ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received - Apr. 25, 1994)

NIFS-282 May 1994

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

Super Ion Acoustic Double Layer

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Abstract

Discovered by a particle simulation is a "super" ion acoustic double layer. The potential jump reaches to a surprisingly large amplitude, which is far beyond the electron thermal energy, say, by more than order of magnitude. An electron beam that gains this energy is generated on the downstream side, of which the spectrum is in good agreement with that of the observed auroral precipitating electrons.

Keywords: Double layer, Open system, Ion acoustic instability,

Aurora, Particle simulation

The ion acoustic double layer was discovered toward the end of 1970's by a particle simulation [1]. This discovery brought forth an idea that the ion acoustic double layer could be a good candidate for the auroral particle acceleration that had long been puzzling in the auroral dynamics. Some years later, satellite and rocket experiments observed electric field phenomena above the auroral ionosphere suggesting the existence of the double layer-like structure [2]. However, there is an essential discrepancy between observations and simulations, namely, that the potential difference of a computer-produced ion acoustic double layer is only of the order of electron thermal energy (< 1 keV) which is not large enough to account for precipitating auroral electrons of the order of 1 - 10keV. Even today, it appears that the mechanism of auroral particle acceleration yet remains to be resolved.

In this paper, we wish to reveal the long time evolution of ion acoustic double layers under a realistic condition where fresh particles are supplied continuously from external agents and nonlinearly disturbed, dirty particles leave the system. In the conventional particle simulation, one usually employs a periodic or a reflecting boundary condition for the particles in order to avoid the dangerous numerical artifacts due to charge imbalance in the discrete space and time domain. In nature, however, unlike a man-made device such as a torus device, it would hardly occur that the same particles periodically circulate from one end to the other of a system, but it is more likely that fresh particles enter into the system and disturbed particles leave from it.

In the auroral magnetosphere-ionosphere system, for instance, the magnetospheric and ionospheric particles are never linked periodically as a matter of fact. Judging from the auroral environment, therefore, the previous simulation model, where the particles leaving from one boundary enter into the system periodically from the other boundary, is far from reality.

In this study we develop a numerical model for an open system in which fresh particles continuously enter into the system and disturbed particles leave the system in a consistent manner without causing any numerical noise [3]. The net incoming particle flux through the upstream boundary is taken to be the same as the net outgoing flux through the downstream boundary. More specifically, at each time step of simulation we count the number of particles (electrons and/or ions) which leave from the simulation box through the upstream and downstream boundaries during the unit time increment. Then, we emit fresh particles into the simulation box through the upstream and downstream boundaries so as to balance the net particle flux of emitted particles and departed particles on the upstream boundary with the net flux on the downward boundary. We also keep the total number of particles in the simulation box.

In the present study we deal with one dimensional system that is in contact with the external plasma sources at the upstream and downstream boundaries. The external plasma sources have such a property that the net particle flux through a boundary, whether upstream or downstream, is kept constant. The electric fields on the upstream and downstream boundaries are assumed to be zero, the electric potential being zero at the upstream and floating at the downstream.

Initially, electrons are distributed in the whole system so as to have a shifted Maxwellian and ions to have a non-shifted Maxwellian. The system size is taken to be $1023\lambda_D$ (Debye length). The drift speed of the shifted Maxwellian electrons, v_d, is 0.6 v_{th}^e (electron thermal speed), the ion-to-electron mass ratio is 100 and the eletron-to-ion temperature ratio is 20. The number of particles of electrons (and ions) per unit cell, which is equal to the Debye length, is 5000, thus, this choice allows us to represent a much more realistic situation than the conventional one where the number is at most 100. We here emphasize that, only by using such a huge number of particles in a unit cell the property of a constant particle flux supplier for an external source has been reasonably satisfied. Typical electron distributions departed through the upstream (x=0) and downstream ($x=1023\lambda_D$) boundaries during the unit time increment, $\omega_{pe}\Delta t = 0.2$, are shown in Fig. 1 ($\omega_{pe}$ is the plasma frequency). By counting the total numbers of the departed electrons through the upstream and downstream boundaries, N_{out}^{up} and N_{out}^{down}, we can inject "fresh" electrons from the boundaries so as to satisfy the following conditions:

$$N_{in}^{up} = \frac{N_0 + N_{out}^{up}}{\sqrt{2\pi}} \int_0^{\infty} \frac{v}{v_{th}} \exp\left[- \frac{(v - v_{drift})^2}{2v_{th}^2} \right] dv$$

$$N_{in}^{down} = \frac{N_{out}^{down} - N_0}{\sqrt{2\pi}} \int_{-\infty}^{0} \frac{v}{v_{th}} \exp\left[- \frac{(v - v_{drift})^2}{2v_{th}^2} \right] dv$$

where N_0 is the given net particle flux per unit time increment from the external source. Examples of injected electron distributions are also shown in Fig. 1. For the ions, we have adopted the reflecting boundary condition for simplicity [4].

In the early phase of evolution (t = 160 τ_{pe}, where $\tau_{pe} = 2\pi/\omega_{pe}$), three weak ion acoustic double layers are generated within the system of 1023 λ_D (see Fig. 2). The structure of each ion acoustic double layer is such that a clear-cut narrow negative potential dip is accompanied by a sudden stepwise rise just behind it. This suggests that the negative dip must be the direct cause of creating the potential jump. This is because drifting electrons are partially reflected back by the negative potential to create an electron void on the downstream side, thereby giving rise to a sharp potential rise behind it. This feature reflects a "triple" layer rather than a double layer and is consistent with Hasegawa and Sato's theory [5].

In the previous simulation [1] the electron current was observed to drastically decrease in association with generation of ion acoustic double layers, indicating the production of anomalous resistivity. In the present simulation, fresh electrons with a constant flux are continuously supplied from an external energy source, hence, the electron current is almost conserved. Accordingly, a net potential difference arises in the system and electrons traversing the system gain energy corresponding to the net potential difference when they leave the downstream boundary. More specifically, the potential exhibits a stepwise jump at each double layer and the overall potential structure becomes a stairs-like structure. Thus, electrons coming from the upstream are accelerated stepwise at each double layer. Similarly, ions coming from the downstream side are accelerated at each double layer. These dynamical and structural features are essentially the same as the previous study [1], except that the potential structure is far noiseless and much clear because of the extremely large number of particles used in the simulation.

A much more striking and unexpected phenomenon observed in the later stage of evolution is the development of a giant stepwise potential structure. The firstly generated weak ion acoustic double layers, which start growing at t $\approx$ 120 τ_{pe}, cannot persist long but are destroyed (t = 200 τ_{pe}). After a while (t $\approx$ 350 τ_{pe}) double layers of the second generation are generated at different positions, thus independently, of the double layers of the first generation. Because of the large residual fluctuations of the first generation double layers, the potential structure contains large fluctuations, although the essential features of the double layers are the same as those of the first generation. The second generation double layers fade out at t = 450 τ_{pe}. Then, the third generation double layer emerges near but behind the position of the upstreammost double layer of the second generation (t $\approx$ 500 τ_{pe}). The stepwise structure keeps growing far exceeding the level of the conventional weak double layer of roughly one electron thermal potential. Surprisingly, the maximum potential reaches to, say, 15 times of the electron thermal energy, as is observed in Fig. 3. To see the overall temporal evolution of the system, the floating potential at the downstream boundary is plotted against time in Fig. 4.

In view of the fact that the drift speed of the electrons injected from the upstream boundary is less than the electron thermal speed (v_d = 0.6 v_{th}^e), creation of such a huge stepwise potential structure as this is really an exciting and unexpected result. One important physical feature associated with this giant double layer is the strong acceleration of electrons. Figure 5 shows the electron distributions at t = 820 τ_{pe} on the downstream side of the structure as well as on the upstream side. It is evident that an electron beam whose average speed exceeds roughly 5 times of the electron thermal speed is clearly created by the giant potential jump. As was the case for the first and second generation weak double layers, the giant double layer also cannot persist long but disappears eventually at t $\approx$ 1000 τ_{pe}.

Closer examination of the evolutions of the electron and ion distributions indicates that a two-stream type of distribution for electrons and ions is nonlinearly developed in an infant stage of this giant structure in its vicinity. The development of the two-stream like distribution can be explained as follows: As a weak potential double layer is created, electrons and ions are accelerated downwards and upwards, respectively, by its potential jump, thereby a two-stream like condition being locally and nonlinearly created, as is evident in Fig. 6. This distribution accelerates self-feeding of the stepwise potential structure. From this self-feeding nature, we call this giant step potential structure a "super" ion acoustic double layer. In contrast to the weak ion acoustic double (triple) layer, this super double layer is not accompanied with a clear negative potential dip but has a simple stepwise structure.

In summary, using a new particle simulation code where the net particle fluxes through the upstream and downstream boundaries are kept constant, it is found that: First, in the early phase of evolution weak ion acoustic double layers are generated in a stairs-like form. The evolution is neither a monotone nor a single-shot. It is repetitive. The duration time is roughly 100 τ_{pe} under the given condition. Each weak double layer has a sharp negative dip followed by a sudden jump. Secondly and most importantly, during the repetitive evolution of weak double layers, it happens that a two-stream like distribution of electrons and ions is met somewhere in the system. Then, self-feeding condition, or self-breeding condition, is satisfied there and a "super" ion acoustic double layer is created. The maximum potential difference reaches to a much higher level than the electron thermal energy, say, 15 times in the present case. This super structure does not persist long but eventually subsides with leaving a highly disturbed structure behind. The duration time is roughly 500 τ_{pe}. Thirdly, this super double layer accelerates electrons to a much higher energy than both the electron thermal energy and the original drifting energy. Suppose that the thermal energy of the plasma sheet electrons is 200eV. Then, several keV auroral electrons can be easily generated on the ionospheric side by a super ion acoustic double layer resulting from highly nonlinear evolution of the ion acoustic instability.

In order to check the physical soundness of the present simulation result, we have been studying more elaborately the super ion acoustic double layer by changing the plasma parameters and conditions. We have definitely confirmed so far that the self-breeding excitation of the "super" ion acoustic double layer is really a physical phenomenon. Let us close this

Letter by pointing out one important clue for this. By changing the drift speed of the shifted Maxwellian in the range from v_d=0.3 to 0.7 v^e_{th}, we have found that (1) ion acoustic double layers are generated when $v_d \gtrsim 0.4\ v^e_{th}$, (2) a super ion acoustic double layer is self-excited when $v_d \gtrsim 0.5 v^e_{th}$, and (3) the maximum amplitude of the super double layer is much, say by order of magnitude or more, larger than the electron thermal energy or drifting electron energy and becomes larger as the drift speed becomes larger.

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[3] Detailed description of the numerical procedure and the technical data will be given elsewhere.

[4] Simulations have been done by adopting the same constant-flux supplying procedure for the ions as used for the electrons, instead of the reflecting boundary condition, confirming that no essential difference is observed.

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Figure Caption

FIG.1 The velocity distributions of electrons departing ("outgoing") and injected ("incoming") from the upward boundary (left) and the downward boundary (right) in a unit time increment.

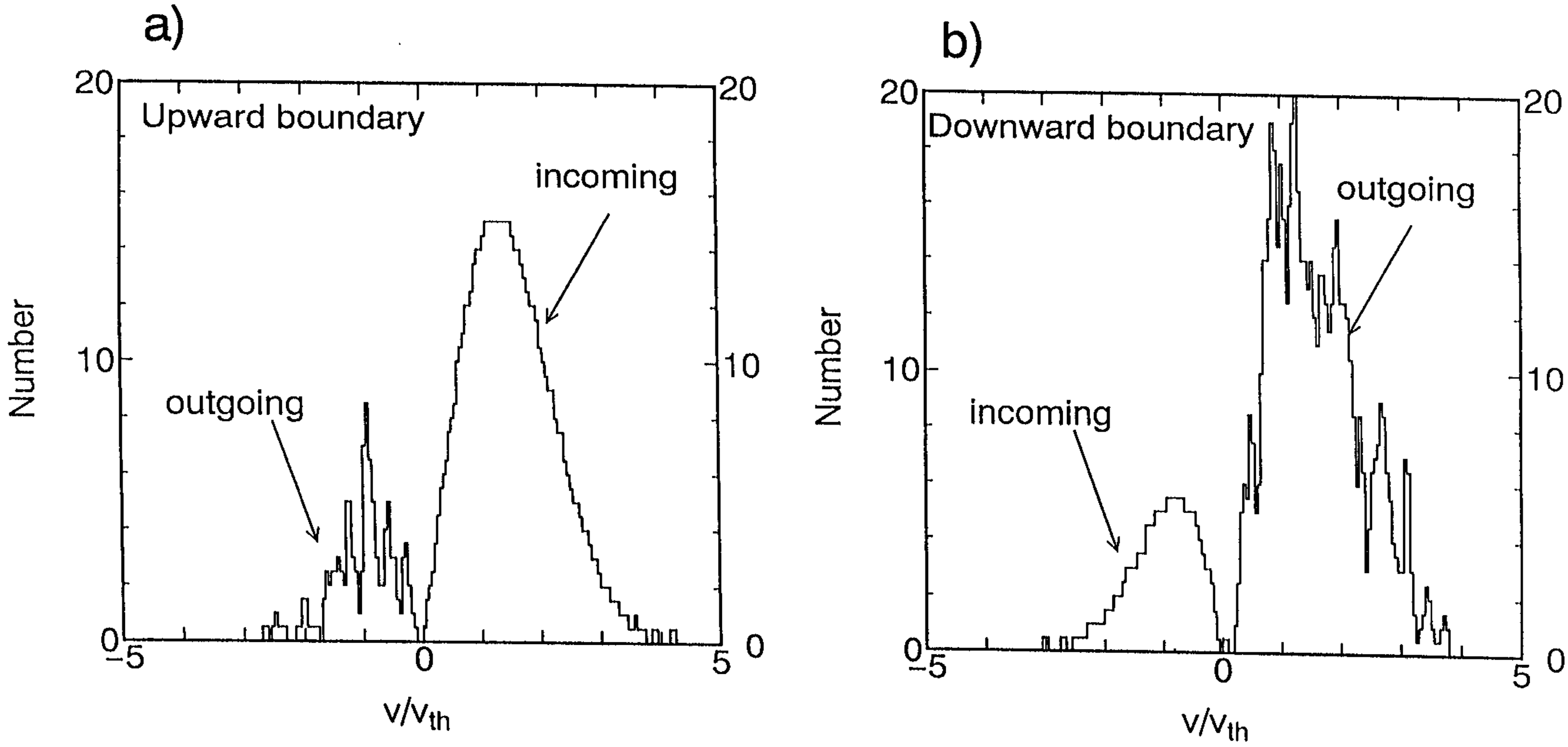
FIG.2 The spatial distribution of the electrostatic potential averaged over 10 τ_{pe} ($\tau_{pe} = 2\pi/\omega_{pe}$) at t = 160 τ_{pe} in the early phase of evolution.

FIG.3 The spatial distribution of "super" ion acoustic double layer (lower panel). For comparison, the normal ion acoustic double layers are shown in the upper panel with the same amplitude scale(see, Fig. 2).

FIG.4 The time evolution of the electrostatic potential at the downstream boundary.

FIG.5 The velocity distribution at $x/\lambda_D = 520$ showing generation of a highly accelarated electron beam by the "super" ion acoustic double layer (upper panel). The lower panel shows the distribution on the upstream side, $x/\lambda_D = 80$.

FIG.6 The velocity distributions for electrons(upper panel) and ions(lower panel) at t = $600\tau_{pe}$ around $x/\lambda_D = 265$ where the "super" ion acoustic double layer would be generated in the later phase, which indicate the realization of a two-stream like distribution.



a)
Upward boundary
incoming
outgoing
Number
v/v_th
b)
Downward boundary
outgoing
incoming
Number
v/v_th

Fig.1

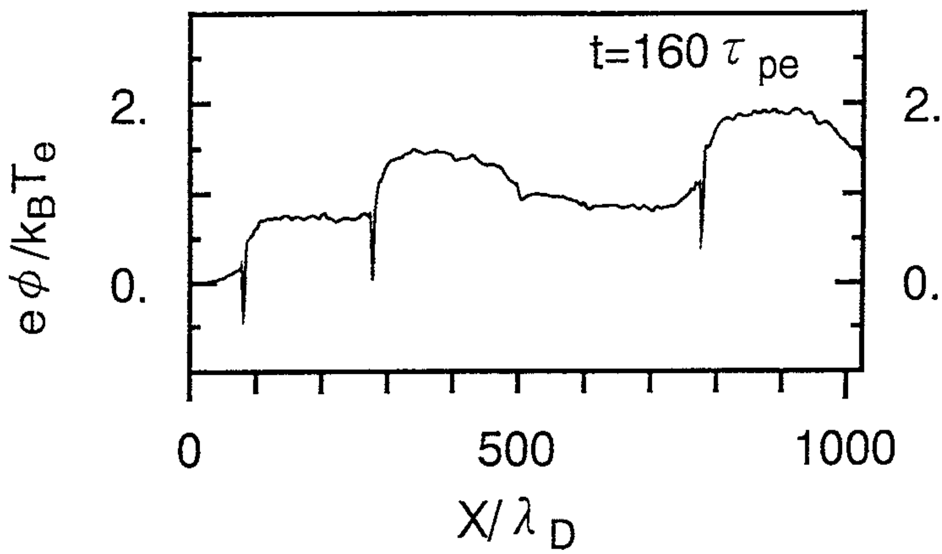


Fig.2

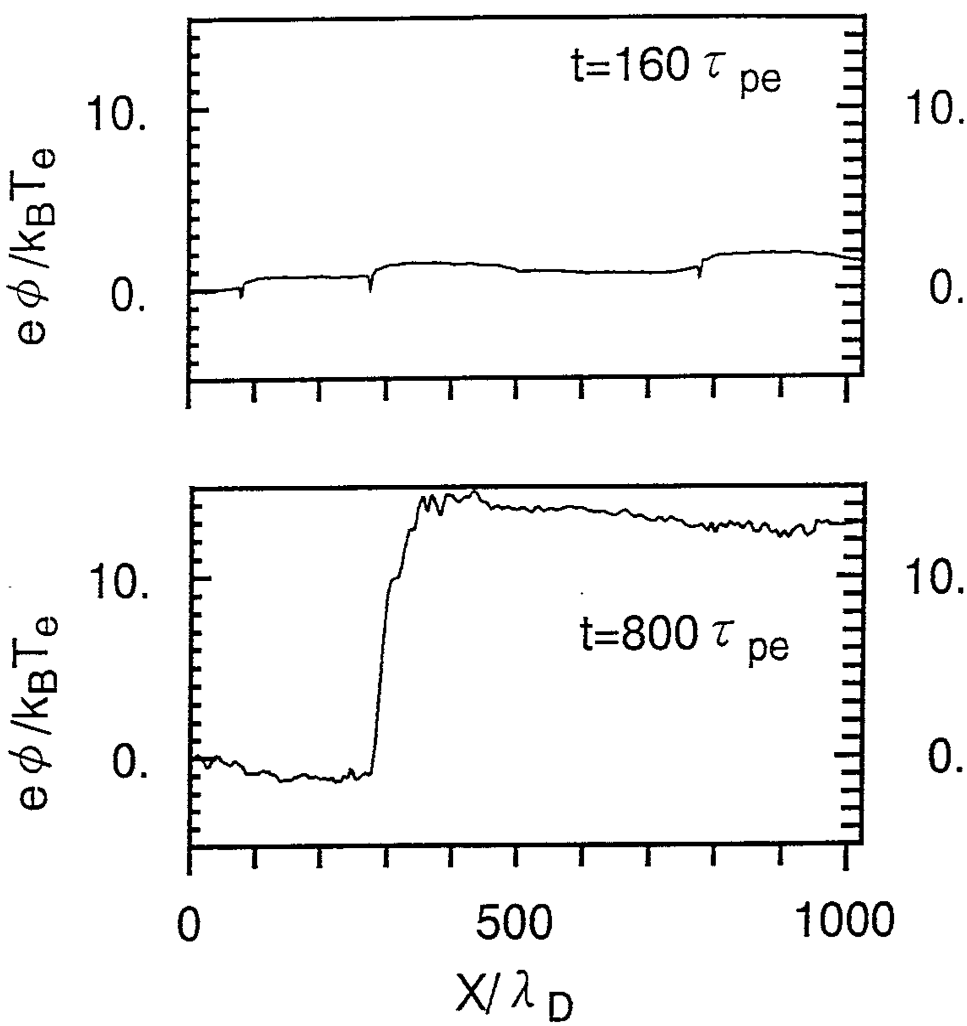


Fig.3

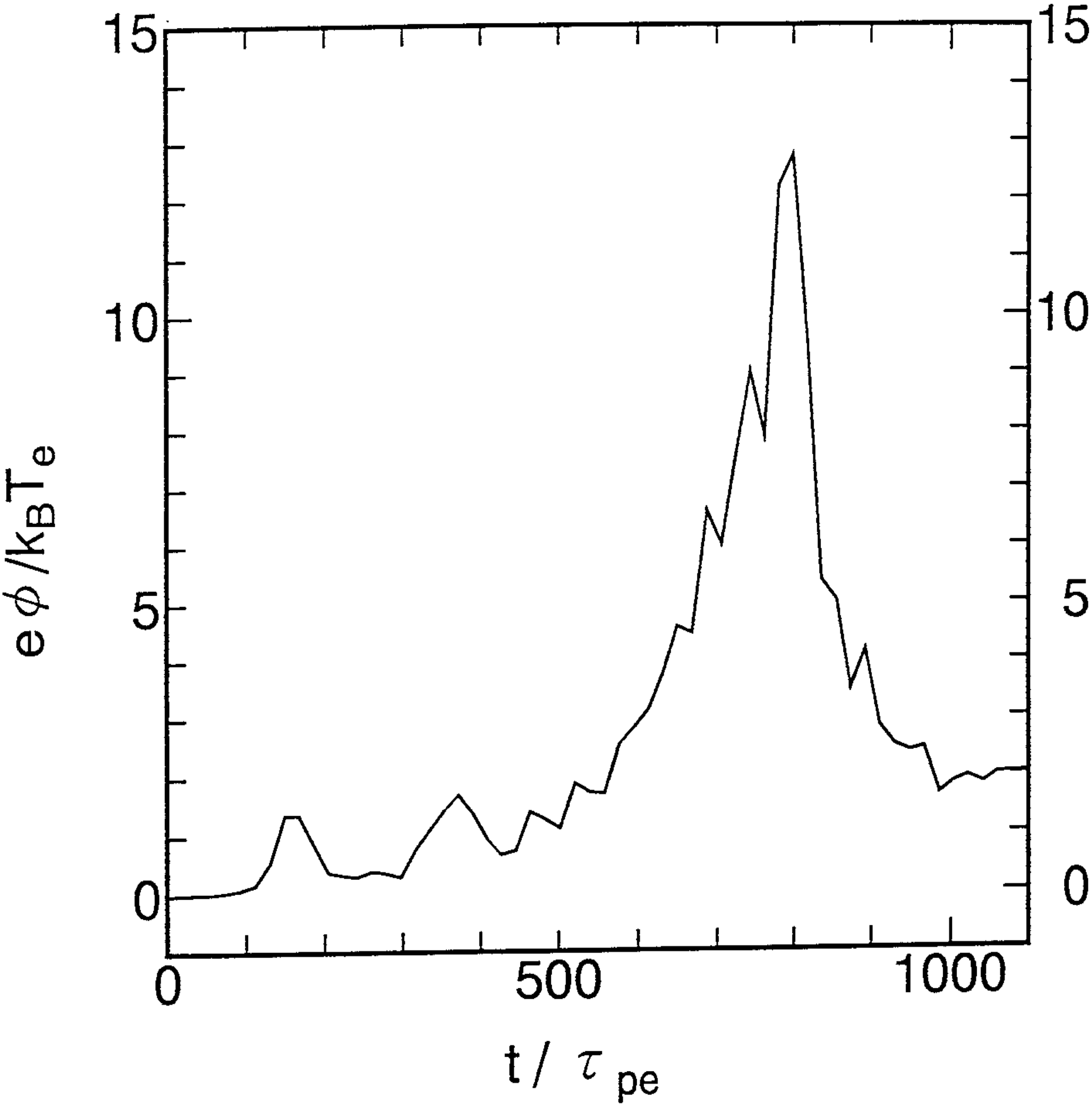


Fig.4

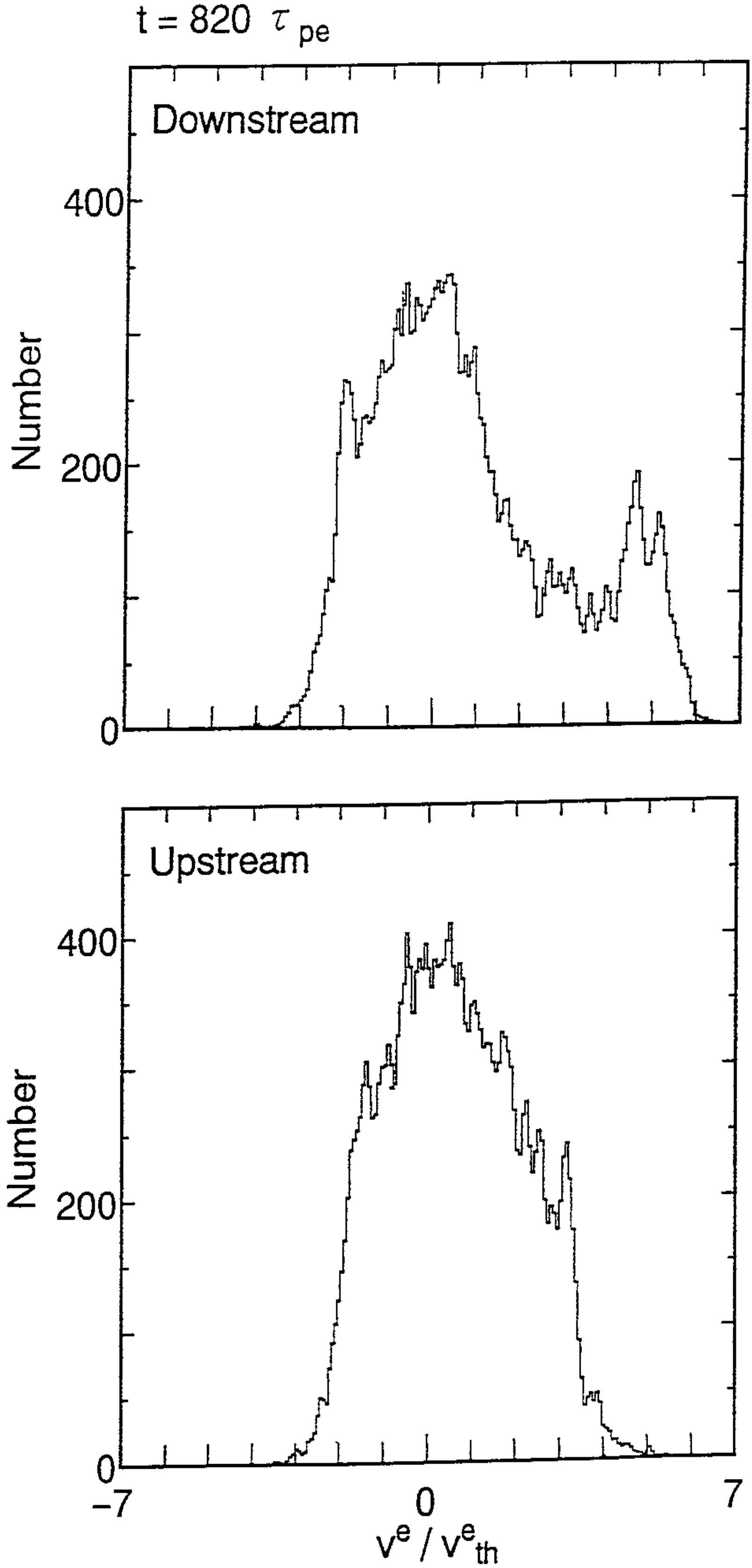


Fig.5

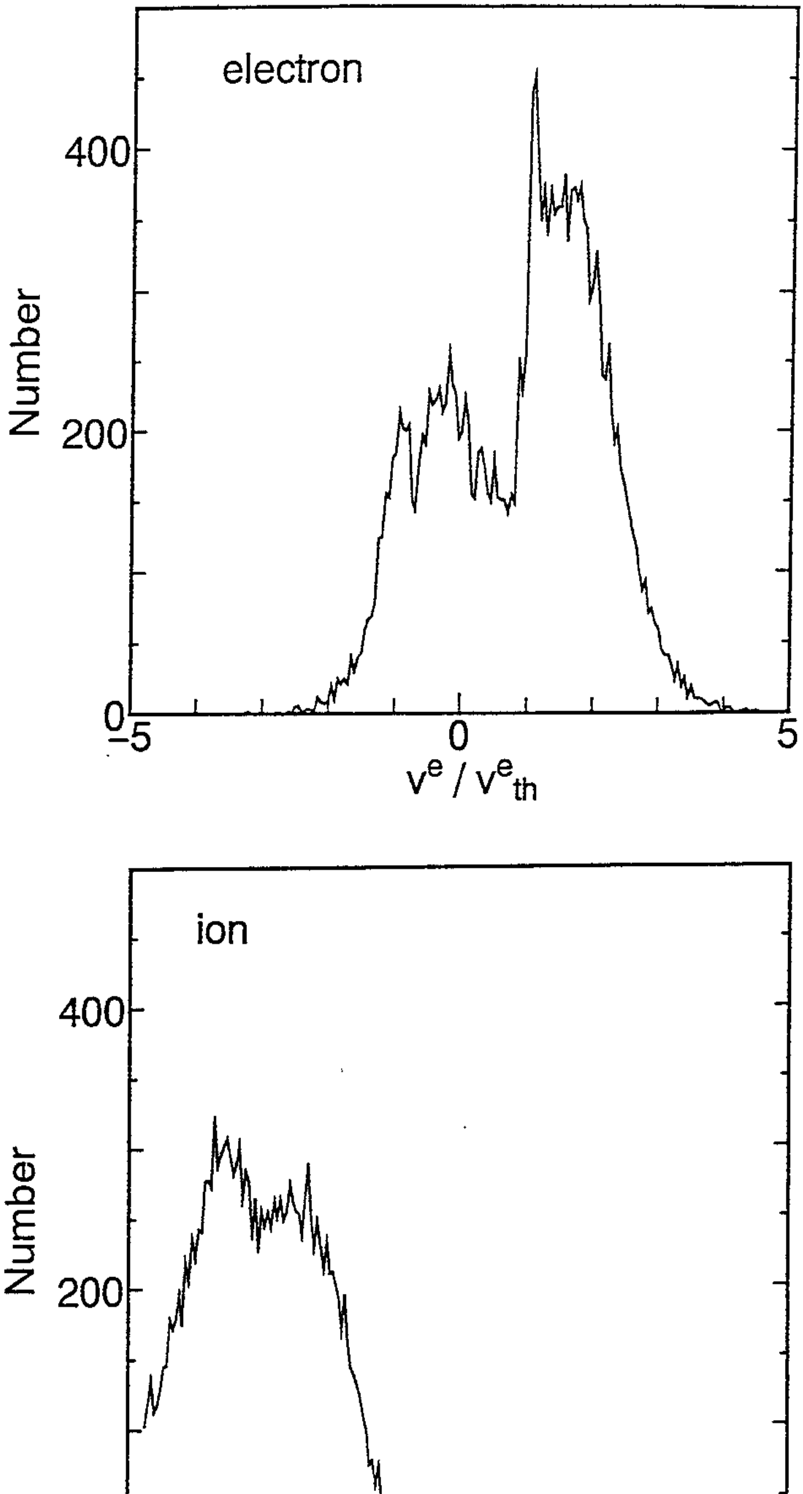

electron
Number
400
200
0
-5
0
5
v^e / v^e_{th}
ion
Number
400
200
0
-0.1
0
0.1
v^i / v^e_{th}

Fig.6

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