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Rapid Change of Hydrogen Neutral Energy Distribution at L/H-Transition in JFT-2M H-mode

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Abstract

Rapid changes of the main ion energy distribution at transitions from L-to-H, H-to-L and during ELMs are studied with the time of flight neutral measurement on the JFT-2M tokamak. At the L to H transition, 200-400μs prior to the start of H_α drop, an increase of the high energy outflux above an energy of 200eV is observed. An energy of more than 200eV for hydrogen corresponds to the collisionless condition $\nu_{*i}<1$ just inside the separatrix. The change of the energy distribution precedes that of the H_α signal and is also found for ELMs and the H to L transition.

Keywords: H-mode, L/H Transition, TOF Neutral Measurement, ELMs, H_α Signal, Energy Distribution Function, Transport Barrier, Main Ions

Since the H-mode transition was first found in ASDEX[1,2], the H-mode discharges were obtained in almost all tokamaks regardless of the heating methods and of the configurations[3-12]. The H-mode transition is now regarded as a general physics phenomenon in high temperature toroidal plasmas. The continuous studies of its physics have shown a new area in the research of high temperature plasmas. Furthermore, the H-mode operation, characterized by the improved particle and energy confinement, is nominated as a standard operation on next step devices such as ITER[13].

The onset of the L- to H-mode transition is well characterized by many observations, such as the sudden reduction of the H_α signal, the reduction of the heat flux to the divertor, and the rapid increase of the temperature and the density near the edge, in connection with the development of steep gradients[2]. Extensive measurements of the spatial structure of the density, the temperature as well as the electric field have been done, and the locations of the thermal and the particle transport barrier have separately been found[14]. However, the origin of the each barrier has not been well understood yet.

In order to explain the sudden reduction of the edge transport at the L/H transition, the formation of a transport barrier at the edge associated with a change of the radial electric field, E_r, or that of the poloidal rotation velocity, V_θ, have been predicted[15-18]. In several measurements, the changes in E_r and V_θ were indeed observed[14,19,20]. With respect to the causality involved in the transition, however, our knowledge is at present quite limited. Since the transition involves a rapid change of Er, both the dynamics of electrons and ions are to be investigated separately. Measurements of the 2nd harmonic electron cyclotron emission (ECE) have revealed that the rise of the edge electron temperature and the formation of a transport barrier of electron appear inside the last closed flux surface, and that they occur faster than the start of the reduction of the H_α signal[2]. Regarding the ion response, the changes of T_i and V_θ have been measured by the charge exchange recombination spectroscopy (CXRS) with impurity ions[14,19,20]. The time resolution of these measurements is 1ms at best. So no argument can be made on the causality among various changes within 1ms. Moreover, no direct information of the main ion response with fast time resolution has been reported. There is a finite time for equilibration between impurities and main ions, and direct measurements on the bulk ion are necessary for the transition physics. The theoretical models have predicted the important role of the main ion loss, in particular the nonlinear response of the loss-cone loss to E_r. To identify the key of transition physics, the main dynamics and the causality among various changes are to be explored.

This letter reports the transient response of main ions at the L/H transition. A time of flight (TOF) measurement[21-23] is made of the low energy (40eV-1keV) hydrogen neutrals. It is found that the increase of the average energy of the neutral flux, <E>, precedes 200-400μs to the H_α reduction. The fact clearly shows the causality; the fast increment of <E> and the formation of the transport barrier occur simultaneously with its time resolution permits. Furthermore, the increase of <E> is found to be mainly contributed from particles which have the energy higher than 200eV. The energy of 200eV coincides the condition of $\nu_{*i} \approx 1$. The precedence of the change of <E> to H_α signal is also confirmed at the onset of the edge localized mode (ELM) as well as the H/L transition. The fast responses of main ions, in particular the collisionless component, are first measured and the causality between the change of main ions and the formation of the transport barrier is clearly identified in this experiment.

The JFT-2M is a medium size tokamak (major radius R=1.31m, minor radius a=0.35m, elongation κ<1.7, toroidal magnetic field B_T<1.5T). The following experimental study on the H-transition physics was performed with a hydrogen NB power of 1.3MW (CO-injection of 0.74MW, CTR-injection of 0.59MW, and primary energy of 32keV) and the plasma current I_p is 230kA with a upper single null divertor configuration. The central line average density $\bar{n}_e$ is $2.7 \times 10^{19} m^{-3}$ at the L/H transition.

The TOF diagnostic system is installed on the top of JFT-2M torus[23]. The hydrogen neutral energy distribution, $d\Gamma/dEd\Omega$ [number/(eV•sr•m^2•sec)], is measured vertically at R=1.24m. The measurable minimum energy is ≈40eV and the maximum one is 1keV/amu, which is determined by the required energy resolution of $\Delta E/E \le 20\%$. The mass of neutral particles cannot be discriminated. We study the case of hydrogen plasmas heated by hydrogen neutral beams. The temporal evolutions of the integrated flux, Γ [$=\int (d\Gamma/dE)dE$], and the averaged energy, <E> [$=\int E(d\Gamma/dE)dE/\int (d\Gamma/dE)dE$], are calculated from the energy spectrum. At the L/H transition, the neutral outflux reduces and the signal to noise ratio (S/N) deteriorates. This phenomena, which comes from the improved particle confinement and associated reduction of neutral particles, prohibited measurements with high time resolution. In order to avoid this difficulty, the new technique of a diagnostic gas puff just in front of the TOF measured position has been utilized. This technique allows us to evaluate the $d\Gamma/dEd\Omega$ (and hence Γ and <E>) with the maximum time resolution of ≈200μs, which is, at present, the fastest measurement of the main ion distribution. The gas puff of about 10Torr•l/sec increases the TOF measured neutral outflux by more than one order of magnitude. The time history of Γ is almost constant in time and does not show a reduction[23] like the H_α signal after the L/H transition. We have confirmed that this does not have a large influence on the H_α measurement, which is alone at 110 degrees in toroidal direction from the TOF measurement . The effects on global quantities such as the transition time, stored energy and MHD behavior is only through a small increase of the density. The digitizing time of the measurements on TOF and H_α is carefully calibrated. The line of sight of H_α does not cover the divertor region. The delay of H_α signal, which arises from the finite time of signal propagation in the scrape off layer (SOL) is less than 200μs. The time delay of between observations on H_α at various positions is examined and is found less than 200μs. In this report, the coincidence can be studied with the time resolution of 200μs.

A rapid change of <E> is observed at L/H transition prior to the H_α reduction. Figure 1(a) shows the time traces of average energy <E> and H_α signal, in which the L/H transition takes place at around 822.7ms. In this discharge, the H-mode extends to t=920ms, associated with some ELM activity. The precedence of the change in the average energy <E> is more clearly seen in Fig.1(c). This Lissajous plot shows that a sudden increase of the average energy by 30-50eV occurs within a time period of 200-400μs. During this rapid rise of <E>, H_α intensity remains at the same level as during the L-phase, and starts decreasing later. The growth of <E> occurs a few hundreds micro second earlier than the H_α intensity starts dropping. The average energy remains approximately constant during a time period of 1ms, and then starts to increase again, up to 300eV, with a characteristic time scale of a few to 10ms. The rapid rise of <E> at an L/H transition and the slow increase after the transition are seen in many discharges; these facts cast a key for the causality in the transition physics and development of the transport barrier.

Figure 1(b) illustrates the ECE electron temperature, T_e^{ECE}, at three different radial positions. The L/H transition is triggered by the sawtooth. This is a well known behavior associated with the transition. The ECE electron temperatures at r/a=0.94 and 0.78 do not show the decrease after the transition takes place. By plotting T_e^{ECE} just inside the separatrix against the H_α intensity, the same behavior as shown in Fig.1(c) is seen. At present, we can not distinguish which of T_e^{ECE} or <E> starts to change first. During the transition (from 822ms to 823ms), the increment of $T_e^{ECE}(0.94a)$ is observed to be 70eV: this is larger than that of <E> (about 50eV).

The increment of the average energy of the main ions is due to the high energy particles, with energies greater than 200eV. In Fig.2, the energy distribution just after the transition (averaged 822.7ms<t<823.3ms, closed circles) and that of the L-phase (averaged 820.0ms<t<822.0ms, open circles) are compared. In the H-phase, these is a large increase of the high energy outflux. During the H-phase, the high energy component increases further (solid line), with keeping its characteristic feature. The energy above which the spectra differ in L- and H-phases is found to be 200eV. The collisionality parameter $\nu_{*i}=[\nu_{ii}qR/(v\varepsilon^{3/2})]$ for the protons of 200eV is about unity for the plasma parameters just inside of the separatrix. The normalized collisionality ν_{*i} is larger than 1 for the main ion temperature at the edge. We found for the first time in this experiment that the difference appears for the collisionless part of spectrum, for which ν_{*i} is less than unity. To study the correlation with the collisionality, we did check the I_p dependence from 160kA to 290kA. The difference of $d\Gamma/dEd\Omega$ between L- and H-modes appears above similar critical energies (about 170-250eV) in all cases. In this series of discharges, the I_p dependence of ν_{*i} was offset by the edge density variation ($\overline{n}_e{}^{edge} \cdot q_{eff}$ was almost constant with different I_p). The difference of the energy spectra also might occur around $\nu_{*i}=1$.

The rapid reduction of <E> is also observed in the case of an H-to L-mode transition. In this case, however, the time resolution is not better than 1ms; we confirmed that the change of <E> occurs within 1ms. The drop of <E> at the H/L transition is due to the reduction of the number of particles with energies larger than 200eV.

The change of the TOF spectrum is also investigated for the ELM activities. Within the maximum time resolution of 200μs, the average energy does not decrease to the L-mode level at all ELMs. We see the clear difference of energy distributions. In Fig.3, the energy spectrum is shown at five time slices during ELM activity. About 860μs prior to the increment of H_α signal, the strong depletion of the particle flux (closed circles) compared with that during a normal H-phase (open triangles and squares) occurs in the energy range of E≥200eV. This depletion is often preceded by the small increase. The spectrum for the energy range of 200eV≤E≤500eV reduces to that of the L-phase. Then the flux whose energy of E≥200eV starts increasing, and exceeds the level of H-phase, reaching the peak (closed square). The peak is observed 1ms after the depletion and coincides with the increasing phase of H_α signal. The energy spectrum at 500μs after its peak recovers to the normal shape of an H-mode. From these observations, one can conjecture that the change of the ion transport barrier starts about 200μs prior to the depletion of the spectrum, and that the later recovery from the depletion indicates the reformation of the transport barrier. The characteristic duration time of the loss of main ions (≥200eV) is about 400-1000μs.

In summary, we have observed a rapid evolution of the spectrum of low energy neutral hydrogen flux (40eV-1keV) with a good time resolution of ≈200μs. It is found that the sudden change of the average energy of the spectrum takes place within the time scale of 200-400μs. The change precedes the start of H_α reduction by 200-400μs. This is the first observation that the change of main ions occurs at the same time as the transport barrier is being established. The precedence of the change of the energy distribution to that of H_α is also confirmed for the case of H- to L-mode transition and ELMs. In these rapid transitions, the main change in spectrum occurs above 200eV, for which protons are in the collisionless regime ($\nu_{*i}<1$). The criteria of $\nu_{*i}<1$ was not completely verified, but the observation on the cases of different plasma current at present confirms this hypothesis.

This observation of the rapid change of the spectra (particularly for ions $\nu_{*i}<1$) is consistent with the bifurcation models of the H-mode, in which the direct loss of collisionless ions are reduced by the radial electric field. The location where the change in the ion distribution occurs, however, can not be clarified in this experiment, because the line of sight of the TOF measurement extends from the SOL to the main plasma. In this measurement during an ELM activity, the change of the neutral energy distribution does not change from the energy spectrum of an H-phase to that of an L-phase. This is in contrast to the DIII-D result that the impurity rotation velocity was found to decrease to the level of L-phase during ELMs. A possible explanation is that the collisionless component, 200eV≤E≤500eV, has the most crucial role in the dynamics of the transition. The depletion time of this component, however, is still shorter than the observation in DIII-D. The difference in the responses of main ion and impurities should be further examined. The other possibility is that ELMs of different kinds are to be examined.

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Figure Captions

Fig.1 (a)Time evolution of the average energy and the H_{α} intensity. (b)Temporal evolutions of the ECE measured electron temperature at 3 different radial positions. (c)The plot of the average energy versus H_{α} intensity from the time period of 819.1msec to 824.9msec. The jump of the average energy occurred at 822.72ms.

Fig.2 Hydrogen neutral energy spectra at L-phase (open circles, averaged from 820.0ms to 822.0ms), L/H transition (closed circles, averaged from 822.7ms t0 823.3ms), and H-phase (solid line, averaged from 832.6ms to 837.6ms).

Fig.3 Hydrogen neutral energy spectra during the first ELM activity shown in Fig.1(a). The H_{α} intensity starts increasing from 825.6ms.

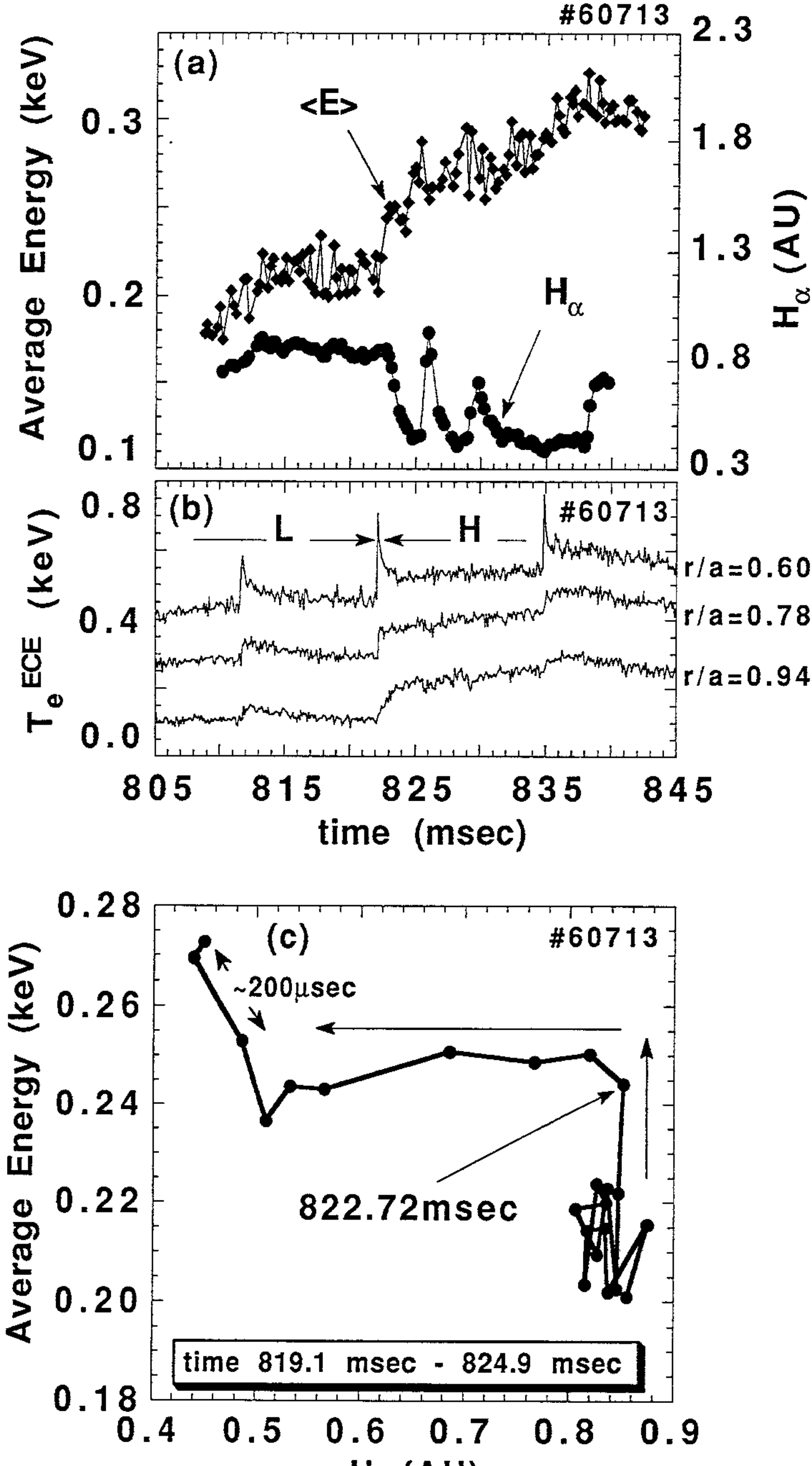

Fig.1 Y.Miura et al.

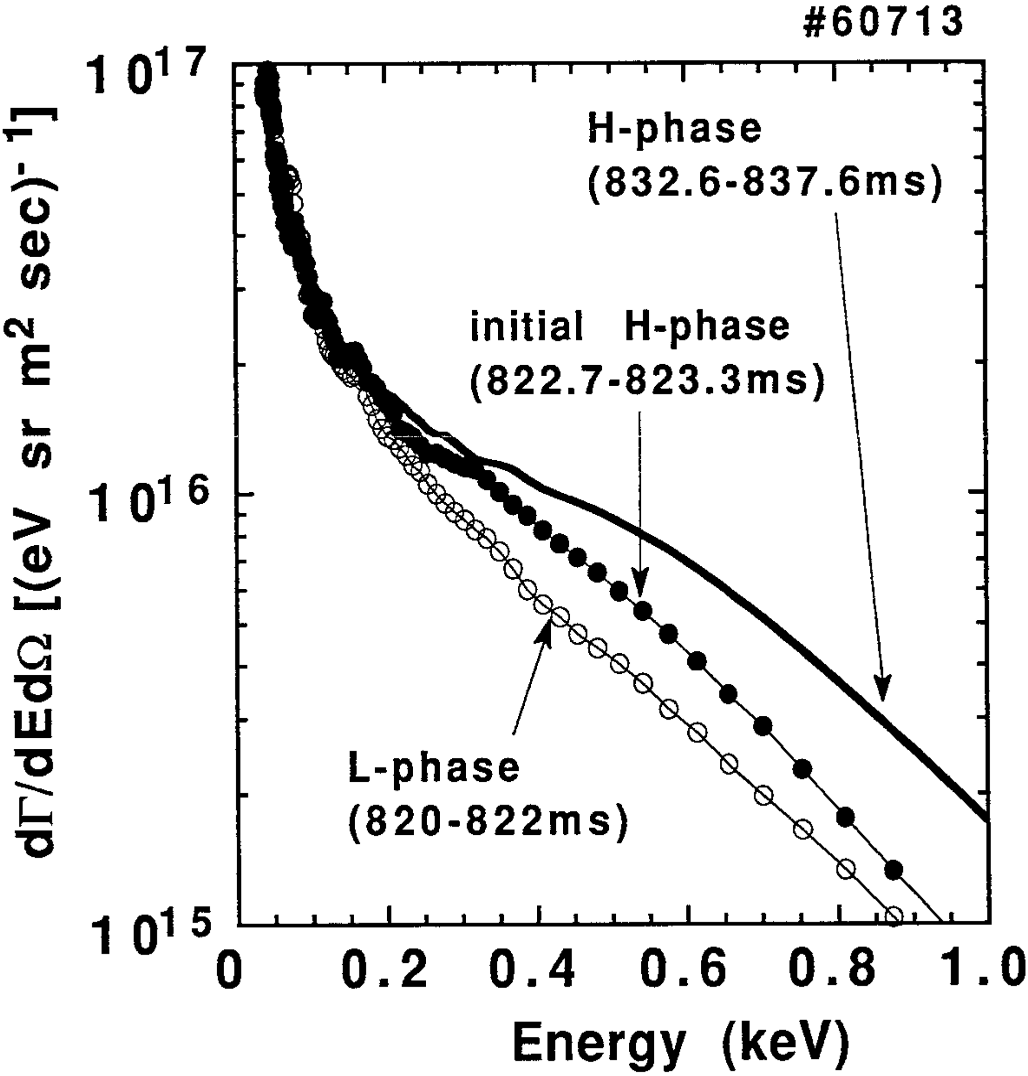

Fig.2 Y.Miura et al.

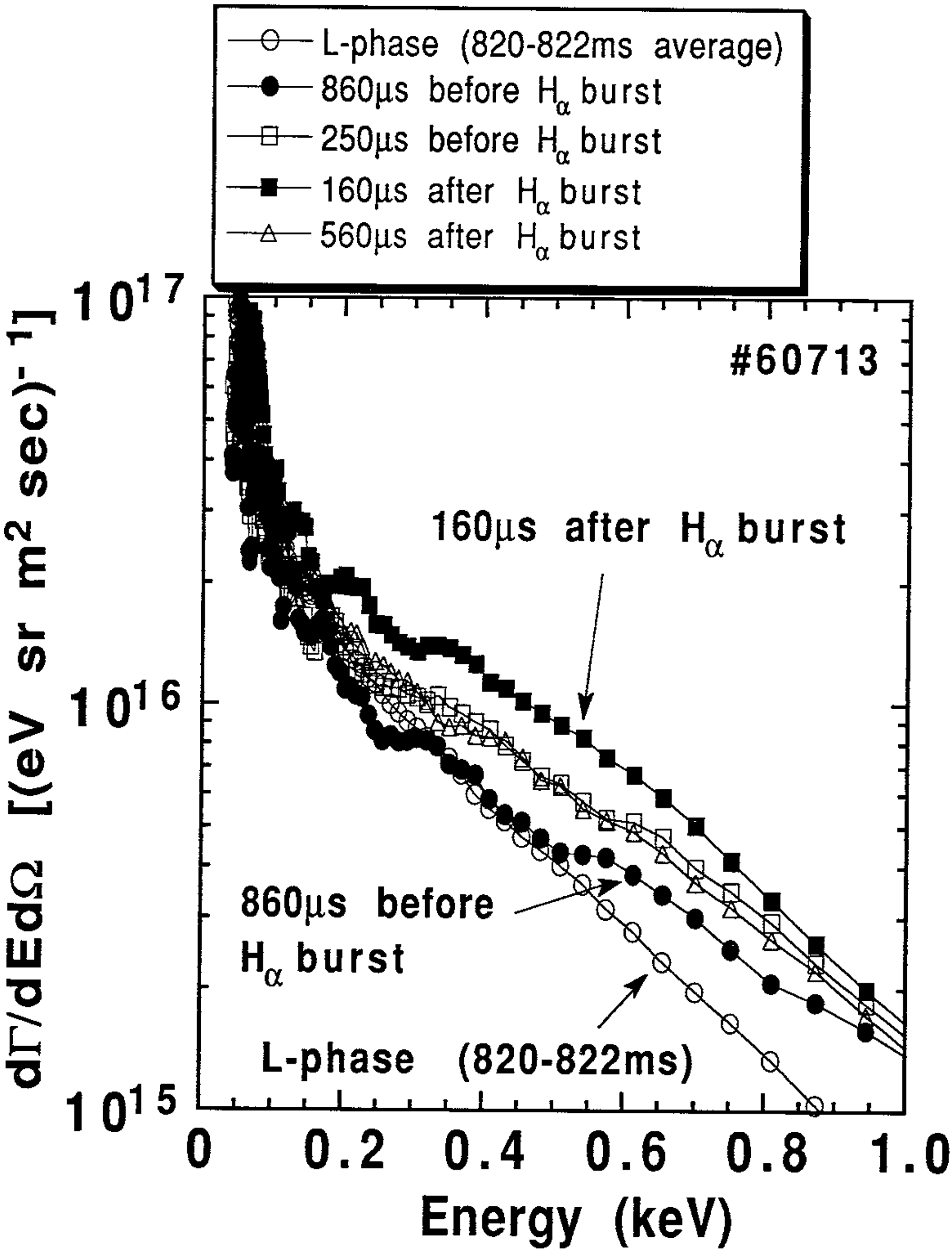

Fig. 3 Y.Miura et al.

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