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Edge Electric Field Profiles of H-mode Plasmas in JFT-2M Tokamak

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A structure of an edge radial electric field E_r inferred from poloidal rotation velocity is compared with that of particle/thermal transport barrier for H-mode plasmas in JFT-2M. Both of E_r and its gradient $\partial E_r/\partial r$ in the thermal transport barrier are found to become more negative at the L/H transition. The shear of radial electric field and poloidal rotation velocity in H-mode is localized within an ion poloidal gyro radius near the separatrix, in the region of ion collisionality $\nu_{*i} \approx 10$-40.

"keyword" tokamak, H-mode, L/H transition, poloidal rotation, radial electric field

Since the H-mode plasma was discovered in ASDEX,[1] it has been observed in many tokamaks.[2-7] Several theoretical models on the transition of L-mode to H-mode plasmas have been presented[8-13]. Recently a radial electric field (E_r) near the plasma periphery has been found both experimentally and theoretically to play an important role in the L/H transition.[14-21] A more negative radial electric field was observed a few ms before the L/H transition in D-IIID[14,15] and a decrease in particle transport was observed with negative E_r, by driving a radial current, in CCT[16]. Theoretical models associated with the radial electric field have been proposed to explain the L/H transition[17-21]. However, the predicted change of the gradient of the radial electric field ($\partial E_r/\partial r$) is different between models. K.C.Shaing's model predicts that a more negative value of E_r, or a more positive value of $\partial E_r/\partial r$, can suppress the fluctuation amplitudes and causes the L/H transition. While Itoh's model predicts that a more negative value of $\partial E_r/\partial r$ reduces the banana width of ions and reduces the electron anomalous flux by the improved micro-stability. Thus it is crucial to measure the gradient or profile of the radial electric field for L- and H- mode plasmas in tokamaks. In this paper we present the radial electric field and temperature gradient profile a few cm inside the separatrix where the transport barrier is produced in H-mode plasmas in JFT-2M[22].

The radial electric field profiles are inferred from poloidal/toroidal rotation and ion pressure profiles using the ion momentum balance equation;

$$E_r = \frac{\partial p_i}{e n_i \partial r} - (B_\theta V_\varphi - B_\varphi V_\theta),$$

where p_i, n_i are the ion pressure and density, B_φ and B_θ are the toroidal and poloidal magnetic fields, and v_φ and v_θ are the toroidal and poloidal rotation velocities. The poloidal/toroidal rotation and ion temperature profiles are measured with multi-channel charge exchange spectroscopy[23-28] using CVI at 5292 Å, for L- and H- mode plasmas. The toroidal arrays (two sets of 34 channels) view the plasma tangentially, across the neutral beam line with a spatial resolution of 1 cm. The poloidal arrays (two set of 23 channels) view only the plasma periphery poloidally with a spatial resolution of 4 mm. Since the poloidal arrays do not view across the beam line, the poloidal measurements have been done using the intrinsic radiation of CVI at 5292Å. The measurements are limited, near the separatrix, to the region where the intensity of CVI radiation increases sharply enough to neglect the integration effect of line-of-sight. The electron temperature profile and its gradient profile are meaured with an ECE radiometer to investigate the location of the thermal transport barrier. Bulk electron density (n_e) and temperature (T_e) are measured with Thomson scattering and the edge n_e and T_e profiles are measured with a electric probe from 5 mm inside to 30 mm outside of the separatrix. The uncertainty of the position of the separatrix calculated with an equilibrium code is estimated to be 5 mm.

Figure 1 shows the time evolution of the poloidal rotation velocity for a plasma with a current of 250 kA, a toroidal field of 1.24 T, q_ψ of 2.8 in a single null divertor configuration. The neutral beam is injected at 700 ms in the co-direction with a power of 0.7 MW. The poloidal rotation velocity 0.4 cm inside the separatrix show a jump at the L/H transition, however the poloidal rotation 1.4 cm inside the separatrix shows no change. On the other hand, The ion temperature 1.4 cm inside the separatrix increases from 50 to 100 eV gradually after the L/H transition, while the ion temperature 0.4 cm inside the separatrix is 40-50 eV both for L- and H-mode plasmas. The poloidal rotation increases in the electron diamagnetic direction in the H-mode regardless of the direction of plasma current and neutral beam injection. The change of poloidal rotation is prior to the change of ion temperature and is fairly localized near the separatrix, while the sharp gradient of ion temperature is also observed more inside. The strong shear of poloidal rotation velocity is observed in the region of $|a-r| < \rho_p \approx 1.3$ cm. The ion/electron temperature, density and poloidal/toroidal rotation velocity are measured in detail before (t = 710 ms) and after (t= 740 ms) the L/H transition to derive radial electric field profiles. Figure 2 shows the ion/electron temperature and electron density profile measured with charge-exchange spectroscopy, ECE radiometer and Thomson scattering, respectively. T_e and n_e at $r/a > 0.98$ are meaured with an electric probe. Both ion and electron temperature profiles show the thermal transport barrier at $r/a > 0.9$, while the particle transport barrier is closer to the separatrix ($r/a > 0.98$).

The poloidal rotation and the electric field profiles for L-mode and H-mode plasmas, inferred from plasma rotations and pressure gradients, are shown in Fig.3. The electric field becomes more negative in H-mode, due to increase of poloidal rotation in the electron diamagnetic direction and the increase of the ion pressure gradient. The gradient of the electric field inside the separatrix, ds = -0.7 cm, becomes more negative, -70 ± 20 V/cm^2, in the H-mode. In order to determine the location of the thermal and particle transport barrier, the gradients of electron temperature and density for L-mode and H-mode plasma are measured with ECE, Thomson scattering and electric probes. The thermal transport barrier is found at 1-2 cm inside the separatrix, while the particle transport barrier is within 0.4 cm of the separatrix as shown in Fig.4(a),(b). Although the uncertainty of the position of the separatrix is 0.5 cm, it is clear that the region of sharp gradient of electron density is much narrower and located more outside than the region of sharp temperature gradient. We note that the particle transport barrier and the thermal transport barrier are produced in the different region of the plasma. The gradients of ion temperature are -10 eV/cm for L-mode and -60 eV/cm for H-mode 1 cm inside the separatrix. These measurements (Fig.3 and 4) seem to indicate that the negative $\partial E_r/\partial r$ causes the improvement of thermal transport and the positive $\partial E_r/\partial r$ causes the improvement of particle transport. However these measurements do not exclude the possibility that the more negative electric field itself, not the gradient, causes the L/H transition.

It is important to compare the measured plasma parameters such as poloidal rotation, electric field, and pressure gradient with K.C.Shaing's and Itoh's models. The poloidal rotation parameter $U_{p,m}$ [$=v_\theta B/v_\varphi B_\theta+\lambda_p/2$, $\lambda_p=\rho_p(\partial p_i/\partial r)/p_i$] changes from 2.3 ± 0.4 to 4.2 ± 0.3 at L/H transition 0.4 cm inside the separatrix. This change of poloidal rotation at L/H transition agrees with the prediction of K.C.Shaing's model[20] within a factor of two or three. However the ion collisionality ν_{*i} decreases from 45 (L-mode) to 10 (H-mode) 1.4 cm inside and increases from 26 (L-mode) to 36 (H-mode) 0.4 cm inside the separatrix. The collisionality where the change of poloidal rotation velocity is observed (0.4 cm inside) does not agree with the critical ν_{*i} (≈ 1.5) for L/H transition in their model. It also is interesting to evaluate the strength of the gradient of radial electric field $\partial E_r/\partial r$, since it can affect the ion orbit and change the banana width of ions by the factor of $(|1-u_g|+C\varepsilon)^{-1/2}$, where ε and C are an inverse aspect ratio and a numerical coefficient.[19,29] The shear parameter of electric field u_g, defined by $\rho_p(\partial E_r/\partial r)/v_{th}B_\theta$, is 0.2 ± 0.3 for L-mode and -1.4 ± 0.4 for H-mode at 0.7 cm inside the separatrix. The gradient of electric field measured in H-mode is large enough to change the banana width. This shear parameter u_g in H-mode agrees with Itoh's model[21] to within a factor of two, however, the significant positive $\partial E_r/\partial r$, which their model predicts in L-mode, has not been observed in JFT-2M plasma. The pressure gradient parameter λ [$=-(T_e/T_i)\rho_p\{(\partial n_e/\partial r)/n_e+\alpha(\partial T_e/\partial r)/T_e)\}$] defined in his model changes from 0.5 to 1.3, at L/H transition and is consistent with the critical value of their model ($\lambda_c \approx 1$). We observe better agreement of the critical values of the transition with Itoh's model than K.C.Shaing's model. However both models still do not fully explain the structure of edge electric field, negative $\partial E_r/\partial r$ in thermal transport barrier and positive $\partial E_r/\partial r$ more outside. In conclusion, both of E_r and $\partial E_r/\partial r$ become more negative in the thermal barrier in L/H transition. Positive $\partial E_r/\partial r$ and particle transport barrier are observed more outside of this thermal barrier both for L- and H-mode plasma.

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Figure captions

Fig.1 Time evolution of (a) poloidal rotation velocity and (b) ion temperature at 0.4 cm and 1.4 cm inside the separatrix. The L/H transition occurs at t = 725 ms.

Fig.2 Radial profiles of (a) electron temperature, (b) ion temperature and (c) electron density of plasma before (t = 710 ms, open circle) and after (t = 740 ms, closed circle) the transition, where r/a is a normalized minor radius.

Fig.3 (a) Poloidal rotation velocity and (b) radial electric field as a function of the distance from the separatrix for L-mode and H-mode plasma, where ds is negative for inside and positive outside of the separatrix.

Fig.4 (a) Electron temperature gradient and (b) electron density gradient as a function of the distance from the separatrix for L-mode and H-mode plasma.

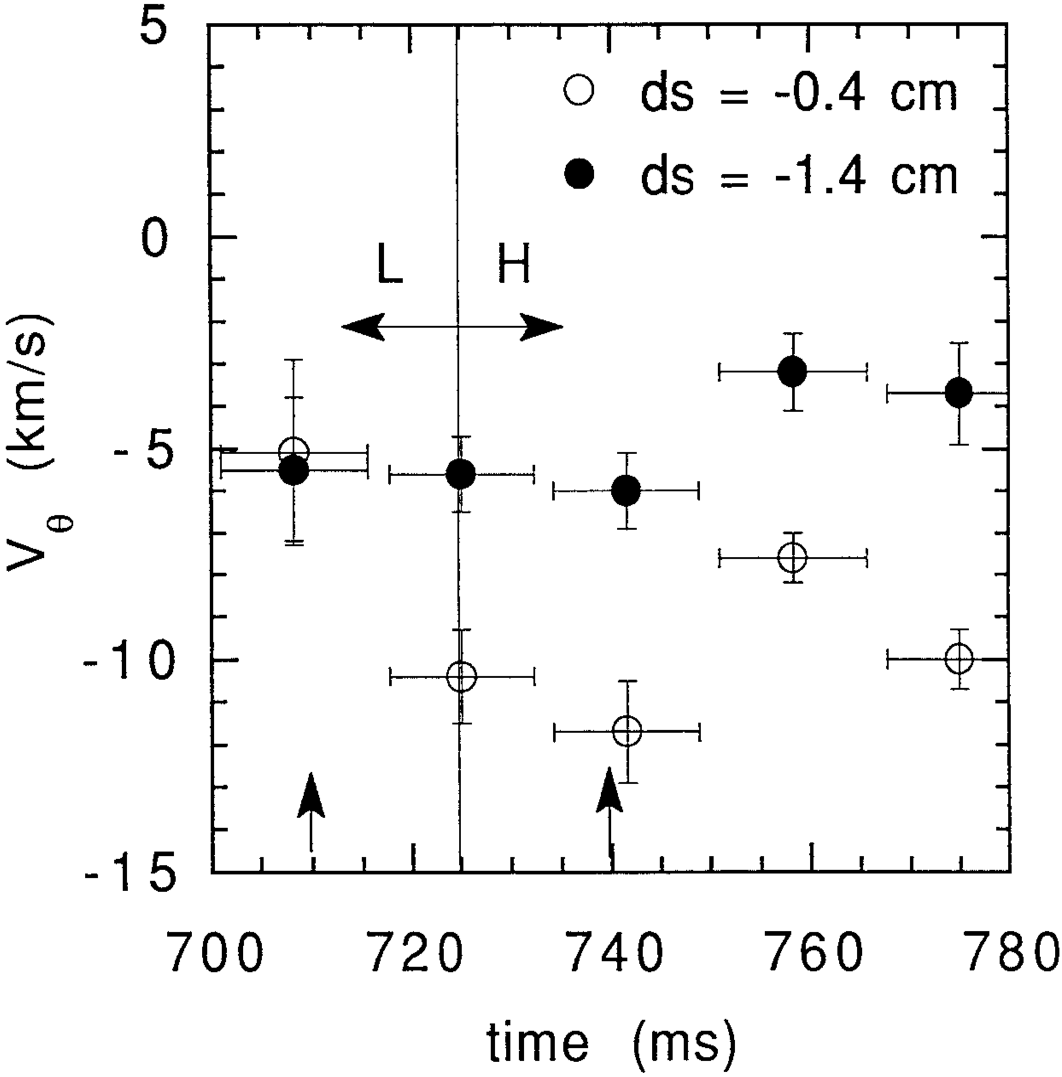
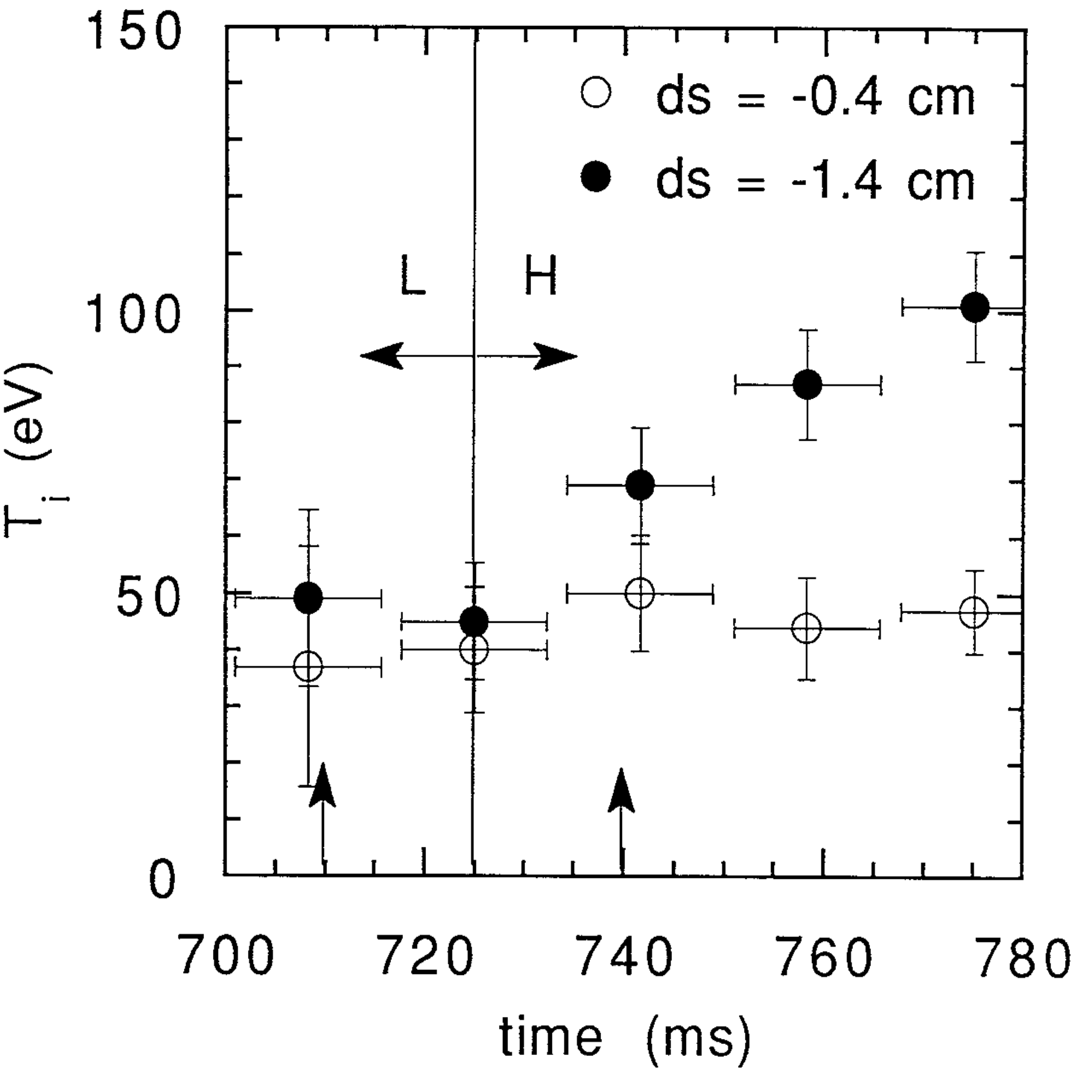


Figure 1 (a)　　K.Ida et al.



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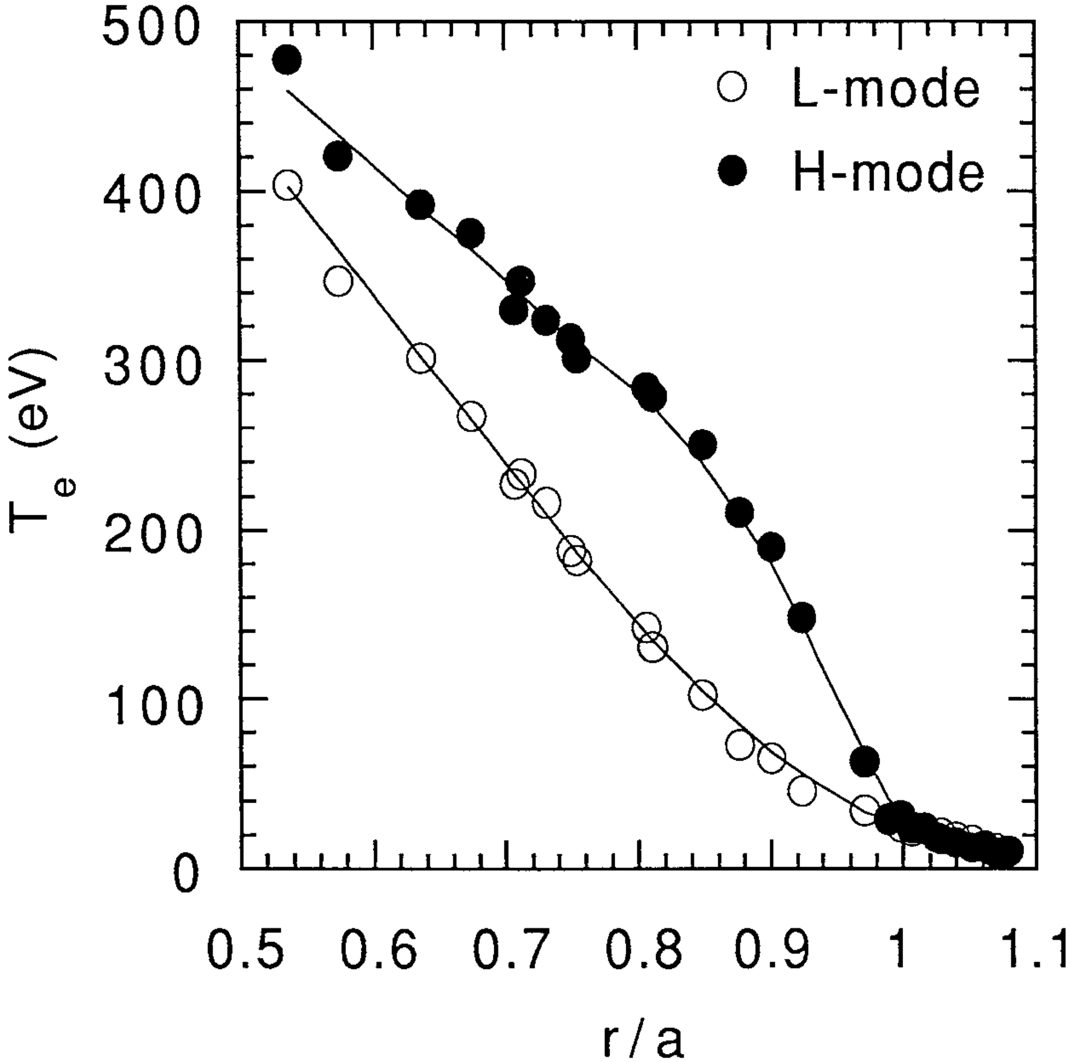

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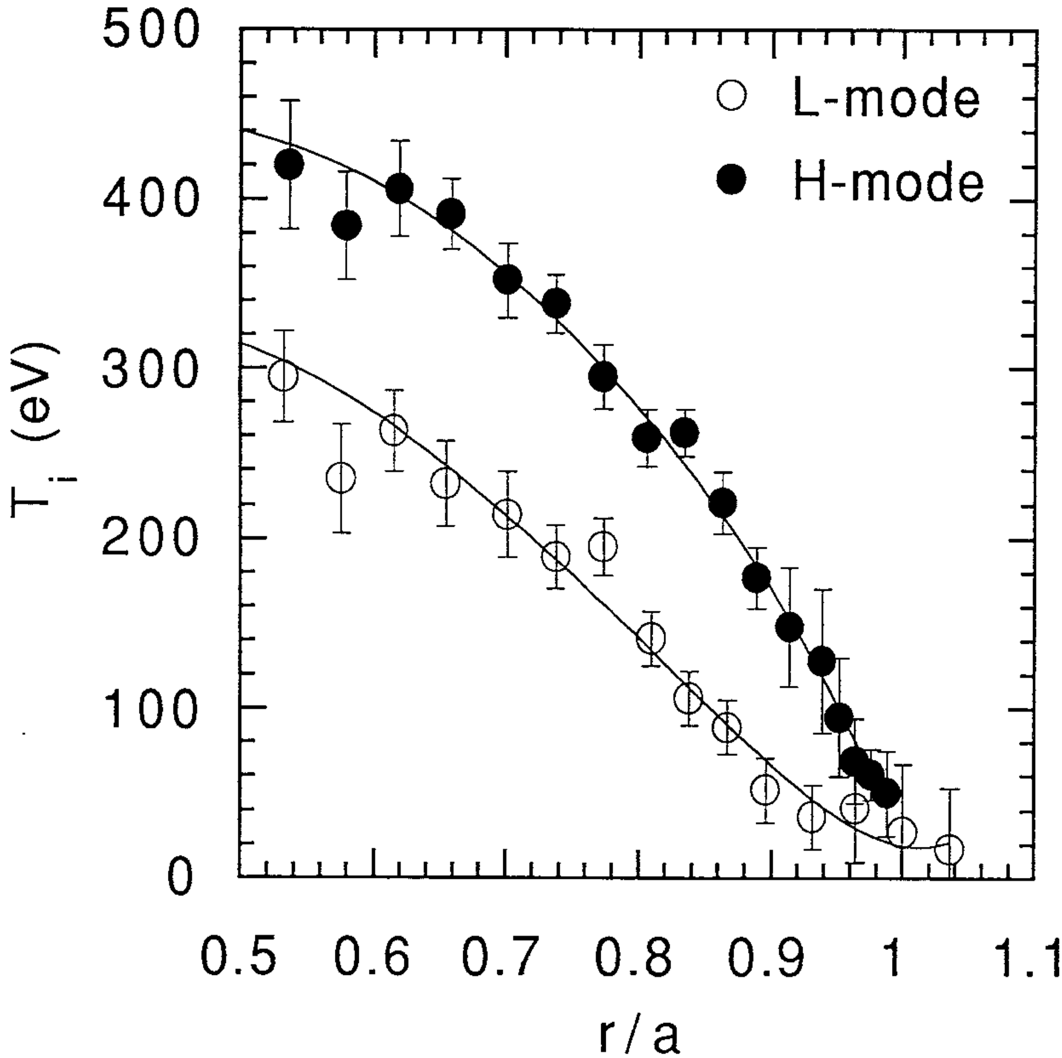

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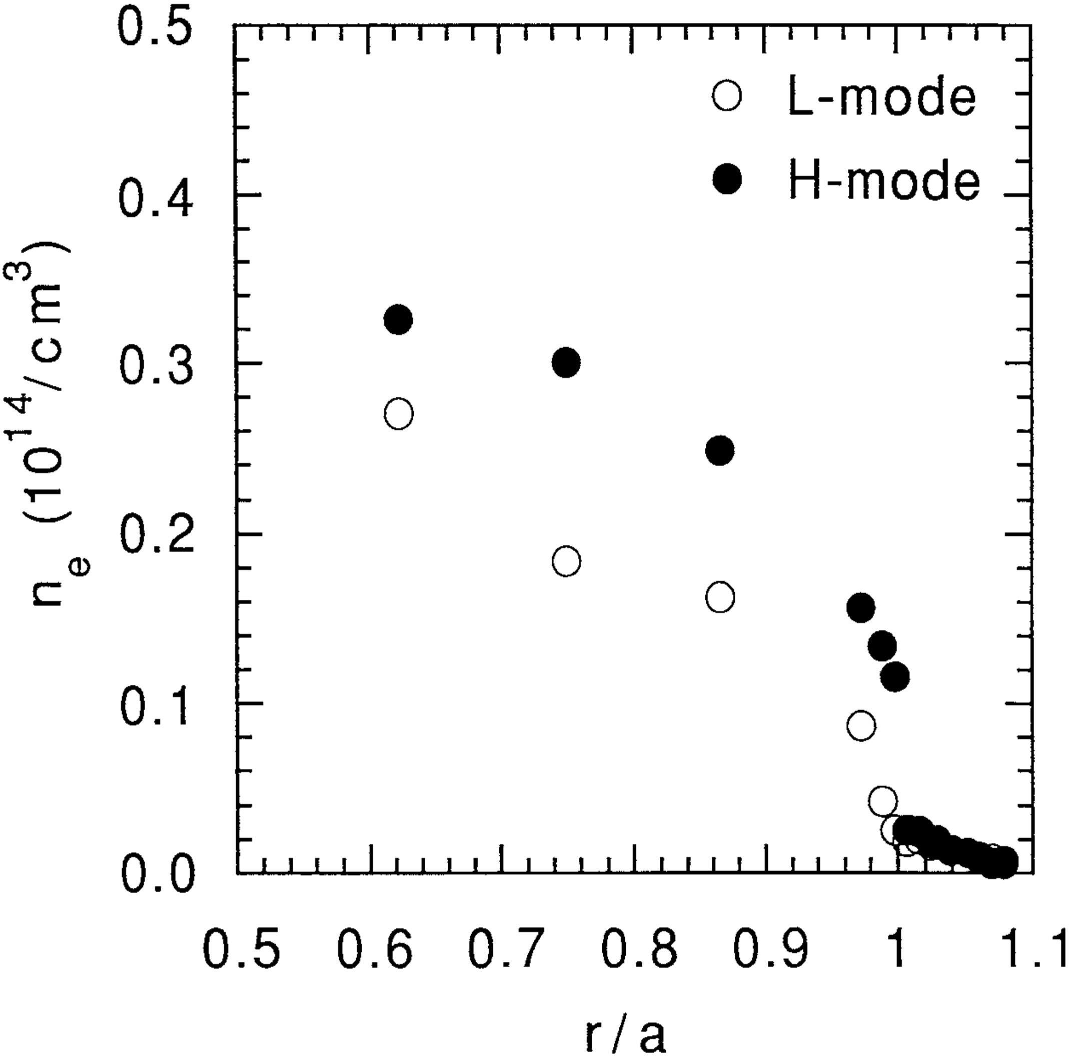
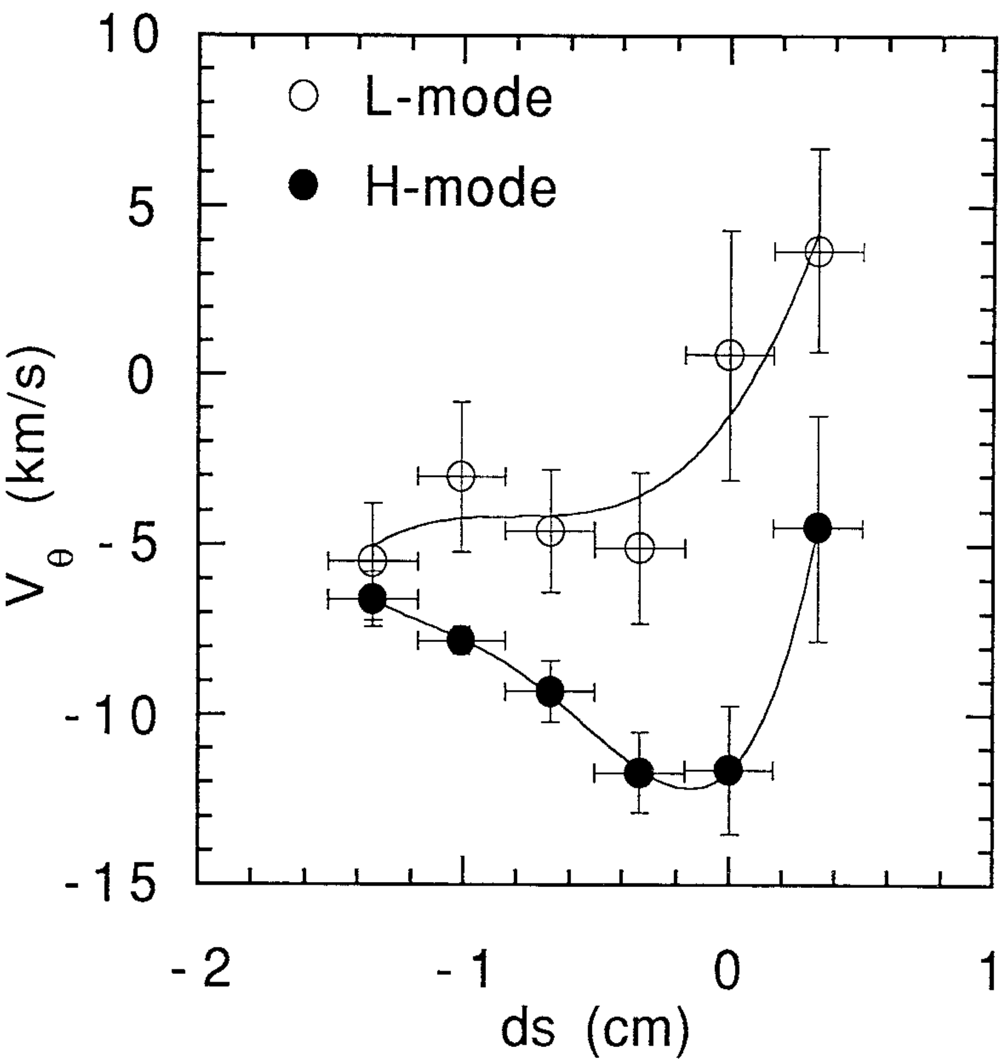


Figure 2 (c) K.Ida et al.



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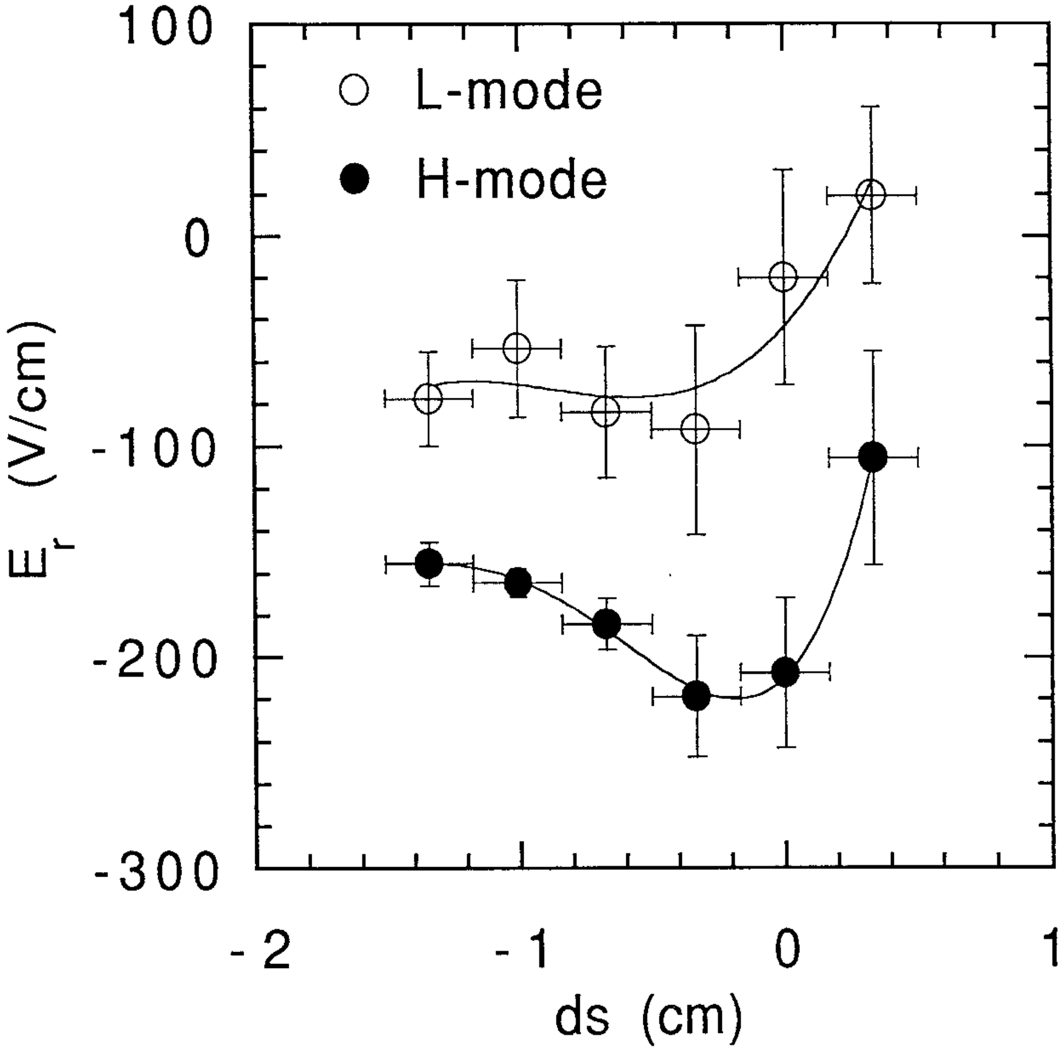

Figure 3 (b) K.Ida et al.

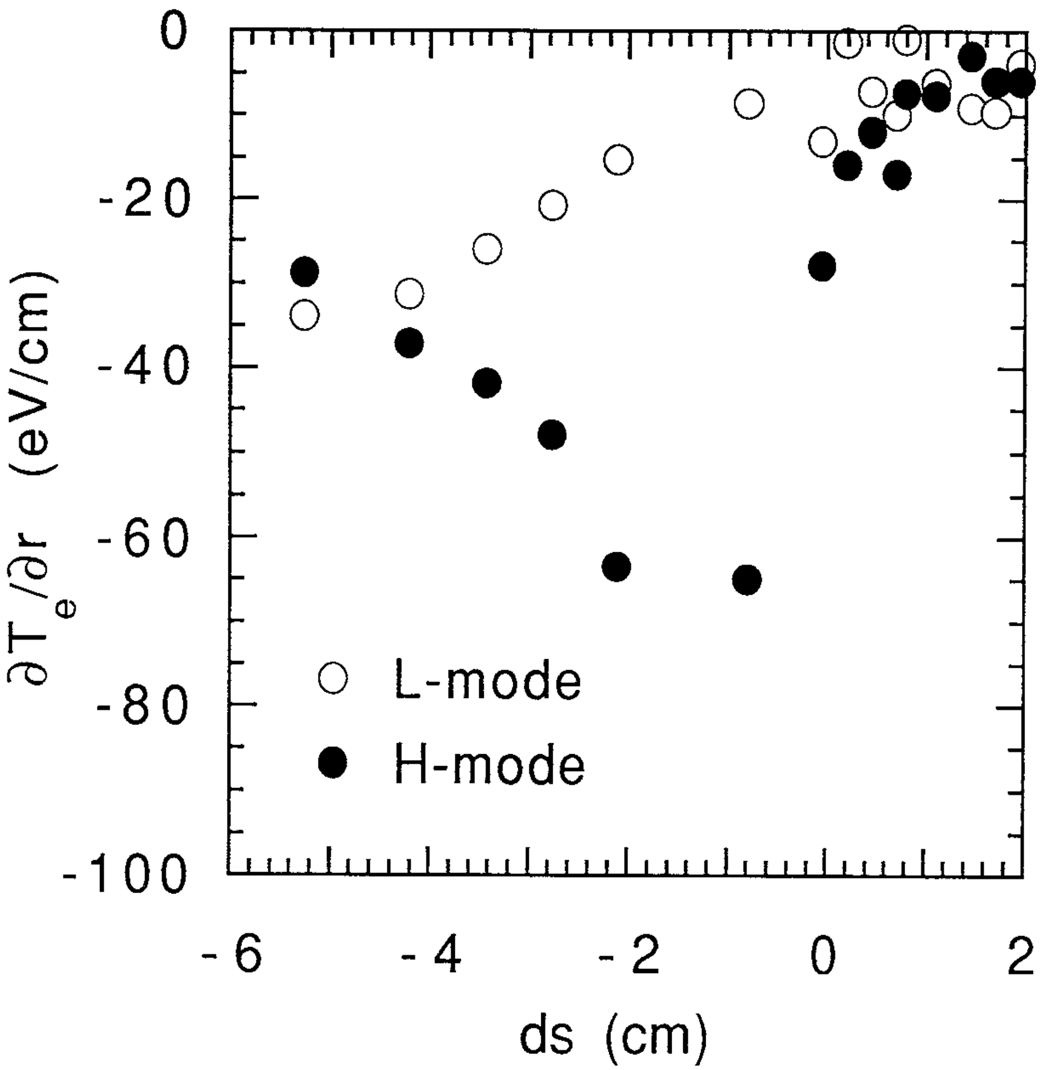

Figure 4 (a) K.Ida et al.

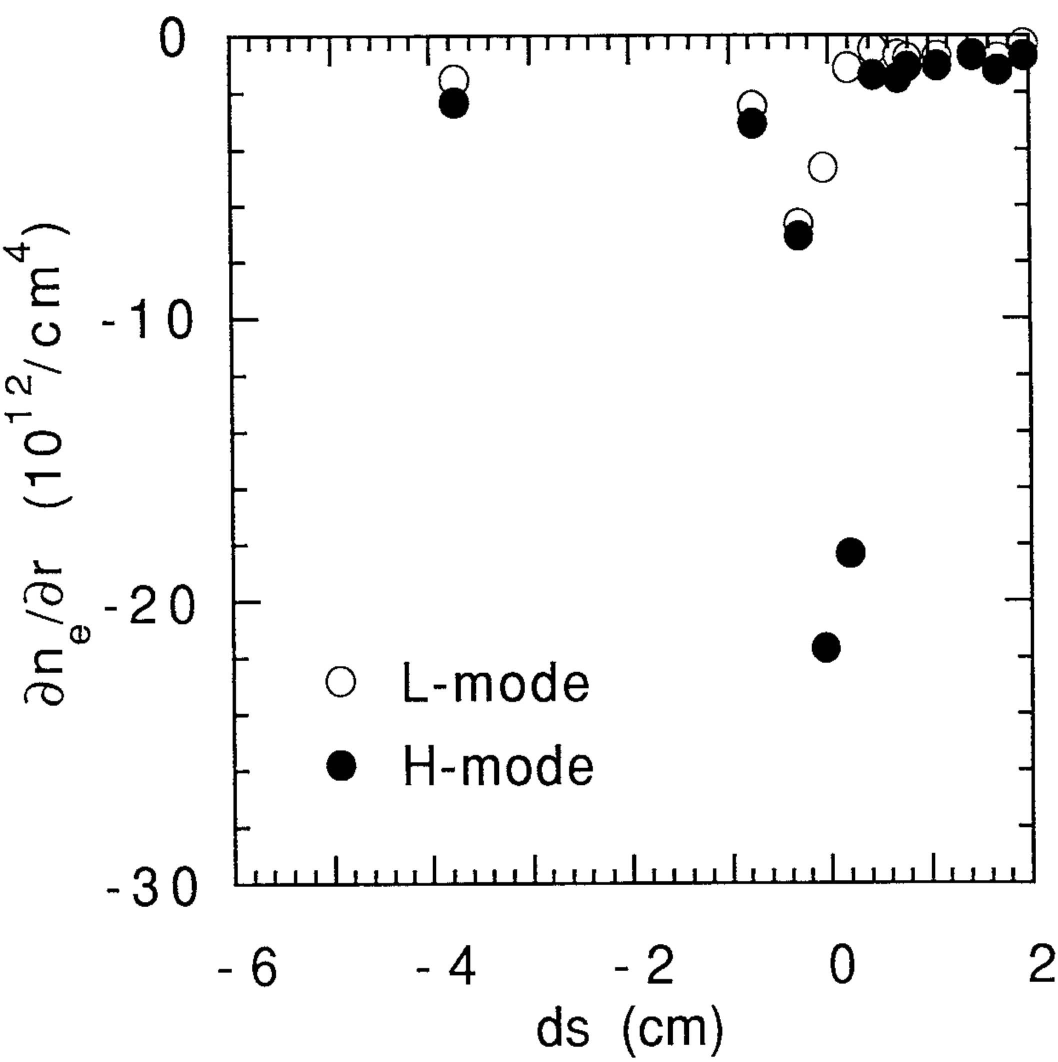

Figure 4 (b) K.Ida et al.