Global Instability Structure in a Linear Beam Confinement System*)

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We investigate instabilities of electron beam particles confined in a cylindrical chamber using a 3-dimensional full particle simulation. The global structure of electron beam plasma changes within 1 μs, and deforms to those formed by the instabilities such and the sausage and kink instabilities. The azimuthal mode of the electron density on the midplane of beam plasma is analyzed and the amplitude of mode number of 1 or more increases at 0.2 μs. It was also found that the temporal change of the electron density on the geometric axis is caused by the plasma oscillation.

Keywords: full particle simulation, electron density, Fourier analysis, azimuthal mode, plasma oscillation

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1. Introduction

Although nuclear fusion researches have been pursued for the purpose of energy production so far, other additional applications are also worth considering. For example, a use of neutrons generated by nuclear fusion reaction is one of them, and it is also applied to means of observing the surface condition of objects [1, 2]. Medical applications of neutrons are also possible. Development of compact neutron sources is also required for boron neutron capture therapy (BNCT) [3,4], which is drawing attention as advanced cancer therapy. Momota *et al.* proposed a small neutron source using the D-D reaction by confining deuterium beam ions in a linear electrostatic confinement device [5]. In order to realize the proposed device, it is necessary to stably confine the beam plasma in the linear confinement device for a sufficiently long time in order to satisfy the desired neutron generation rate. There are concerns about the occurrence of various instabilities that causes structural change such as kink and sausage macroscopically and two-stream instability of opposed beam microscopically. In Momota's research, it is evaluated that these instabilities can be suppressed by strengthening the axial magnetic field by the solenoid [5]. However, in order to verify the validity of the evaluation in Ref. [5], analysis using a model that can take into consideration even nonlinear phenomena was required.

Matsui *et al.* conducted a full particle simulation on a beam plasma in a linear magnetic field [6]. From this study, electron behaviors are dominant in a global motion of the beam plasma, and a change of density distribution was observed within 1 μs after its equilibrium state was given. Although instabilities were not observed to destroy the entire structure, however a density change similar to the structural changes accompanying the occurrence of kink instability and sausage instability were observed. No detailed analysis, however, was made on the structural change of the plasma, and it was left as a future study.

Based on the analysis results of Matsui *et al.*, it is the purpose of this research to investigate the macroscopic structural change in detail from the Fourier analysis of the oscillation component generated in the electron beam plasma and lead to the elucidation of the cause of instability. Through this simulation research, we believe it will be possible to define design guidelines for small neutron source reaction vessels that will be developed in the future.

2. Simulation Model

The calculation model used in this study is described in detail in Matsui's paper [6]. We adopt a full particle simulation model that handles particles of both electrons and ions as particles. Since the Lorentz factor is about 1.06, it is better to take effects of relativity into account. Nevertheless this time we continue to use Matsui's model and solve the classical equations of motion to calculate the trajectory of electrons. We solve the wave equation for scalar and vector potential and seek a time evolution of electromagnetic fields. The density and flow velocity of ions and electrons are calculated by summing up super particles in a cell for calculation and calculating the value of the grid point according to the technique of the particle-in-cell method. Calculation conditions are shown in Table 1. Here, the directions of x, y, and z are shown in Fig. 1 respectively. There is no external magnetic field in this calculation model. The calculation region has a square cross

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Table 1 Parameters of reaction chamber and particles.

Calculation region length in x	1.0	m
Calculation region length in y	1.0	m
Calculation region length in z	2.0	m
Ion temperature	50	eV
Beam radius	0.15	m
Beam energy	30	keV
Number of super-particles (electron)	2.0×10^6	-
Number of super-particles (ion)	2.0×10^6	-
Weight of super-particles	10^6	-

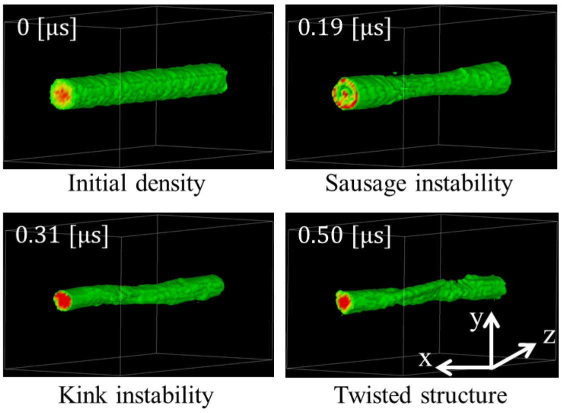

Fig. 1 The 3-dimensional distributions of electron density.

section of 1.0 m vertically and horizontally from −0.5 m to 0.5 m in the xy plane of a rectangular parallelepiped region. Its length is 2 m from −1.0 m to 1.0 m and the length direction is taken in the z axis. The periodic boundary conditions is applied in the z axis direction to avoid end-losses of super-particles.

3. Results and Discussion

Matsui *et al.* showed the characteristic change of the structure in the electron density distribution of the linear electron beam plasma [6]. Starting the calculation with the equilibrium state as the initial condition, 1 μs has 1) a structure in which the plasma pinches radially at a certain point in the z axis direction: sausage instability, 2) a structure in which the cross section (i.e., xy plane) at a certain z position deviates in different directions: kink instability, 3) the shape of cross section deforms, and the phase of deformation shifts along the z axis, so it turns out that it changes to a twisted structure, and so on.

Figure 1 shows the 3-dimensional electron density distribution at the moment when the instability occurred. This research takes over that of Matsui *et al.* and adds quantitative analysis of the global structure of beam plasma as follows. The electron density in the xy plane at the center of the z axis (i.e., midplane) is shown in Fig. 2 at the same time as Fig. 1. From Fig. 2, in the case of 0.19 μs, electrons are concentrated in the center of the xy plane, and the diameter of the plasma is getting smaller than that in the initial distribution. At 0.31 μs, it is confirmed that the electron density peak shifts from the center of the xy plane. Subsequently, it is found that the electron density has a double peak distribution at 0.50 μs. Also, as a whole, a shape like an ellipse is seen.

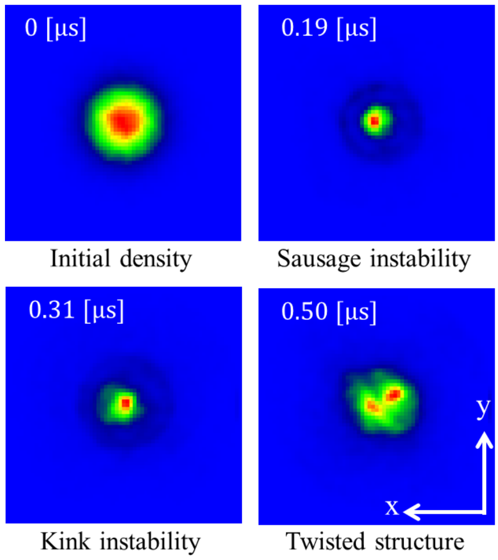

Fig. 2 For the electron density in the xy plane at the center of the z axis.

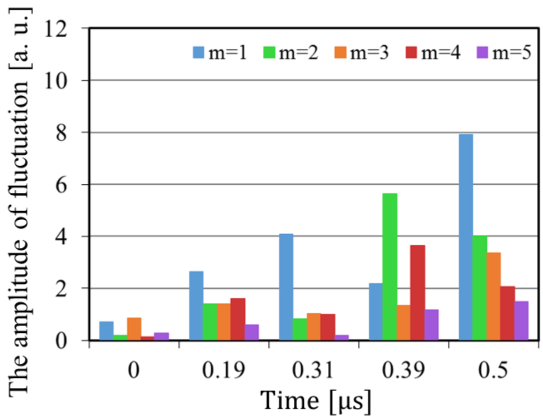

Fig. 3 Comparison of the amplitude of fluctuation for each azimuthal mode in the time when instabilities occur.

Here, an azimuthal mode analysis is performed by Fourier transformation in the azimuthal direction with respect to the electron density in the xy plane at the center of the z axis. The positions in the radial direction are set to $r = 0.5\sigma$, 1σ, 1.5σ, 2σ [m], where the initial standard deviation σ of the electron density is 0.1 m. Fourier analysis is performed on the azimuthal distribution of the electron density deviation from its average value at each radial position. Figure 3 shows a comparison of the amplitude of fluctuation for each azimuthal mode at the instant when the instabilities occur. Here, m represents the number of

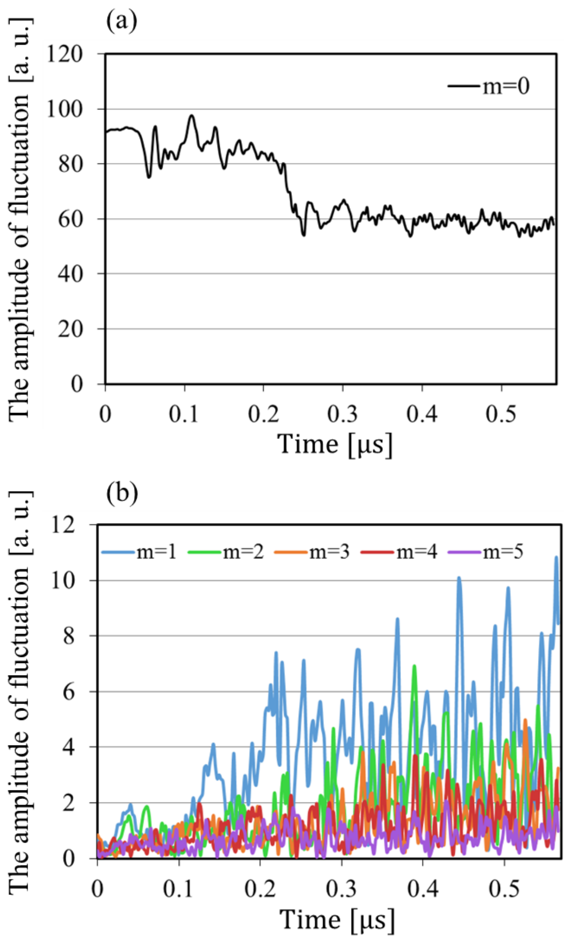

Fig. 4 Temporal change of the amplitude of fluctuation for (a) $m = 0$ and (b) $m = 1, 2, 3, 4,$ and 5.

azimuthal modes.

Although the amplitude of $m = 1$ slightly increases during the 0.19 μs from the start of the calculation, it can be seen that there is no large increase in the amplitude value. It is understood from the comparison with Figs. 2 and 3 that a local pinch such as the sausage instability exists, and from this result it is expected that the plasma is compressed even though it is slightly eccentric. At time 0.31 μs, it is found that the amplitude of $m = 1$ further increases. It is shown that the shape change is analyzed on the midplane and that the influence of the shift here is small. Nonetheless the characteristic change of the kink instability is expressed. When the time is 0.39 μs, it is suggested that the cross sectional shape is elliptical. Also, as the deformation of the plasma shape progresses, it can be seen that the amplitude of each mode is larger at 0.50 μs. Especially, the amplitude of $m = 1$ is large due to the double peak shape, because it is considered that the center of mass for the beam plasma is shifted from the geometric axis as is clear from Fig. 2.

Figure 4 shows the temporal change of amplitude with respect to each mode. As the amplitude of $m = 0$ is larger by one order or more than the amplitude of the other modes, it is shown in another graph as Fig. 4 (a). When the time exceeds 0.20 μs, the amplitude decreases to $m = 0$, indicating that deformation in the azimuth direction occurs at this time. It can be seen that the amplitude of $m = 1$ mode begins to gradually increase from 0.1 μs and rapidly increases at 0.20 μs. Although the amplitude of $m = 2$ is the maximum when 0.39 μs shown in Fig. 3, but the amplitude of $m = 1$ is the largest in the number of modes larger than $m = 0$ through almost the entire calculation time.

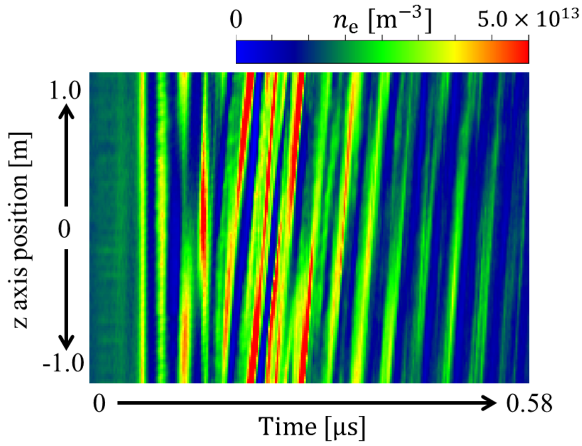

Fig. 5 Temporal change of the electron density in z axis direction at the center of the xy plane.

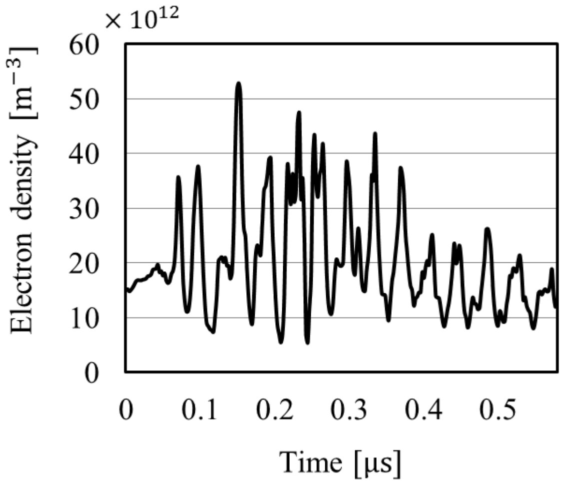

Fig. 6 Temporal change of the electron density at the center of z axis.

Figure 5 shows the temporal change of the 1-dimensional electron density profile along the z axis at the center of the xy plane, and Fig. 6 shows the temporal change of the value of electron density at the center of the z axis in Fig. 5. Here, the Fourier transform in the time axis direction is performed on the electron density value in Fig. 6, and the angular frequency is analyzed. Figure 7 shows the power spectrum obtained from the temporal change of the electron density at the center of the z axis.

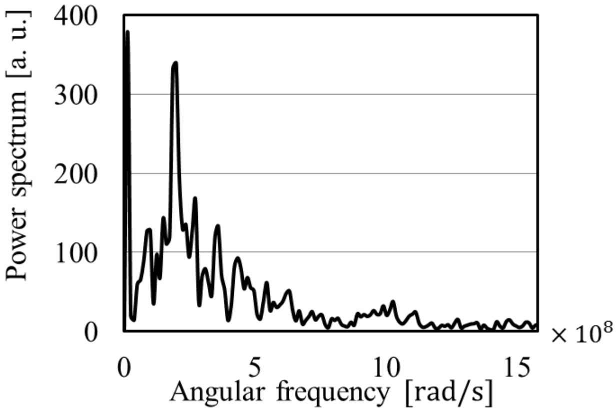

Fig. 7 The power spectrum of electron density fluctuations.

It is found from Fig. 7 that the peak of power spectrum is at $\omega = 1.98 \times 10^8$ [rad/s]. This result is compared with the theoretical value of the angular frequency of plasma oscillation, which is written in the form:

$$\omega = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}.$$

Here, e is the elementary charge, ε_0 is the vacuum permittivity, m_e is the mass of the electron, and n_e is the electron density. The electron density seen in Fig. 7 ranges from the maximum value $n_{max} = 5.29 \times 10^{13}$ [m^{-3}] and the minimum value $n_{min} = 0.54 \times 10^{13}$ [m^{-3}]. Therefore, these density values correspond to the maximum value of the angular frequency $\omega_{max} = 4.10 \times 10^8$ [rad/s] and the minimum value $\omega_{min} = 1.31 \times 10^8$ [rad/s] , respectively. Therefore, the obtained angular frequency by the full particle simulation is within the range of the electron plasma oscillation in the beam plasma. Comparing the theoretical value with the value obtained by analyzing the angular frequency, it is found that the value is close. Therefore, it can be said that the temporal change of the electron density in the z axis direction is caused by plasma oscillation.

4. Concluding Remarks

In this study, we investigated the global instabilities of the electron beam plasma confined in the linear chamber using the 3-dimensional full particle simulation. In our earlier work, it has been found that the changes in global density structure occurs. Therefore, taking over our previous work, we have carried out the mode analysis for the azimuthal density distribution in order to find the deformation of beam plasma structure.

As a result of the mode analysis on the electron density distribution, it was found that the amplitude for the m = 0 mode decreased from 0.2 µs, and it was found that the structure change of the higher mode number occurred. The typical 3-dimensional shape changes such as sausage instability and kink instability were also seen in time variations of amplitude of $m = 0$ and $m = 1$ and 2; it is obtained from the mode analysis.

Time variation of the electron density distribution along the geometric axis was also investigated. It was revealed that the peak of the power spectrum is close to the theoretically expected frequency of plasma oscillation.

In this full particle simulation, the reproducible time is limited to 1 µs because it is restricted by the electron time scale. A global structure change of the beam plasma, however, was also observed during this short time. It is a future task to confirm whether this instability is suppressed by applying an external magnetic field. Also, relativistic effects are neglected in this calculation; it is also a future task to introduce them.

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