# Reduction effect of neutral density on the excitation of turbulent drift waves in a linear magnetized plasma with flow

Y. Saitou[a)]
*Faculty of Engineering, Utsunomiya University, Utsunomiya, Tochigi 321-8585, Japan*

A. Yonesu
*Faculty of Engineering, Ryukyu University, Nishihara, Okinawa 903-0213, Japan*

S. Shinohara
*Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

M. V. Ignatenko
*Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

N. Kasuya
*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*

M. Kawaguchi, K. Terasaka, and T. Nishijima
*Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

Y. Nagashima, Y. Kawai, M. Yagi, and S.-I. Itoh
*Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

M. Azumi
*Japan Atomic Energy Agency, Naka, Ibaraki 319-1184, Japan*

K. Itoh
*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*

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The importance of reducing the neutral density to reach strong drift wave turbulence is clarified from the results of the extended magnetohydrodynamics and Monte Carlo simulations in a linear magnetized plasma. An upper bound of the neutral density relating to the ion-neutral collision frequency for the excitation of drift wave instability is shown, and the necessary flow velocity to excite this instability is also estimated from the neutral distributions. Measurements of the Mach number and the electron density distributions using Mach probe in the large mirror device (LMD) of Kyushu University [S. Shinohara *et al.*, Plasma Phys. Control. Fusion **37**, 1015 (1995)] are reported as well. The obtained results show a controllability of the neutral density and provide the basis for neutral density reduction and a possibility to excite strong drift wave turbulence in the LMD. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2743030]

## I. INTRODUCTION

In the study of transport phenomena in high-temperature plasmas, drift wave turbulence has been considered to play a key role.[1] Recent research on zonal flows, however, has suggested that "drift wave-zonal flow turbulence" is rather important as a self-regulating system (see, for a review, Refs. 2 and 3). Drift wave turbulence is studied extensively in laboratory experiments in order to understand a new paradigm on transport phenomena. The study of detailed processes in turbulence, by use of linear magnetized plasmas, has been revitalized, and progress has been reported.[4–14] Not all of the experiments have shown weak turbulence, and the excitation of strong turbulence and the study on its characteristics are crucial. To achieve this, investigation in regard to conditions for excitation of strong turbulence by simulations and/or theories is useful in realizing the strong turbulence in the experiment.

In the previous extended magnetohydrodynamics (MHD) simulation,[15,16] it was shown that the growth rate of the drift wave turbulence relates to the ion-neutral collisions. This shows a necessity to decrease the neutral density, causing the reduction of the ion-neutral frequency, to realize the drift wave turbulence. Furthermore, a Monte Carlo simulation[17] on neutral particles in the plasma confined linear device was performed. It was demonstrated that ion flow velocity is one of the key parameters that governs the neutral density. When the ion flows fast, the neutral particle production due to recombination mainly takes place around the end plate and the neutral particle could be exhausted by a vacuum pump placed near the end plate. On the other hand, when the ion flow velocity is slow, the recombined neutral particle is supplied anywhere the recombination occurs such as the surface and the inside of the plasma column. In that

[a)]Electronic mail: saitou@cc.utsunomiya-u.ac.jp

 

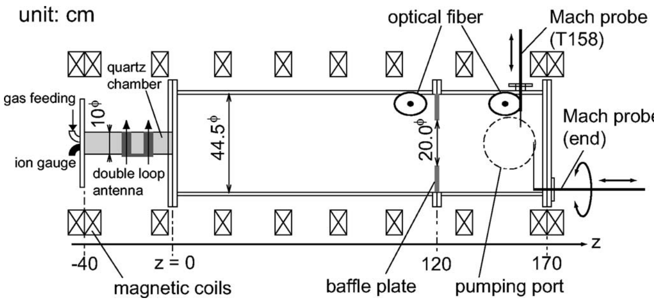


FIG. 1. Schematic drawing of the LMD.

case, vacuum pumps have to be placed along the plasma column to exhaust the neutral particle.

In this paper, we first survey a theoretical background for realizing strongly unstable drift waves using the extended MHD and Monte Carlo simulations, and then report the experimental plasma parameters for which the control of neutral particle is possible in the linear magnetized plasma. The simulation codes are developed based on the large mirror device (LMD) at Kyushu University whose geometry and layout are given in Fig. 1. Geometrical and plasma parameters used in these simulations are close to those obtained in the experiments using the LMD.[13,18]

First, by the extended MHD simulation, we survey a necessary condition for the unstable drift wave excitation. It will be reported that there is a threshold value of the ion-neutral collision frequency, which should be reduced for the drift wave excitation. It is, in general, difficult to reduce the ion-neutral collision frequency directly in the experiment by only lowering the feeding gas. Therefore, to control the neutral density by other means is important. For the purpose, effects of the Mach number (the plasma flow velocity normalized by the ion acoustic velocity), the electron temperature, and use of the baffle plate on the neutral density profile are also investigated by the Monte Carlo simulation.

These theoretical backgrounds motivate the measurement of the Mach number of plasma flow, the ion temperature, and the neutral particle temperature. The laboratory experiments were also performed using the LMD to measure the Mach number by Mach probes, and the ion and neutral temperatures by a spectrometer. The basic data were obtained for establishing a reduction method of the neutral density in order to realize the strong drift wave turbulence.

## II. THEORETICAL BACKGROUND

### A. Extended MHD simulation

A three-dimensional numerical simulation code called "numerical linear device" has been developed.[15] The three-field (density, potential, and parallel velocity of electrons) reduced MHD model is extended to describe the resistive drift wave turbulence in cylindrical magnetized plasmas. Using this model, the linear eigenmode analysis has been performed to identify unstable modes, which give a quantitative estimation of a necessary condition for turbulence excitation in the LMD.

For describing the resistive turbulence,[19,20] the continuity equation, vorticity equation, and Ohm's law are used to obtain the fluctuating density, potential, and parallel velocity of electrons,

$$\frac{dN}{dt} = -\nabla_{\parallel}V - V\nabla_{\parallel}N + \mu_N\nabla_{\perp}^2 N, \tag{1}$$

$$\frac{d\nabla_{\perp}^2\phi}{dt} = \nabla N\cdot\left(-\nu_{in}\nabla_{\perp}\phi - \frac{d\nabla_{\perp}\phi}{dt}\right) - \nu_{in}\nabla_{\perp}^2\phi - \nabla_{\parallel}V - V\nabla_{\parallel}N + \mu_W\nabla_{\perp}^4\phi, \tag{2}$$

$$\frac{dV}{dt} = \frac{M}{m_e}(\nabla_{\parallel}\phi - \nabla_{\parallel}N) - (\nu_{ei}+\nu_{en})V + \mu_V\nabla_{\perp}^2 V, \tag{3}$$

where $N=\ln(n/n_0)$ is the logarithmic form of the normalized plasma density; $n$ is the plasma density and $n_0$ is the maximum plasma density; $V=v_{\parallel}/c_s$ is the electron velocity parallel to the magnetic field normalized with the ion acoustic velocity, $c_s$; $\phi=e\varphi/T_e$ is the normalized electrostatic potential; $T_e$ is the electron temperature; $d/dt=\partial/\partial t+$ is the convective derivative; $M$ and $m_e$ are masses of ion and electron; $\nu_{in}$, $\nu_{ei}$, and $\nu_{en}$ are ion-neutral, electron-ion, and electron-neutral collision frequencies, respectively; and $\mu_N$, $\mu_V$, and $\mu_W$ are artificial viscosities. The values of the viscosities are assumed $\mu_N=\mu_V=\mu_W=1\times10^{-4}$. The boundary conditions of fluctuations in the radial direction are set to $\tilde{N}=\tilde{\phi}=\tilde{V}=0$ at $r=0$ and $a$ when the azimuthal mode number is not 0, $\partial\tilde{N}/\partial r=\partial\tilde{\phi}/\partial r=\partial\tilde{V}/\partial r=0$ at $r=0$, and $\tilde{N}=\tilde{\phi}=\tilde{V}=0$ at $r=a$ when the mode number is 0, where $r=a$ gives an outer boundary of the plasma column.

In order to compare simulation results with the experimental results described in the latter section, the logarithmic form of the normalized profile of the plasma background density $N$ is given as a fitting function of the experimental result as follows, with conditions of $N(r=r_c)=0$, $dN/dr$ is continuous, and $dN/dr=0$ at $r=0$:

$$N = \begin{cases} N_1\left[\left(\dfrac{r}{r_c}\right)^2 - 1\right]^2 & (r < r_c) \\ N_0\left\{\exp\left[-\left(\dfrac{r-r_c}{L_N}\right)^2\right] - 1\right\} & (r_c \le r \le a). \end{cases} \tag{4}$$

Under experimental conditions, where a hollow density profile is realized, we employ parameters $N_0=4$, $N_1=-1$, and $L_N=4$ cm. In Eq. (4), $r=r_c=2.5$ cm is the radius of the plasma column where the density takes the maximum value. The hollow radial density profile is shown in Fig. 2.

Using this profile, the analyses on the linear growth rate are carried out. (The fixed boundary condition is chosen for perturbations at $r=a$; see Ref. 15 for details.) As shown in Fig. 3, various azimuthal modes are excited under the present condition. The modes with $2\le m\le 15$ have positive growth rates and become unstable. Especially, $m=5-6$ has the maximum growth rate. In exciting such an unstable mode, the ion-neutral collision is important.

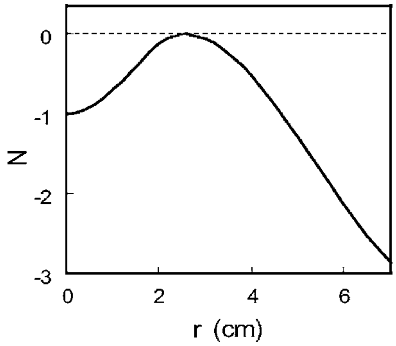


FIG. 2. Radial profile of $N$ when the neutral pressure is 1 mTorr. The parameters of the fitting cure are $L_N=4$ cm, $r_c=2.5$ cm, $N_0=4$, and $N_1=-1$.

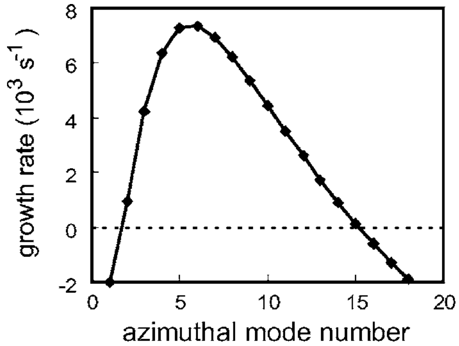


FIG. 3. Dependence of the growth rate on the azimuthal mode number. The mode with $m=5-6$ has the largest growth rate.

An upper bound of ion-neutral collision frequency $\nu_{in}$ is obtained, below which the instability can be excited. Figure 4 shows the threshold in the $B$-$\nu_{in}$ phase space for $m=3$, and 7, for different electron temperatures, $T_e$, where $B$ is the strength of the magnetic field, the plasma radius $a=7$ cm, and the device length $l=170$ cm. The threshold value of $\nu_{in}$ lies approximately $10^4$ s$^{-1}$ at $B=900$ G. Therefore, it is necessary (for exciting the turbulent resistive drift wave) to make $\nu_{in}$ smaller by reducing the neutral density, $n_n$, and/or by increasing the ionization ratio. The increase (decrease) of $B$ ($T_e$) is favorable to enter the unstable conditions.

### B. Monte Carlo simulation

In order to evaluate the distribution of the neutral density, $n_n$, in the device, a numerical code has been developed[17] by means of the Monte Carlo method.[21,22] In the simulation, the system is considered as a two-dimensional one, and the plasma is assumed to be uniform in the axial direction. Three sources of the neutral particle are considered: gas injection, recombination on the end plate, and recombination in the plasma. The neutral particle is exhausted from the device due to the ionization or the use of vacuum pumps. In the present calculation, the neutral self-elastic collision is important under a neutral pressure of several mTorr. For simplicity, the recombination in the plasma is considered to take place at the lateral surface of the plasma column. In addition, a baffle plate can be installed, which is utilized to isolate injected particles or the end-plate source from the main plasma region. In the former case, the baffle plate is expected to facilitate the accumulation of the neutral particle to the plasma production area. In the latter case, the plate redirects the neutral particle to the pumping area.

The neutral particle density is estimated using the Boltzmann equation in steady state:

$$\boldsymbol{v} \cdot \nabla f_n = C_n(f_n,f_n) + C_i(f_n,f_i) + C_e(f_n,f_e) + S_{in} + S_{ep} + S_{pl}, \tag{5}$$

where $\boldsymbol{v}$ is the velocity of the neutral particle; $f_n$, $f_i$, and $f_e$ are the neutral, ion, and electron distribution functions; $C_n$, $C_i$, $C_e$ are neutral-neutral, neutral-ion, and neutral-electron collision terms as a function of the distribution functions; and $S_{in}$, $S_{ep}$, and $S_{pl}$ are source terms due to gas injection, recombinations of ions at the end plate, and in the plasma, respectively.

In the simulation, plasma parameters such as the plasma density are assumed to be similar to the previous MHD simulation. A pump with a pumping speed of 400 l/s is located at $z=165$ cm, and typical values of $T_e=3$ and 5 eV are used. The flux of the neutral gas at the production tube area ($z<0$) is adjusted to coincide with the gas pressure of 1 mTorr. When the electron temperature is low, $T_e=3$ eV, $n_n$ at $r=2.5$ cm strongly depends on the Mach number $M$ of the axial plasma flow, as shown in Figs. 5(a) and 5(b). In the case of $M=0.01$, the axial $n_n$ profile is mainly determined by the recombined neutral particles coming out of the lateral plasma. The presence of the baffle plate, 20 cm in diameter, located at $z=120$ cm, increases $n_n$ in the main region. In contrast, the larger $M$ enhances the recombination at the end plate ($z=170$ cm) and $n_n$ in the main plasma is reduced by

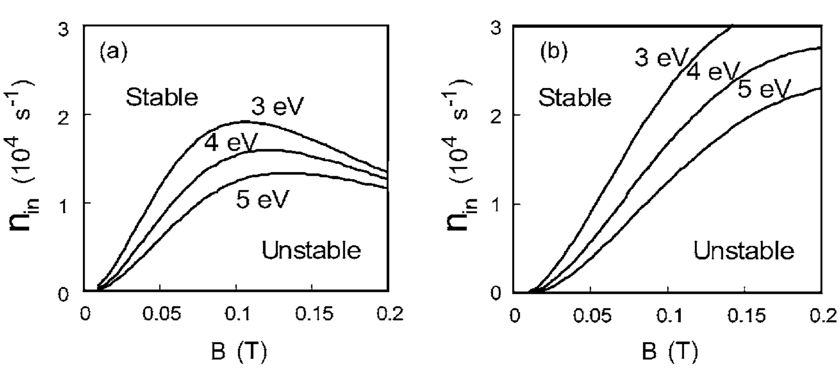


FIG. 4. Stability threshold for ion-neutral collision frequency. The cases with mode number (a) $m=3$ and (b) $m=7$ are shown.

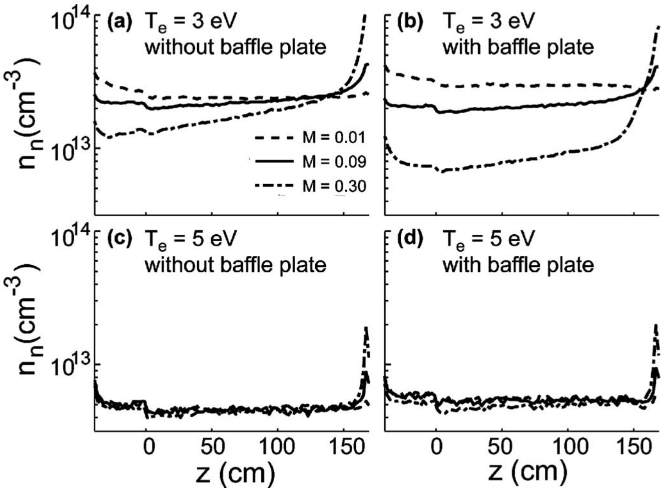


FIG. 5. Effect of Mach number, $M$, on the axial profile of neutral density at $r=2.5$ cm; (a, b) $T_e=3$ eV; and (c, d) 5 eV. Left-/right-half figures are without/with the baffle plate, respectively.

using the baffle plate. There is a critical Mach number, $0.08<M_c<0.1$: If $M$ is below (above) the critical value then $n_n$ is increased (decreased) by the baffle plate.

If the electron temperature is high, $T_e=5$ eV, the neutral density $n_n$ at $r=2.5$ cm is small comparing to the case of $T_e=3$ eV, as shown in Figs. 5(c) and 5(d). This means that the ionization rate in the plasma is high. Here, the $n_n$ profile is almost determined by the particles recombined at the plasma surface and the contribution of the recombination at the end plate is weak. Therefore, the distribution of $n_n$ does not strongly depend on $M$. The averaged axial $n_n$ profile is almost flat in the $z$ direction, since the recombination takes place everywhere at the plasma boundary.

From Fig. 5, it is expected that the baffle plate is effective to reduce $n_n$. In order to summarize the dependencies, relative change of the radially averaged neutral density, $\Delta n=(\langle n_0\rangle-\langle n_1\rangle)/\langle n_0\rangle$, at $z=85$ cm by the baffle plate, are calculated, as shown in Fig. 6, where $\langle n_0\rangle$ and $\langle n_1\rangle$ are the neutral densities without and with the baffle plate, respectively. If $\Delta n>0$, the baffle plate is effective and makes the neutral density lower. A Mach number, where $\Delta n=0$, gives the critical Mach number. Typical values of $T_e=3$, 4, and 5 eV, are used with the fixed ion temperature of 0.5 eV. The flux of the neutral gas at the production tube area ($z<0$) is adjusted to coincide with the gas pressure of 1 mTorr again.

Figure 6(a) shows that the baffle is effective for $T_e=3$ eV as long as $T_n=0.1$ eV when $M>0.03$. This means that the recombination in the bulk plasma is not dominant and the neutral particle is exhausted by the pump effectively. On the other hand, the recombination in the bulk plasma is dominant for $T_e=4$ and 5 eV and the baffle plate does not change the neutral density prominently regardless of the Mach number.

The velocity of neutral particle depends on its temperature. To see the effect of $T_n$, the same simulation for $T_n=0.03$ eV is shown in Fig. 6(b). It is found that the difference between cases of $T_n=0.1$ and 0.3 eV is small. This is due to the fact that the distance between the end and baffle plates is small. The small distance is equivalent to make the recombination probability small in the region between the baffle and end plates, so that the neutral temperature is not important in the present condition.

## III. LABORATORY EXPERIMENT

In developing the drift wave turbulence, the importance of the plasma flow speed, the neutral density, and the baffle plate was clarified in the preceding sections. To establish a way to control $n_n$ in the experiments, we are planning to install an enhanced pumping system in the device. The design of the efficient neutral exhaustion critically depends on the Mach number of plasma flows. In order to measure the flow, the Mach probe and spectroscopic measurements have been executed on LMD.[13,18] A schematic drawing of the LMD is shown in Fig. 1. An axial length of the device is 170 cm and an inner chamber diameter, 44.5 cm. A magnetic field up to 1.2 kG is applicable along the chamber axis. High-density plasma was produced by a double-loop antenna equipped at one end of the device with an injecting rf power of 2 kW. A baffle plate of 20 cm in diameter was placed at $z=120$ cm.

Two conventional Mach probes whose electrodes are 0.4 cm in length and 0.08 cm in diameter were inserted, as seen in Fig. 7(a). One probe is movable in a range of $-10<x<10$ cm along the radial direction at $z=158$ cm; the other scanned by $-25<\theta<25°$ and movable along the $z$ axis ($125<z\leq 165$ cm) [see Fig. 7(b)]. The former and the latter are referred to as "Mach probe (T158)" and "Mach probe (end)" in the figure, respectively.

Argon gas was fed at a pressure of 1 mTorr. In the present experiment, the magnetic field was uniform and its

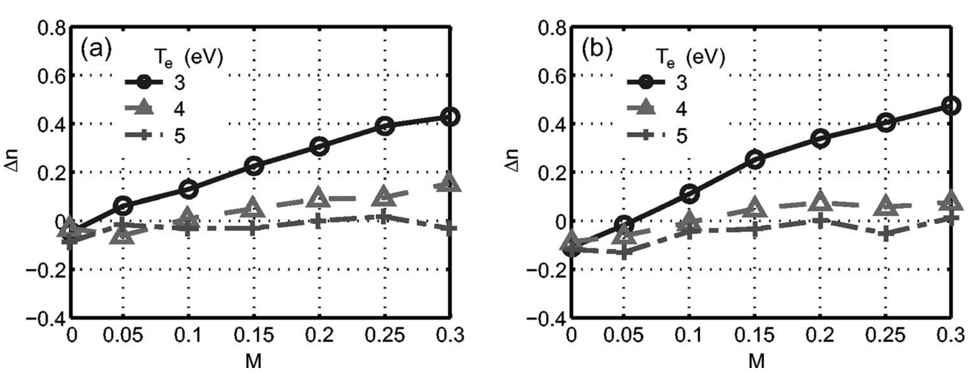


FIG. 6. Effect of the baffle plate on the neutral density at $z=85$ cm. (a) Neutral temperature $T_n=0.1$ eV and (b) $T_n=0.03$ eV (room temperature). Here, $\Delta n=(\langle n_0\rangle-\langle n_1\rangle)/\langle n_0\rangle$, where $\langle n_0\rangle$ and $\langle n_1\rangle$ are the radially averaged neutral densities without and with the baffle plate, respectively.

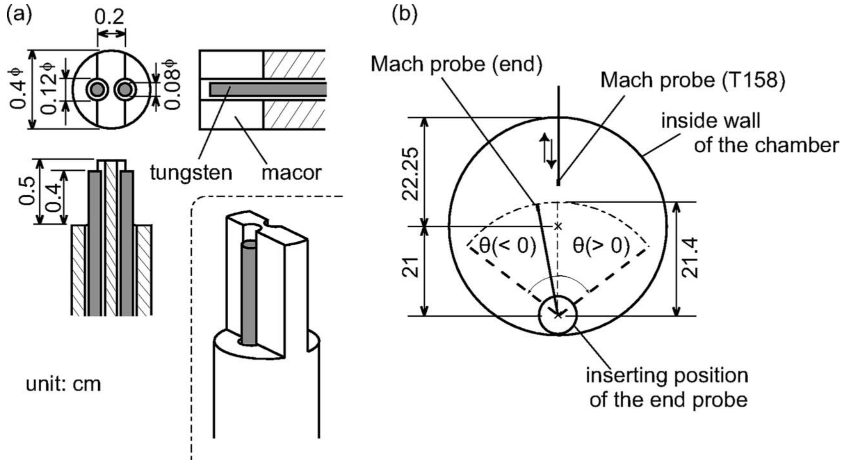


FIG. 7. (a) Outline of the conventional Mach probe tips and (b) geometry of the end and T158 probes viewing from downstream to upstream of the LMD.

strength was 900 G. As shown in Fig. 8(a), the electron temperature was around 4 eV in the upstream region ($z \sim 60$ cm), and the plasma density was up to $10^{13}$ cm$^{-3}$.

The ion and neutral temperatures, $T_i$ and $T_n$, in the central region of the plasma column were measured from the Doppler broadening by a spectrometer with a focal length of 150 cm, and the observation points were at $z=108$ and 151 cm. The wavelengths of the observed lines were 420.068 nm (ArI), 434.845 nm (ArII), and 487.986 nm (ArII), which showed that $T_i \simeq 0.6$ eV and $T_n \lesssim 0.2$ eV, respectively. Here, the neutral temperature was higher than the room temperature.

The electron density distributions were measured using the ion saturation current of an upstream electrode of the

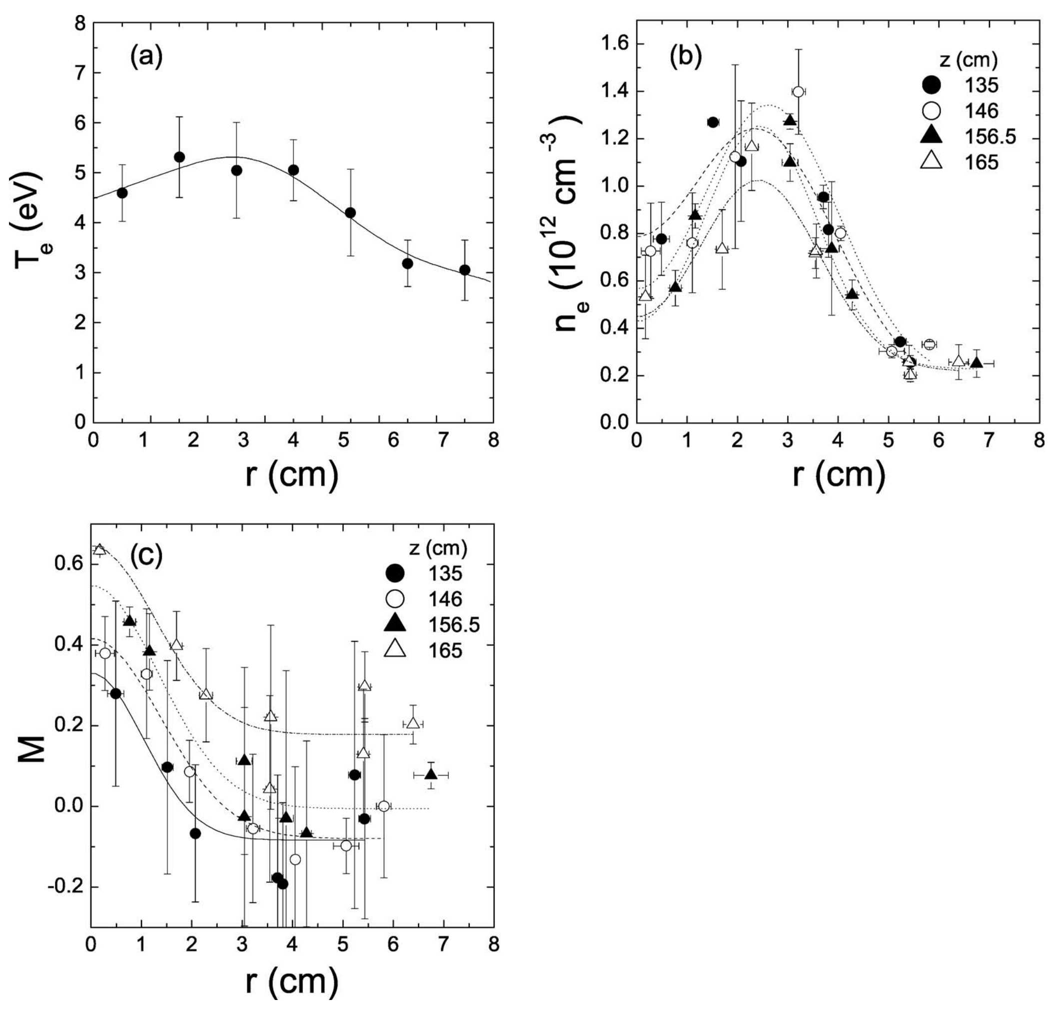


FIG. 8. Radial distributions of (a) the electron temperature at $z=60$ cm, (b) the electron density measured by the upstream electrode of the Mach probe, and (c) Mach number at several $z$'s. The experimental condition is as follows: Argon gas is 1 mTorr and the strength of uniform magnetic field is 900 G.

Mach probe. In deriving this density, we assumed that the $T_e$ is close to that at $z \sim 60$ cm, and the electron temperature profile, which is shown in Fig. 8(a), was used. The radial profile of the density is hollow as shown in Fig. 8(b) (see also Fig. 2). At $z=60$ cm, the peak density was approximately $10^{13}$ cm$^{-3}$. There was a tendency that the density slightly decreased along the axial direction. We have considered that the electron temperature gradient along the magnetic field is much weaker than that of density, owing to the high conductivity. This was also backed up by previous observations.[18,20,23] Figure 8(c) shows the radial profiles of Mach number, $M$, for various axial positions. In the central region of the plasma, $M = \ln(I_u/I_d)/\kappa \simeq 0.3$ at $z=135$ cm in the case of the unmagnetized-kinetic model ($\kappa=1.26$) (Refs. 24 and 25), where $I_u$ and $I_d$ were the ion saturation currents of the Mach probe facing the upstream and the downstream of the plasma flow, respectively. In determining $M$, there was an ambiguity by a factor of 2, depending on physical models. Approaching the end plate, $M$ tended to increase gradually.

## IV. DISCUSSION AND SUMMARY

We have investigated a condition for realizing turbulent drift waves by the extended MHD simulation, Monte Carlo simulation, and laboratory experiment. The extended MHD simulation has given the following results: The ion-neutral collision frequency has to be less than the threshold value to make the drift wave unstable in the device. In order to reduce the ion-neutral collision frequency, it is necessary to reduce the neutral density and/or increase the ionization ratio and/or heat the electron. From this point of view, lowering the neutral density is required in the laboratory experiment, because raising the ionization ratio and/or the electron temperature is more difficult than reducing the neutral particle density externally in general.

The Monte Carlo simulation has shown the possibility to decrease the neutral density, and, as a result, the ion-neutral collision frequency, indirectly by a proper choice of the Mach number, the electron temperature, and the baffle plate position. Under the plasma parameters obtained in the laboratory experiment ($T_e \simeq 3$–5.5 eV and $M \geq 0.3$ at $z=135$ cm), it is expected that the neutral density, $n_n$, is decreased by the higher electron temperature for a fixed Mach number. In addition, the large reduction of the neutral density, $\Delta n$, is found in the case of the high Mach number when the electron temperature is low.

Furthermore, as a result of the Monte Carlo simulation, the effect of the baffle plate was studied. The baffle plate divides the main ($z<120$ cm) and the end regions, and the actual recombined area determines the usefulness of the pump: The recombined neutral particles in the bulk plasma are not exhausted by the pump when the recombination takes place in the bulk plasma since the recombined neutral particles are isolated from the pump by the baffle plate. On the contrary, the recombined neutral particles are exhausted by the pump when the recombination takes place at the end plate since the recombined neutral particles are repelled by the baffle plate. The former/latter is dominant when the Mach number is small/large and the electron temperature is high/low. To reduce the neutral density, it is expected to place both the baffle plate and the vacuum pump at a proper position, which is determined mainly by the Mach number and the electron temperature, and to exhaust the recombined neutral particles effectively.

From the simulation results described above, the importance of the neutral density was found to excite the turbulent drift wave in the LMD; that is, the neutral density has to be lower than the critical value for the purpose. The laboratory experiment showed the following results: The electron density at $z \geq 135$ cm had a hollow profile ($\leq 1.6 \times 10^{12}$ cm$^{-3}$) under the present experimental condition. The measured ion and neutral temperatures were $T_i \simeq 0.6$ eV and $T_n \leq 0.2$ eV, respectively, where $T_e$ was estimated approximately to be 3–5.5 eV. From Mach probe measurements, based on the unmagnetized kinetic model, the obtained $M$ at the plasma center was from 0.3 ($z=135$ cm: upstream) to 0.6 ($z=165$ cm: downstream). Judging from the simulating result, these values show the possibility to reduce the neutral density by the baffle plate.

In summary, it was found that lowering the ion-neutral collision frequency is required for destabilizing the drift wave and it can be realized by reducing the neutral density under a proper choice of the Mach number, the electron temperature, and the baffle plate position. In fact, in the LMD, the neutral density reduction is possible by the installation of baffle plates and the additional vacuum pumps and, hence, it is possible to make the drift wave unstable. More precise measurements on Mach number and density distribution, $T_e$, $T_i$, and $T_n$, as well as enhanced neutral pumping, will be performed to survey the most suitable experimental conditions for exciting the turbulent drift wave. Based on the experiment and the simulations described above, the enhanced pumping system including the baffle plate has been designed and installed.[26]

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