{C}_{60}^-$  are locally produced there as a result of electron

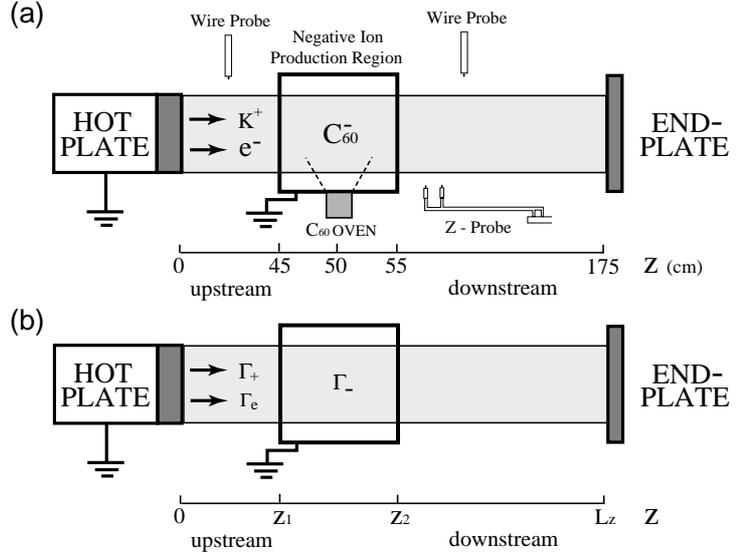
attachment. Most of plasma parameters are measured by movable Langmuir and ion-sensitive probes.

A computer simulation is performed by means of a one-dimensional electrostatic particle simulation code which is based on a Q-machine configuration. The simulation model is schematically shown in Fig. 1(b). A grounded electrode as a plasma emitter is placed at  $z/\lambda_{Ds} = 0$ , and a floated electrode as a plasma terminator is placed at  $z/\lambda_{Ds} = 511$ . All results are obtained with the time step  $\omega_{ps}\Delta t = 0.2$ . Here,  $\lambda_{Ds}$  and  $\omega_{ps}$  are the Debye length and the electron plasma frequency defined by using the plasma source parameters, respectively. The positive ion to electron mass ratio is fixed to be  $m_+/m_e = 400$ . The ratio of the emitted electron to positive ion flux is  $\Gamma_{es}/\Gamma_{+s} = (m_+/m_e)^{1/2} = 20$ , yielding the electron-rich condition.

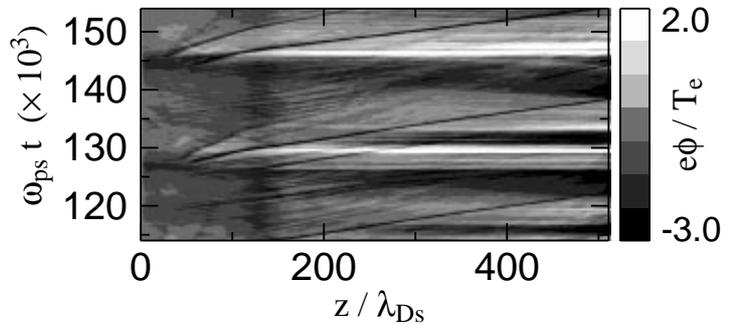
In a localized region of the plasma ( $z_1 \leq z \leq z_2$ ,  $z_1 = 80\lambda_{Ds}$ ,  $z_2 = 180\lambda_{Ds}$ ), some of electrons attach to  $C_{60}$  particles, and are replaced by negative ions in the way that a total momentum is conserved. The negative ion to electron mass ratio is fixed to be  $m_-/m_e = 7360$  by taking the experimental value of  $m_-/m_+ = 18.4$  into account. The spatial distribution of the  $C_{60}$  particles are assumed to be Gaussian, and the velocity distribution is Maxwellian with the  $C_{60}$  particle to electron temperature ratio  $T_{c60}/T_e = 0.29$ . For simplicity, the number of negative ions produced per a unit time  $N_-$  is assumed to be proportional to the number of electrons  $N_e$  in the negative ion production region ( $z_1 \leq z \leq z_2$ ), and is represented by  $N_- = \gamma N_e$ , where  $\gamma$  is the negative ion production rate. In this paper, we present the result of one typical case with  $\gamma = 3.7 \times 10^{-4}$ .

### 3. Simulation results

Figure 2 shows the space-time distribution of the potential  $\phi$  during  $\omega_{ps}t = 114 \sim 154 \times 10^3$  in the case of negative ion production. It is found that a pulse of negative ion density is intermittently generated by a strong two-stream instability of positive and negative ions at  $\omega_{ps}\tau \sim 16000$  in the upstream region ( $z/\lambda_{Ds} \sim 60$ ), propagating



**Figure 1.** Schematic diagram of experimental setup (a) and simulation system (b).

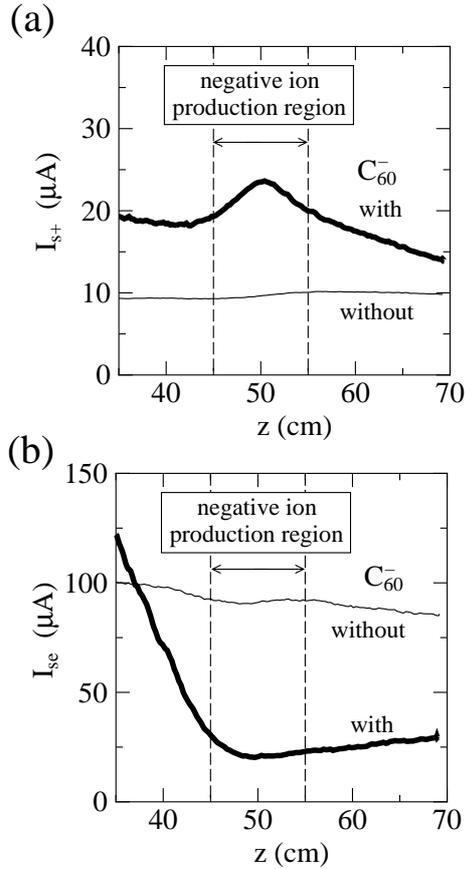


**Figure 2.** Space-time distribution of the potential during  $\omega_{ps}t = 114 \sim 154 \times 10^3$ .

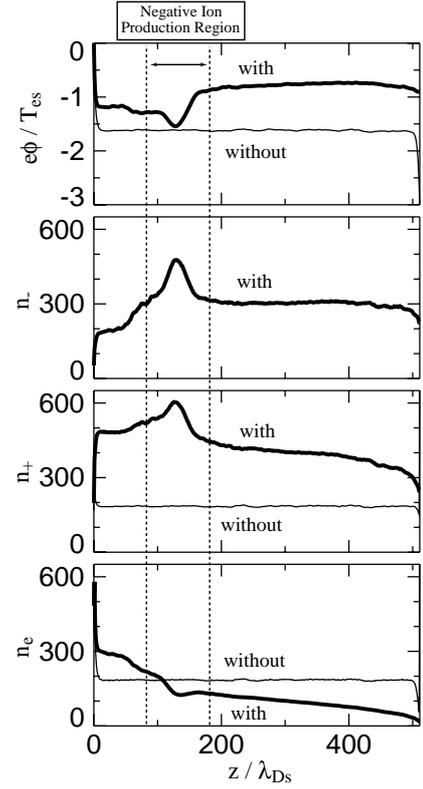
to the negative ion production region. When the pulse arrives at the center of the production region ( $z/\lambda_{Ds} \sim 130$ ), a double layer with large potential difference is formed due to reflection of electrons.

Negative ions are strongly accelerated by the double layer and a large-amplitude pulse of negative ion density is created by their bunching. The potential profile in the negative ion-rich region becomes depressed ( $d^2\phi/dz^2 > 0$ ). The large-amplitude ( $e\Delta\phi/T_{es} \sim 2$ ) solitary wave with negative potential generated in such a way propagates toward the downstream region with speed  $v_{ph}/v_{the} \sim 4.7 \times 10^{-2}$ .

Spatial profiles of potential  $\phi$  and densities of negative ion  $n_-$ , positive ion  $n_+$ , and electron  $n_e$  are shown in Fig. 3, which are averaged during  $\omega_{ps}t = 11.7 \sim 12.0$  (without negative ions) and  $\omega_{ps}t = 114 \sim 154 \times 10^3$  (with). Since most of the negative ions are produced around the center of the production, huge negative ions



**Figure 4.** Profiles of positive ion (a) and electron (b) saturation currents along magnetic-field lines.



**Figure 3.** Time averaged profiles of potential (top), densities of negative ion (second), positive ion (third), and electron (bottom).

are densely populated there. Positive ions are correspondingly concentrated for shielding out negative charge.

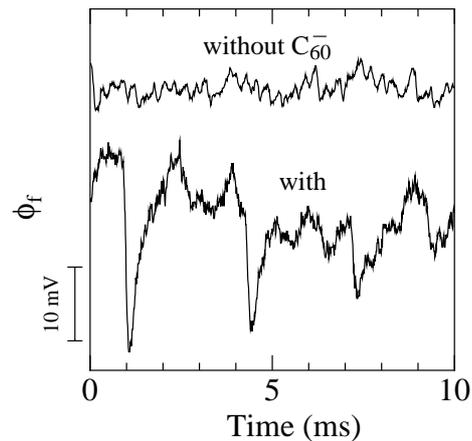
Some of the positive ions and electrons flowing toward the downstream region are reflected by the double layer generated intermittently. This is the reason why the positive-ion and electron densities become higher in the upstream region.

#### 4. Experimental results

Figure 4 gives axial profiles of positive-ion and electron saturation currents of the Langmuir probe at  $r = 0$  cm. Here the contribution of the negative ions to the probe saturation current is negligibly small. The negative-ion density is observed to be higher in the production region because produced negative ions barely diffuse along the magnetic field for its huge mass. Thus the positive-ion density apparently increases and the electron density decreases around the center of the production region.

On the other hand both the positive-ion and electron densities are observed to increase in the upstream region. As already indicated, this phenomenon is considered to be due to the reflection of positive ions and electrons around the center of the production region in the presence of the intermittent formation of a double layer.

Figure 5 shows temporal evolutions of the floating potential of the probe at  $z = 51$  cm and  $r = 0$  cm. Considering the simulation result, observed spiky signals indicate that negative solitary waves are intermittently generated and pass there in the case of  $C_{60}^-$  production.



**Figure 5.** Floating potential of probe as a function of time at  $z = 51$  cm.

## 5. Conclusion

Effects of a local production of huge negative ions on a plasma structure are investigated by means of a Q-machine experiment and a particle simulation. The local production is observed to be accompanied by the subsequent generation of two-stream instability of positive and negative ions, double layer with large potential difference, and propagating solitary waves with negative potentials.

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