Alfvén-Wave Heating Experiment in the Heliotron-*D*

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Plasma heating experiment is performed using a low-frequency shear Alfvén wave in the Heliotron-*D* device. The excitation of the wave is confirmed, and an efficient plasma heating is observed; electrons are heated up to about 2 times and ions more than 1.5 times of the initial temperatures by applying an rf pulse of 400-kW power level.

The possibility of heating a plasma by using a shear Alfvén wave has been proposed by Hasegawa and Chen.[1] The heating mechanisms of this method are collisional dampings of the wave and the Landau damping of a "kinetic Alfvén wave." The kinetic Alfvén wave can be excited through a linear mode conversion of the shear Alfvén wave at the point where a spatial resonance [$\omega = k_{\parallel} v_A(r)$, where v_A is the Alfvén speed] of the wave occurs and it propagates toward higher-density regions of the plasma when an electron temperature is sufficiently high. Tataronis and Grossmann[2] have shown theoretically the absorption of the rf energy and the loading of the plasma at the Alfvén-wave frequency range.

We have reported preliminary results of the shear Alfvén-wave heating and shown the existence of the spatial resonance of the wave and the heating both of the electrons and ions.[3,4] Golovato, Shohet, and Tataronis[5] have also reported the heating experiment in the Proto-Cleo stellarator and observed the temperature increase of the plasma. In their experiment, however, the excitation of the shear Alfvén wave has not been clearly shown. It may also be said that the structure of the rf antenna used in Ref. 5, which was just the air-core transformer as employed in many toroidal devices, had a possibility of high-frequency Ohmic heating of the plasma column surface when the rf power was applied. In this Letter we report detailed experimental results of the plasma heating and a measurement of an equivalent loading resistance in conjunction with the excitation of the shear Alfvén wave.

An experimental device is a toroidal machine called Heliotron-*D*.[6] The device has three kinds of coils in order to produce a confining magnetic field: helical coil, toroidal coils, and vertical coils. The helical coil plays the most essential role in producing the confining field. The coil parameters are as follows: $l = 2$, κ (number of pitches around a torus) $= 12.5$, major radius $R = 1.085$ m, minor radius of the helical coil $r_h = 13$ cm, and average radius of the plasma $r_p = 10$ cm. We have used such a configuration that α^*, the ratio of the toroidal component of the helical field B_h produced by the helical coil on the minor axis to the toroidal-field strength B_t produced by the toroidal coil, is 0.2, and the total toroidal-field strength B_0 is 2–3 kG. The helical coil was installed inside the stainless-steel vacuum vessel and supported by thin Inconel wires with the use of a stainless cage.

An antenna structure to be used in the heating experiment was setup inside the vacuum chamber and at a position between the cage and the helical coil. The arrangement of the antenna structure and the diagnostic apparatus is schematically shown in Fig. 1. A helium plasma was produced by an Ohmic discharge with a plasma current, I_{OH}, of 5–15 kA and a loop voltage of 20–25 V. The plasma density n_e, ranging between 3×10^{12}–2×10^{13} cm^{-3}, was measured by 4-mm microwave interferometry; the electron temperature, $T_e = 30$–300 eV, was measured at the plasma column center by the Thomson scattering of a laser light, and the ion temperature at the column center, $T_i = 20$–50 eV, by the Doppler broadening of the He II 4686 line. The positions at which the tem-

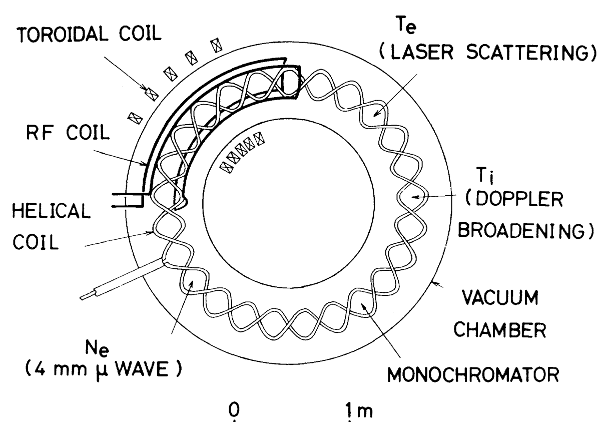

FIG. 1. The top view of the Heliotron-*D* showing the experimental arrangement.

peratures were measured were located at almost an opposite side of the torus from the antenna structure, then it facilitated to confirm entire heatings of the toroidal plasma.

The rf antenna was composed of four copper pipes of 1.2-cm diameter arranged parallel to the toroidal direction and the toroidal length of the antenna section is 1.45 m which corresponds to a wavelength of 2.9 m and a toroidal-mode number of $n \cong 2$. An azimuthal-mode number, m, of the antenna is ± 2. The dimension of the antenna was decided so as not to excite the compressional Alfvên wave, and the phase velocity of the wave ($\cong v_A$) to be smaller than the electron thermal velocity, V_{Te}. The copper pipe was covered with insulators to prevent an rf breakdown. The rf power was fed into the plasma through a coaxial cable, a matching circuit, and the antenna from a power generator which had the maximum output power of 1 MW and the fixed frequency of 405 kHz.

The input power absorbed in the plasma was measured by a directional coupler inserted between the power generator and the matching circuit. We confirmed that we could neglect the power absorption by the antenna system itself and by the environing vacuum vessel. The load resistance of the whole system was found to be less than 0.1 Ω while that of the plasma was 1–5 Ω. The rf current flowing in the antenna conductor is 200–300 A. The induced poloidal-wave field $\tilde{B}_\theta$ near the plasma center is 3–5 G. The equivalent loading resistance of the plasma was also measured with using a signal generator (SG) of a low level output less than 1 W.

The dependences of the resistance on the plasma density are shown in Fig. 2. In the case that the signal generator is used, the resistance is nearly constant at higher densities and becomes small with decreasing the density. The resistance for $B_0 = 2.4$ kG at $n_e \cong 1\times10^{13}$ cm^{-3} is larger than that for $B_0 = 2.9$ kG. This fact can be explained by the dispersion relation of the shear Alfvên wave,

$$\omega_0^2 = (4B_0^2/\mu_0 n m_i R^2)(1 \pm |q^{-1}|)^2, \quad (1)$$

$$q^{-1} = \iota_{OH} + \iota_F,$$

where we use standard notations and q^{-1} is an effective rotational transform[7] of the magnetic field including both that originated from the helical field, ι_F, and the Ohmic current, ι_{OH}. In our experiment, the direction of the poloidal field produced by the plasma current was chosen to be inverse to that of the vacuum poloidal field in order to obtain a convenient experimental condition,

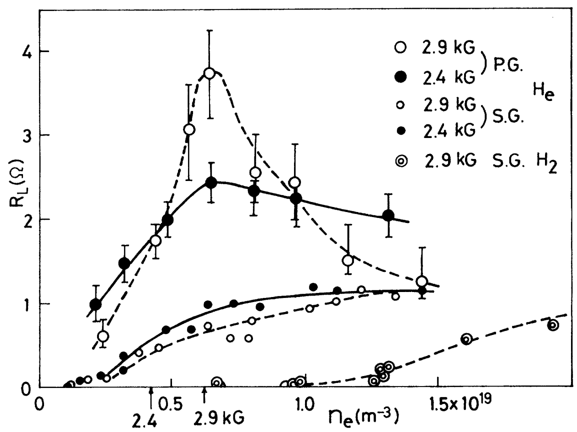

FIG. 2. The equivalent load resistance as a function of the plasma density.

and then the value of q^{-1} at about the plasma center is kept roughly constant 0.4–0.6, the resonance density is simply proportional to B_0^2. When the density is decreased, the spatial resonance should occur only in the vicinity of the plasma center, then the coupling between the plasma and the antenna becomes weak and accordingly the load resistance becomes small. Since the resonance density is high in the strong magnetic field, the resistance is small in the high magnetic field at a relatively low fixed density. In order to check this more clearly, a hydrogen gas was also used in place of a helium gas. The resonance density in a hydrogen plasma should be four times higher than that in the helium plasma. The double circles illustrated in Fig. 2 indicate an experimental result for the hydrogen plasma measured with the signal generator. It is clearly shown that the resistance begins to decrease at the density about four times higher than that of the helium plasma. This fact can be explained by the dispersion relation (1). The poloidal component of the wave magnetic field in the plasma was also measured with small magnetic probes. The amplitude becomes maximum at the radial position where the density and the static magnetic field satisfy the relation (1). The wavelength in the toroidal direction is almost equal to the fundamental wavelength of the rf antenna. These results imply the excitation of the shear Alfvên wave. However, the mode conversion of the shear Alfvên wave into the kinetic Alfvên wave is not directly confirmed at present.

In the case that the power generator (PG) is used, the value of the resistance is close to that of the SG case at high densities, while it increas-

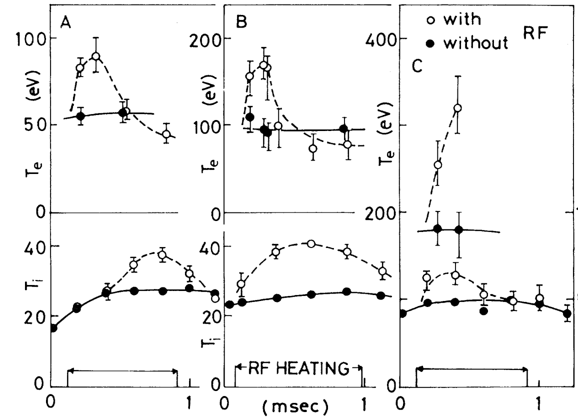

FIG. 3. Dependences of the electron and ion temperatures on time. $B_0 = 2.9$ kG. (a), $n_e = 1\times10^{13}$ cm^{-3}, $I_{OH} = 12$ kA; (b), $n_e = 6\times10^{12}$ cm^{-3}, $I_{OH} = 12.4$ kA; (c) $n_e = 6\times10^{12}$ cm^{-3}, $I_{OH} = 14.5$ kA.

es much greater than that of the SG case and becomes maximum at $n_e \sim 6\times10^{12}$ cm^{-3}. The increase may be caused partly by the change of the plasma parameters due to the application of the high rf power. The rf pulse gives rise to change the electron temperature and the density as will be discussed later. However, the increase of the loading resistance could not be explained by only taking into account of the change of these parameters, i.e., the increase of the electron temperature and the density gives rise to increase the resistance by less than a factor of 2. This fact suggests that some enhancements of the loading and the efficient heating seem to occur.

The time variation of the plasma parameters with and without the rf power is shown for three different plasma parameters in Fig. 3. The upper curves in the figure show the variation of the electron temperature and the lower curves that of the ion temperature. The electron temperature is almost doubled at the maximum values in each densities and the temperature increment of the ions is about 15–20 eV. It should also be noted that the electrons at the column center is mostly heated. The electron temperature rises quickly at the beginning of the rf pulse, however, it decreases during the pulse also quickly down to the level without the rf pulse. The temperature of ions increases gradually and falls after the rf pulse in case of the high plasma density but it begins to fall during the rf pulse in case of the low density similar to the behavior of the electron temperature. The plasma density increases gradually by about a factor of 2 at the end of the rf pulse. This seems to be caused by the ionization of residual neutral particles due to the rf field. The rise time of the density is not so short as to be able to explain the rapid fall of the electron temperature. The plasma current does not change while the loop voltage drops slightly and no large-amplitude fluctuations are observed during the rf pulse. The energy-confinement time of the device is 100–150 μsec under the experimental condition without the rf pulse. We have not yet measured the change of the confinement time during the rf pulse. The detailed mechanism of the temperature fall is not clear and under investigation at present.

The heating mechanism of the plasma are mostly the Landau damping of the kinetic Alfvén wave with respect to the electrons and the collisional damping of the shear Alfvén wave for the ions under our experimental conditions although the excitation of the kinetic Alfvén wave is not directly confirmed. Under our experimental conditions, normalized electron-ion and ion-ion collision frequencies, ν_{ei}/ω and ν_{ii}/ω is approximately 0.16 and 0.015, respectively. The ratio between the collisional damping and the Landau damping, $\delta_{\rm coll}/\delta_{\rm L}$, is 0.04 for electrons. The Landau damping for ions is almost 0. The heating rate of the electrons and the ions within the experimental parameter range can be written in simplified forms,

$$n\,dT_e/dt = C_e n^{-1/2} T_e^{1/2} A^2,$$

i.e.,

$$dT_e/dt = C_e n^{-3/2} T_e^{1/2} A^2, \qquad (2)$$

for electrons and,

$$n\,dT_i/dt = C_i n T_i^{-3/2} A^2,$$

i.e.,

$$dT_i/dt = C_i T_i^{-3/2} A^2, \qquad (3)$$

for ions, where C_e and C_i are constants which depend weakly on the plasma parameters and A correspond to the amplitude of the externally applied rf field. Figure 4 shows a dependence of the peak electron temperature increment T_e on the background electron temperature with the plasma density, the Ohmic current, and the rf power kept nearly constant. It is clearly shown that the temperature increment increases with the increase of the base temperature; the dependence qualitatively coincides with relation (2). In the low electron temperature case, most of the rf power seems to be absorbed by the ionization

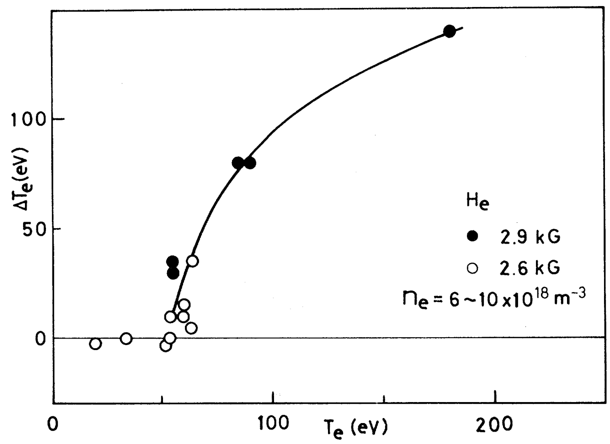

FIG. 4. Temperature increments of the electron vs background electron temperature.

of neutral particles and the excitation of the kinetic Alfvén wave becomes difficult, and presumably there are no significant heatings. These facts are in good agreement with the theory.[1]

Another possible and important mechanism for plasma heating is a nonlinear process[8] for the kinetic Alfvén wave. The efficient heating of the plasma and the enhancement of the loading resistance (Fig. 2) may be attributed to the nonlinear process. A further experiment is necessary and under preparation to give clear account for this process.

In conclusion, it has been shown that the shear Alfvén wave is excited in the toroidal plasma and is effective to heat the entire plasma. The remaining problem is to investigate the decay of the temperatures during the rf pulse.

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Plastic Deformation of Free-Standing Crystals of hcp ^{4}He

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A method has been developed for producing free-standing crystals of hcp ^{4}He. Stress-strain relations have been measured for such crystals plastically deformed under conditions of unconstrained shear. An upper bound for the flow stress of 5×10^4 dyn/cm^2 is determined. Comparison is made with experiments on constrained crystals.

We have studied the plastic properties of solid ^{4}He and report the first measurements of stress-strain relations for single crystals deformed under conditions of uniaxial stress, i.e., unconstrained shear. These experiments are aimed at investigating the migration and generation of dislocations and point defects in solid helium, which in turn is motivated by the possibility of quantum effects in the motions of these defects. It has been pointed out[1] that point defects in solid helium may exist as delocalized excitations that can move practically freely through the crystal. In addition, dislocations, and particularly kinks on dislocations, may be treated in a similar fashion.[2] One might expect, therefore, that the response of such a dislocation to an applied stress may be