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# Ion Heat Pulse after Sawtooth Crash in the JFT-2M Tokamak

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**Abstract**

The ion heat pulse after sawtooth crash is studied with the time-of-flight neutral measurement on the JFT-2M tokamak. The rapid change of the bulk ion energy distribution near the edge is observed after sawtooth crash. The delay time is measured and the effective measuring position is estimated by a neutral transport code, then the thermal-conductivity, $\chi_i^{HP}$, of about 15±10m$^2$/sec is evaluated for the L-mode plasma. The simple diffusive model with constant $\chi_i^{HP}$, however, does not explain the amplitude of the pulse in the ion energy distribution.

Keywords: Heat Pulse Propagation, Ion Energy Loss, Sawtooth, Time-of-Flight Measurement, Neutral Particles

Understanding the transport process in a toroidal plasma is one of the most urgent tasks in magnetic fusion research. After the measurement of density and temperature with good spatial resolution, the effective heat diffusion coefficient, $\chi_{eff}=-q/(n\nabla T)$, is evaluated and it is found to be anomalous[1]. The transient response of a plasma shows an interesting transport behavior, for example the decay time of the plasma energy after switching off the ICRF heating power is different from the energy confinement time[2]. The difference between a transient response and an evaluated $\chi_{eff}$ at a stationary phase seems to be the property of a toroidal plasma. After first being observed on the Princeton ST tokamak[3], the electron heat pulse propagation after sawtooth crash is a tool to measure an electron heat diffusivity from the transient response[4]. It is well known that the electron heat diffusion coefficient from the heat pulse propagation, $\chi_e^{HP}$, can be much larger than the $\chi_{eff}$. The density pulse[5] after sawtooth crash was also found and its mutual interaction[6] is discussed recently. The heat diffusion coefficient of ion in a stationary phase is sometimes larger than that of electrons[7,8] and plays a key role in the high power heating experiments. The ion heat pulse propagation, however, has not been investigated in spite of its importance of the understanding of confinement. The resonant loss of energetic ions at the fishbone instability[9] is reported as a fast transient behavior of ions. But the transient response of the bulk ions has not been studied well.

This letter reports the transient response of main ions after sawtooth crash and shows the existence of ion heat pulse for the first time. A time-of-flight (TOF) measurement[10,11,12] is made of the low energy ($E \leq 1$keV) hydrogen neutrals with fast time resolution

(~200μsec). It is found that the average energy of the neutral flux, <E>, responses after a sawtooth crash. This response is faster than the energy exchange time between electrons and ions and than the change of $H_\alpha$ intensity as well. The contribution to the change of TOF signal comes from near edge. Therefore, it is shown clearly that there exists an ion heat pulse after a sawtooth crash. $\chi_i^{HP}$ of about $15\pm10 m^2/sec$ is evaluated. The change of <E> is found to be mainly contributed by particles which have energy higher than about 200eV, which coincides with the collisionless condition of hydrogen ion, $\nu_{*i}\leq1$ near edge. However, the comparison between a calculated and the measured neutral energy distribution shows that the simple diffusive model with constant $\chi_i^{HP}$ does not completely explain the ion heat pulse behavior.

The JFT-2M is a medium size tokamak (major radius R=1.31m, minor radius a=0.35m, elongation $\kappa<1.7$, toroidal magnetic field $B_T<1.5T$). The following experimental study of sawtooth effects on an ion energy distribution was performed with a hydrogen NB power of 1.3MW (co-injection of 0.74MW, counter-injection of 0.59MW, and primary energy of 32keV). The plasma current $I_p$ is 230kA with an upper single null divertor configuration. We study the sawtooth during the L-mode phase before the L/H-transition. The central line average density is about $2.5\times10^{19}m^{-3}$ during L-mode.

The TOF diagnostic system is installed on the top of JFT-2M tokamak as shown in Fig.1 schematically. The hydrogen neutral energy distribution, $d\Gamma/dEd\Omega$ [number/(eV•sr•$m^2$•sec)], is measured vertically at R=1.24m. The line of sight measurement does only include the outside sawtooth inversion radius, which is measured by the second harmonic electron cyclotron emission (ECE). The measurable minimum energy is about 10eV and the maximum one is 1keV/amu, which is determined by the required energy resolution of $\Delta E/E \leq 20\%$. The mass of neutral particles cannot be discriminated. We study the case of hydrogen plasmas heated by hydrogen neutral beams. The temporal evolution of the integrated neutral flux, $\Gamma\{=\int(d\Gamma/dE)dE\}$, the power flux, $P\{=\int E(d\Gamma/dE)dE\}$ and the averaged energy, $\langle E \rangle\{=\int E(d\Gamma/dE)dE/\int(d\Gamma/dE)dE\}$, are calculated from the energy spectrum. In order to increase the signal-to-noise ratio (S/N), the technique of a diagnostic gas puff just in front of the TOF measured position has been utilized sometimes. This technique allows us to evaluate the $d\Gamma/dEd\Omega$ (and hence $\Gamma$, P and $\langle E \rangle$) with good S/N and the fastest time resolution of about 200μs, which is limited by the rotation velocity of the chopper wheel in TOF neutral spectrometer. The gas puff of about 10 Torr•l/sec increases the TOF measured neutral out flux by more than one order of magnitude. The time history of $\Gamma$ is almost unchanged in time in this case. The digitizing time of the measurements on TOF and $H_\alpha$ is carefully calibrated. The line of sight of $H_\alpha$ measurement is almost the same viewing angle as TOF measurement, which does not cover the divertor region. The digitizing time of the measurements on TOF and ECE is not calibrated. We have used the same trigger for those two digitizers, but there might have ambiguity of one sampling time of the digitizer (100μs). In this report, the coincidence can be studied with the time resolution of ±100μs.

The temporal evolution of ECE electron temperatures, the averaged energy $\langle E \rangle$, the power flux P and $H_\alpha$ Intensity are shown in Fig.2. NB heating is started form 800msec. The diagnostic puff is not applied in this case. The rapid jump of the averaged energy and rather slow increase of the power flux are observed. In this discharge, the L/H transition takes place at 845msec triggered by a sawtooth. The delay time of peak ECE electron temperature at r/a=0.94 is about 0.7msec. The delay time of peak <E> is about 0.5-0.7msec and that of P is about 1.5-2msec after the crash. The change of <E> is clearly faster than the electron ion energy exchange time which is larger than about 1-2msec at the edge plasma parameter($n_e \simeq (0.5-1)\times10^{19}m^{-3}$, $T_e \simeq 50eV$, $z_{eff} \simeq 2$ ). Since the jump of <E> occurs earlier than the increase of the $H_\alpha$ intensity, then the jump of <E> is not the effects from the increase of the neutrals, which is normally observed after sawtooth crash. But the integrated neutral flux and power flux behave like an $H_\alpha$ intensity. The neutral power flux includes the increase of the neutral density itself. Then we can concludes that the bulk ions are directly affected by a sawtooth and there exists an ion heat pulse after sawtooth crash. The increase of the average energy of the bulk ions is due to the particles, with energies greater than 200-250eV. In Fig.3, the energy distributions just before (averaged 8 spectra, $819<t<821$msec) and after (averaged 6 spectra, $821.5<t<823$msec) sawtooth crash are compared. There is a large increase of the high energy neutral out flux. The collisionality parameter $\nu_{*i}=\nu_{ii}qR/v\varepsilon^{3/2}$ for protons of 200eV is about unity for the plasma parameters just inside separatrix.

In order to interpret the time delay in <E> in terms of the thermal conductivity, the analysis on the birth point of the observed neutral is necessary. This line of sight TOF measurement is a measurement of main ion energy distribution which is weighted by a neutral density in each position. Though we can not know the origin of its neutral flux exactly, we can estimate a position of the main contribution to the measured out flux by a Monte Calro neutral transport code[13]. Figure 4 shows the calculated total neutral out flux and the contribution from each position. In this calculation the energy of neutrals from the wall is monochromatic to be 5eV. The ion temperature profile from CXRS measurement, and the electron temperature and density profile from Thomson scattering are used as a typical L-mode one. The position at $\rho=1$ ($\rho=r/a$) corresponds to the separatrix and that at $\rho=1.45$ corresponds to the divertor plate. The calculated total out flux is reproduced the measured out flux within the error. The neutral out flux inside separatrix shows the strong attenuation in the low energy part. Considering the poloidal gyro radius of about 2cm for 300eV proton, the estimated origin of the measured out flux ($200\text{eV} \leq E \leq 500\text{keV}$) is around the separatrix and the contribution from the core ($\rho<0.93$) is small. If the change in $\langle E \rangle$ is the response of the arrival of heat pulse propagating to the edge, then this assumption allows us to evaluate the ion diffusivity, $\chi_i^{HP}$, from the delay time of $\langle E \rangle$ after a sawtooth crash. We also assume that the crash time of ion is the same as that of the electron. If the ion temperature perturbation by a sawtooth is described by a diffusive model, which is usually used for the evaluation of an electron heat pulse diffusivity[14], then the ion temperature perturbation is written approximately as

$$\tilde{T}_i(r,t)=T_0(r_s{}^4r^2/\chi^3t^3)\exp(-3r^2/8\chi t) \qquad (1),$$

and the time at which $\tilde{T}_i(r,\tau_{delay})$ reaches its maximum is $\tau_{delay}=r^2/8\chi$ . The estimated $\chi_i^{HP}$ is about $15\pm10\text{m}^2/\text{sec}$ from $\tau_{delay}$ of

0.7±0.3msec with using the estimated neutral origin from r=0.29m and with assuming that ion temperature crash occurs at the same time of the electron temperature crash. The $\chi_i^{HP}$ value of $15\pm10 m^2/sec$ is almost the same as the electron one, $\chi_e^{HP}$, in this case. The line of sight measurement has a disadvantage in identifying the origin of the observed neutrals. But the energy distribution measurement with fast time resolution allows a test to examine the validity of the simple diffusive model to describe the ion heat pulse propagation. With the help of Eq.(1) and constant value of $\chi_i^{HP}$, the expected neutral spectra is calculated. In this calculation, a density perturbation by sawtooth is neglected. The perturbation of the form of Eq.(1) shows a rapid reduction of amplitude as $\Delta T \propto r^{-4}$. The theoretical formula (1) predicts a very small amplitude near edge. Since the effective origin of the neutrals of our interest (100-500eV) are near edge, as is shown in Fig.4, the predicted variation of $d\Gamma/dE$ in this range is too small to explain the observation in Fig.2. (Even if we choose $T_0=3T_i(r=r_{inv})$, which would be unrealistic, the observed pulse amplitude in $d\Gamma/dE$ was not reproduced.) [We note the similar discrepancy is also found in the response of the electron temperature. For electrons, a similar value of $\chi_e^{HP}$ compared to ions is obtained. The experimental data on $\tilde{T}_e(r)$ , however, shows the behavior like $r^{-3}$. This has much slower radial decay in comparison with theoretical prediction.] This means that the simple diffusive model with constant $\chi^{HP}$ does not explain the ion heat pulse behavior. The clear difference in $d\Gamma/dE$ is observed only for collisionless ions. The different effects on the different energy particles should be studied further.

In summary, we have observed the ion heat pulse after sawtooth crash with a good time resolution of the neutral measurement. By using the Monte Calro calculation for the neutral transport, the origin of the neutral out flux is evaluated. The rapid change of the averaged energy occurs faster than the energy exchange time between the electron and ion, and also faster than the change of $H_\alpha$ intensity after sawtooth crash. It shows that it is not the effects of the change of neutral itself, but the direct effect from the sawtooth crash. In the energy distribution, the change is observed as a large increase of the high energy neutral out flux, from which ions have collisionless condition $\nu_{*i}<1$ just inside the separatrix. The heat diffusivity of ion is evaluated as $15\pm10 m^2/sec$ from the time delay of the peak of $\langle E \rangle$ assuming that the change of $\langle E \rangle$ is the direct response from the arrival of the ion heat pulse propagation. However, the calculated energy spectra by the neutral transport code with assuming the change of ion temperature by the simple diffusive model do not reproduce the measured energy spectra. The observed change of the energy distribution is too large compared with the neutral calculation result. The rapid ion change is clearly the direct effect by the sawtooth, but now there is no evidence of the propagating behavior of ion heat pulse. It should be studied further by some ion measurements with good time and spatial resolution.

The rapid change of ions which have collisionless condition just after sawtooth crash plays also an important role for the L/H-transition. Almost all H-mode are triggered by a sawtooth in JFT-2M experiment and our previous report[15] shows the important role of ion at the L/H-transition. This observation of the ion behavior during an L-mode sawtooth crash is the same as that at L/H-transition. This may be the reason why most of H-mode are triggered by a sawtooth. Some theories predict an important role of ion loss[16,17] for the L/H-transition. The neutral transport calculation shows that the origin of the measured neutrals are around separatrix even in the line of sight measurement. However, in the present experiment, the origin cannot be identified so precisely as to distinguish inside or outside of the separatrix. This should be examined further and is left for the future work.

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**Figure Captions**

Fig.1 TOF diagnostic system installed on the top of JFT-2M. The line of sight only includes the outside sawtooth inversion in this experiment.

Fig.2 Temporal evolution of (a) the ECE-measured electron temperature at five different radial positions, (b) the average energy and power flux, and (c) the $H_\alpha$ intensity.

Fig.3 The neutral energy distributions just before (open circles, averaged 8 spectra and $819<t<821$msec) and after (closed square, averaged 6 spectra and $821.5<t<823$msec) sawtooth crash are compared.

Fig.4 The calculated neutral energy distribution and its contributions form each position. $\rho=1$ is the position of the separatrix. Open circles show the measured neutral out flux.

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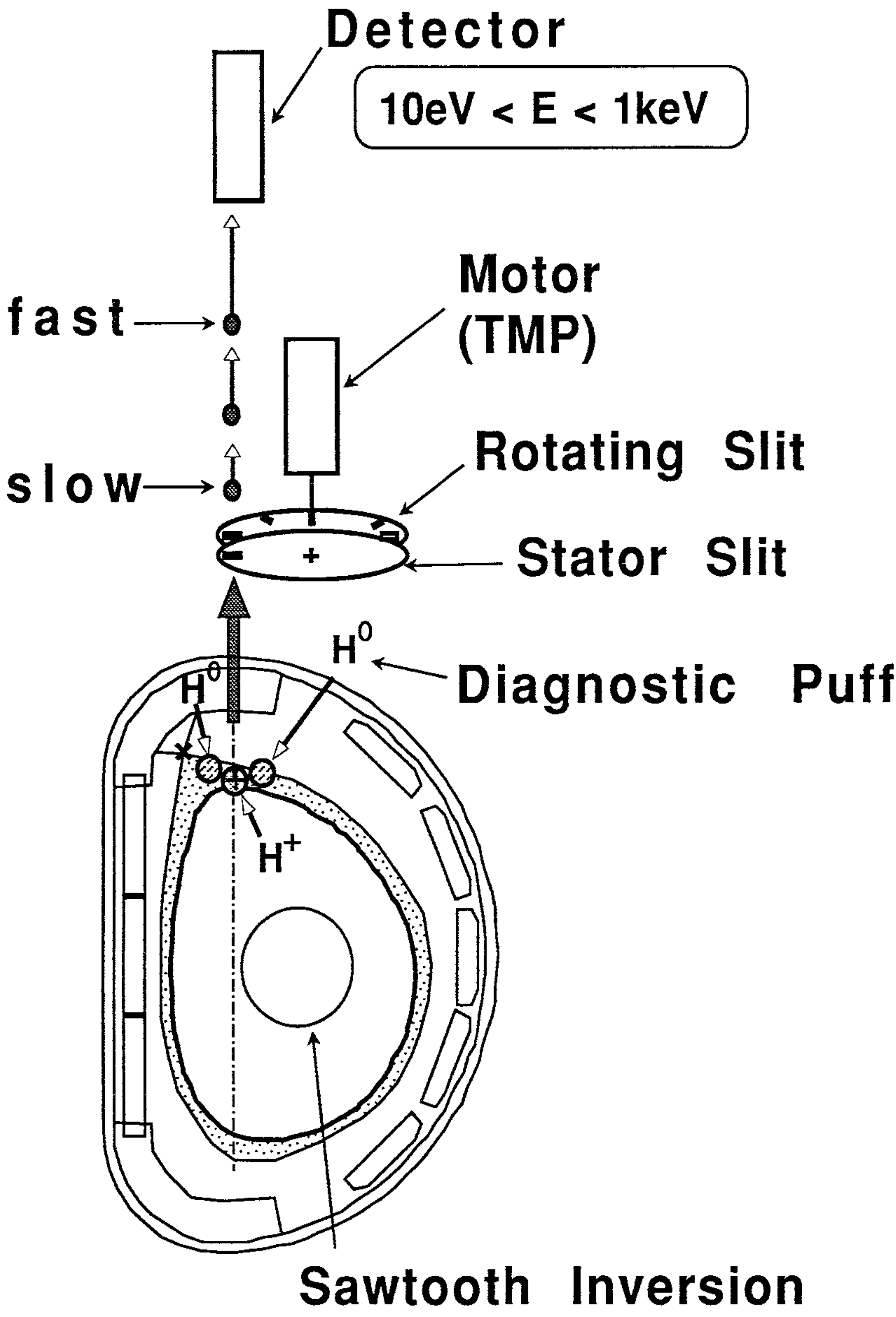


Fig.1 Y.Miura et al

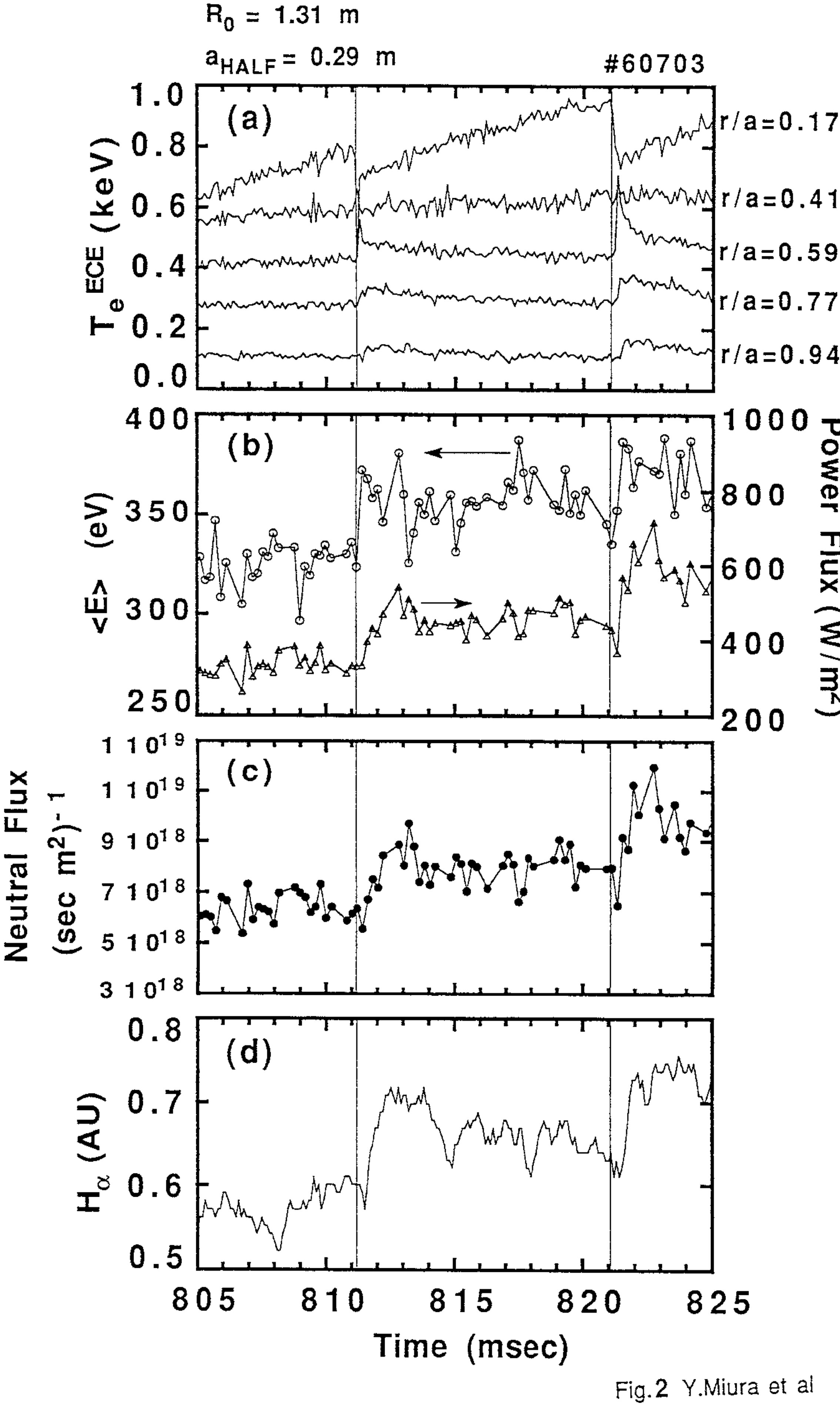


Fig.2 Y.Miura et al

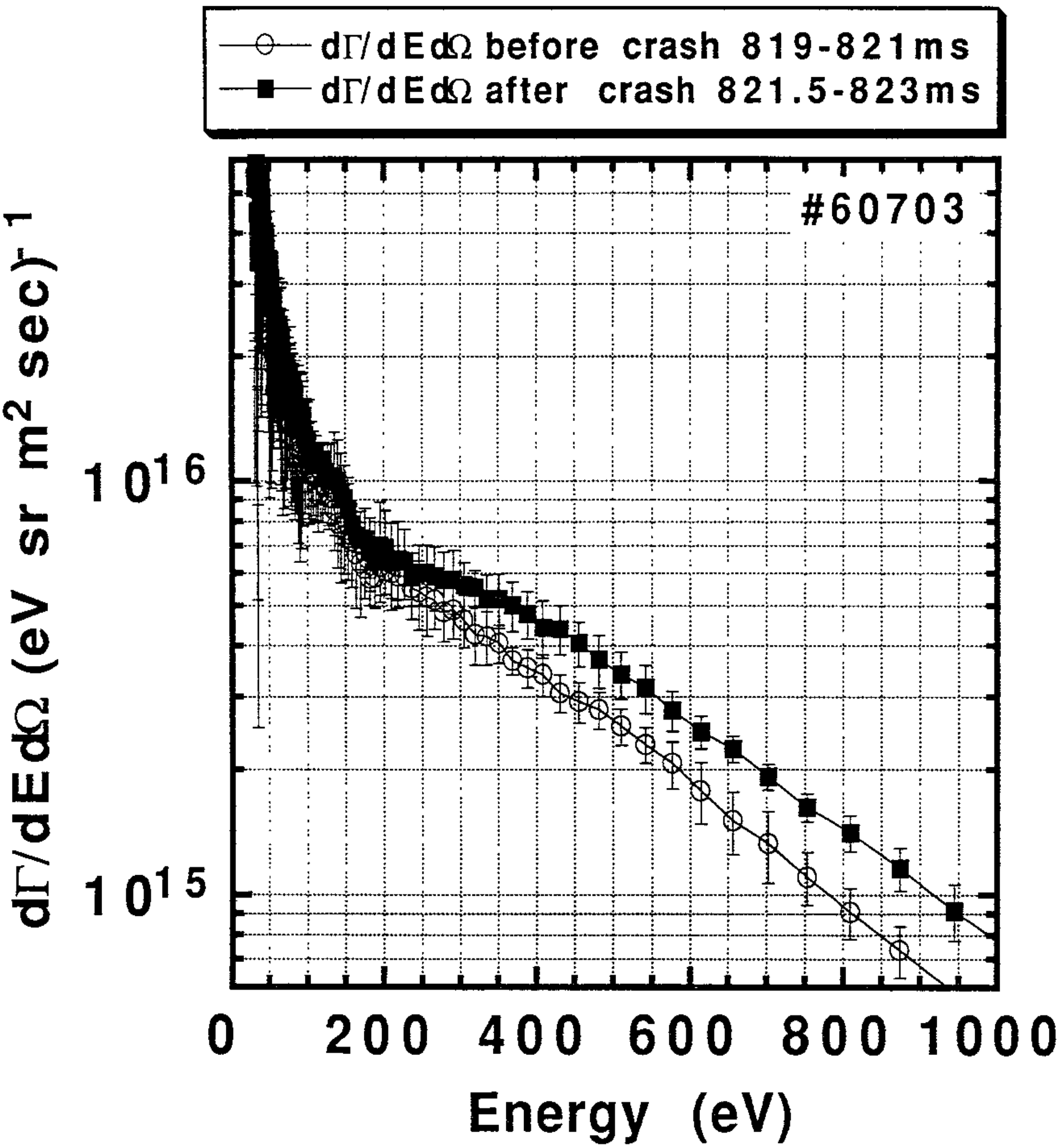


Fig.3 Y.Miura et al

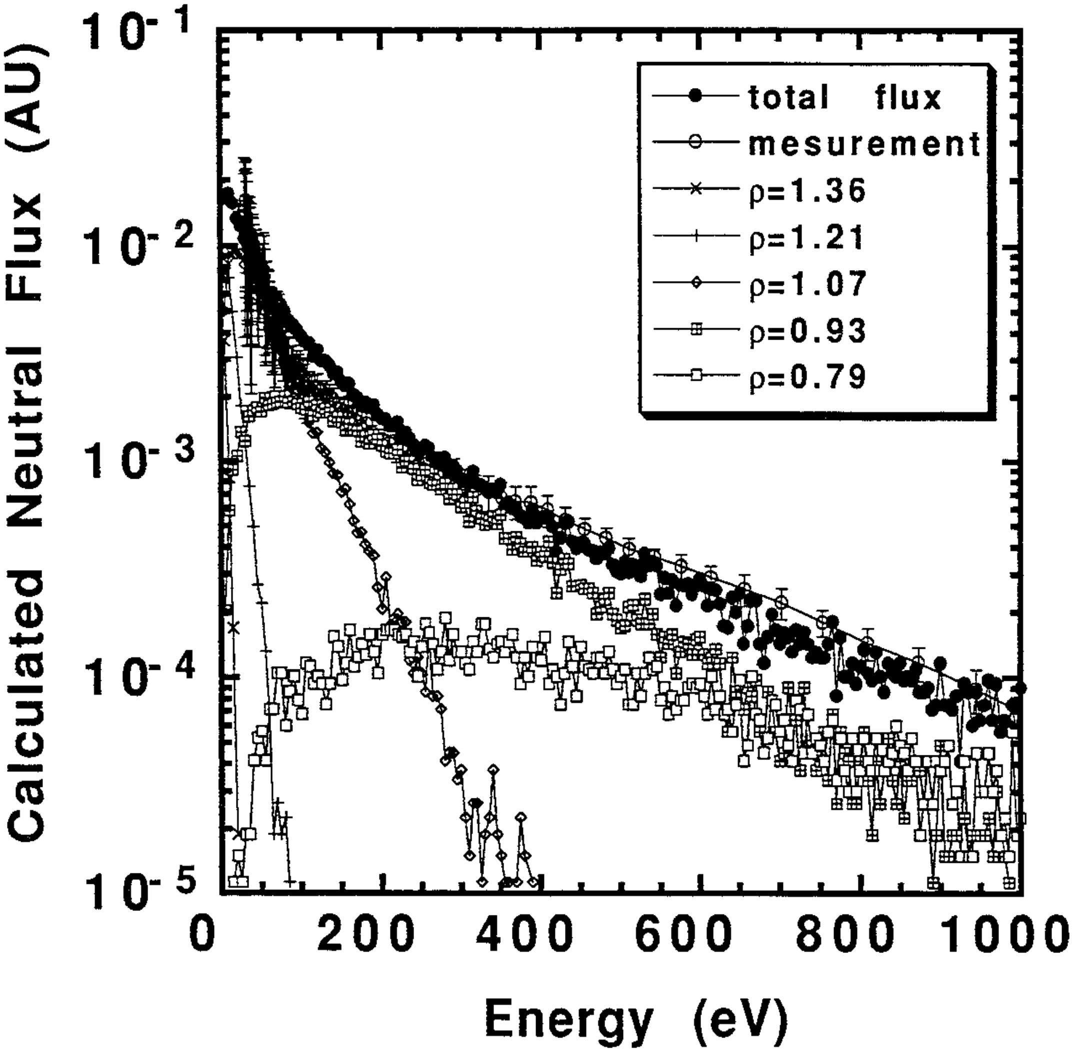


Fig.4 Y.Miura et al

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