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OBSERVATION OF DUSTS BY LASER SCATTERING METHOD IN THE JIPPT-IIU TOKAMAK

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ABSTRACT. Laser scattering signals which indicate the presence of small dusts (diameter ≤ 2 μm) were occasionally observed in the JIPPT-IIU tokamak chamber. This phenomenon was reproduced by deliberately spreading carbon dusts from the top of the vacuum chamber. No noticeable effect on the plasma was observed for dust-fall of up to at least 10^6 dusts (10 μg) in 20 ms during discharge. Dusts fallen just before the plasma start-up seemed to be confined but soon be ejected in less than 30 ms.

Key Words: Plasma wall interaction, impurity, dust, tokamak, JIPPT-IIU

The plasmas in present-day tokamaks or stellarators are, more or less, contaminated by the elements heavier than hydrogen isotopes which will be the fuel in reactors. The presence of these heavier elements (impurities) has crucially adverse effects on the performance of fusion plasmas[1,2]: enhanced power loss due to radiation and dilution of fuel. The impurities are generated [3] by such processes as desorption[4], arcing[5,6], sputtering [7,8] at the plasma-facing solid materials. Most of the impurities are introduced into the plasmas in the form of gases (atoms or molecules) but some are in the form of solids such as flakes [9] and micro particles[10]. Goodall[11] observed the behavior of solids during plasma discharge through visible light using a high speed films and named them UFO. Ohkawa[12] speculated that dust-particle is a possible source of impurity in tokamaks and showed that the motion of particle is different according to its size. The size of the observed solids materials spans from several tens μm for micro particles[11] to probably a few mm for flakes. Missing of micro-particles of the size smaller than a few tens μm across may reflect the limitation of measurements used and particle-formation processes. In order to correctly assess the effects of solid particles, if truly present, on the fusion plasma performance, more data such as the distribution of size and the composition should be accumulated.

In this letter we report evidence for much smaller solid particles (we call these dusts) of size < 2 μm across in a tokamak chamber which was unexpectedly observed by an existing Thomson scattering system.

In the Thomson scattering measurement using a 100 Hz Nd:YAG laser (0.4 J pulse energy, 20 ns pulse width) [13] on the JIPPT-IIU tokamak[14], we occasionally observed large scattered signals like that shown in Fig.1. These signals appeared on channels 5, 6, 21, 22, 25 and 27 at times ranging from 0 ms to 220 ms after current disruptions with amplitudes ranging from 25 pC to 512 pC. In some cases when plasma performance is poor, these signals also appear during plasma discharge. If these signals are real Thomson scattering, the deduced electron temperature Te and density ne indicate sudden appearance of localized unbelievably high energy-density plasma. It is not only interesting itself to clarify what these signals are but also important for raising the reliability of the Thomson scattering data. For ease of understanding the circumstance, we briefly describe the experimental setup referring to Fig.2. The toroidal vacuum chamber has a minor radius a_c=32.5 cm and a major radius R= 93 cm. The plasma, limited by carbon tiles set at the inner side, has the minor radius a ≈23 cm. A laser beam, 1.2 mm in diameter at the center and 2 mm at the plasma edge, traverses the center of the vacuum chamber from top to bottom. The stacked 28 polychromators 'see' through an F/number = 2.7 objective lens scattering volumes of ϕ2.0 mm x 10 mm located every 1.5 cm along the laser beam from - 24 cm to 18.5 cm. The solid angle of the collection optics varies from 0.08 sr for the central to 0.04 sr for the edge regions. The scattered light which enters a polychromator is sorted in three color bands (x, y, z) by three interference filters and then detected by avalanche photo diodes (APD). The outputs of APDs are fed to charge sensitive analog-to-digital converters (ADC) (Lecroy 4300) at 100 ns wide time-gates generated by a laser monitor. Additional two gates at 20 μs and 40 μs after each laser shot are used to monitor the background radiation and the circuit noise.

Observations concerning these signals are: (1) these signals appear simultaneously on three outputs (x,y,z) of polychromators; (2) these signals do not appear when the collection lens is masked by a paper cover, which excludes the possibility that these signals are induced by x-ray; (3) these signals appear only at the time of laser shot, indicating that these are scattering of YAG laser by something; (4) the polychromators on which these signals appear are not always adjacent each other, indicating that the something is smaller in size than the separation between the viewing scopes of two neighboring polychromators (1.5 cm); (5) in most cases, the signals occur at times 0- 300 ms after current disruptions at which time no plasma is present; (6) when a plasma current disrupts with many these signals, the next shot sometimes fails to form a plasma current accompanying these signals; (7) for very low density plasma these signals sometimes appear at the edge region during plasma discharge; (8) in general, the performance of plasmas is poor when these pulses appear occasionally. Exceptions to the observations (1) – (3) occur when plasma is in the runaway mode and the resulting intense x-ray excites APDs frequently. Because of very small duty of observation (100 ns gate/ 10 ms repetition time = 10^{-5}), the occurrence of the exception is, however, very rare. Considering overall the above, we suppose the dust particles which are generated by harsh plasma-wall interactions at current disruptions as the most probable candidate for the something observed after current termination. We further suppose that the most of the dusts thus generated fall onto the bottom of the vacuum chamber, but some stick to the wall. These sticking dusts may be easily released by small disturbance, bringing about the peculiar signals during plasma discharge in the following shots as speculated by Ohkawa[12]. The above is supported by the fact that when vacuum was vented many fine particles were found attached at the chamber wall.

We roughly estimate the size of the dust assuming its spherical shape. Scattering of light by a fine metallic or dielectric sphere with arbitrary radius b is described by the Mie formula [15]. As a result of simultaneous excitations of several electric and magnetic multi-poles in the sphere, the scattering behavior (the directional dependence of the intensity, polarization etc.) are very complicated except for the limiting cases of $q \equiv 2\pi b / \lambda_L >> 1$ or $q << 1$ (Rayleigh scattering). However, for an order of magnitude estimate, it will be justified to assume that the light is scattered isotropically with the total cross section of $2\pi b^2$. Then the expected signal $q_{j\alpha}$ [C] from the j-th spectral channel on the α-th polychromator is

$$q_{ja} = R_{ja}\,(1064)\quad 2\pi b^2\,(\Delta\Omega_a\,/4\pi)(\varepsilon_{LASER}/\pi r_{LASER}^{\,2})$$

where R_{ja} (1064) is the responsivity [C/J] at λ=1064 nm of the j-th filter-detector-amplifier combination, $\Delta\Omega_a$ = 0.04~ 0.08 sr is the solid angle of collection optics for the α-th polychromator, $\varepsilon_{LASER}/\pi r_{LASER}^2$ = (1.3 ~ 3.5) x 1 0^5 J/m^2 is the energy density of the laser. Though the filters in the polychromators are specified to block the light at the YAG laser wavelength (λ_L =1064 nm), they have still a finite transmittance (~10^{-5}) giving R_{ja} (1064) ≈ 0.2 C/J. With this relation, the radius of the dust which yields the full scale amplitude in Fig. 1 (512 pC) is estimated to be ~0. 4 μm for the central and ~ 1 μm for the edge observations. The observed signals scatter in magnitude from 25 pC (limited by noise) to over 512 pC (limited by over flow), implying the presence of dusts of sub-micrometer across. We have not yet collected enough number of dust-scattering events to deduce the dust-size distribution taking account of the Gaussian profile of the laser beam.

Let us briefly consider the implications of the dusts for the plasma performance. The effects of the dusts on the plasma are different depending on the instance of the dust fall: (1) From causality, dusts falling after a plasma termination, which we most often observed, have no direct effect on the plasma. (2) Dusts falling during plasma discharge will be heated, melted, evaporated and ionized near the surface of the plasma and then impeded by the magnetic field to enter deeply into the plasma. The effect is, therefore, similar to gas puffing. However, for the field of view with a size comparable to the dust size the dust-fall can introduce some peculiar effects such as very large amplitude density fluctuation (impulse) and the associated enhanced particle transport. (3) Dusts falling just before the plasma production can have a great impact on the foregoing plasma performance[11, 12] ; the dusts exist deeply inside of the vacuum chamber at the start of plasma, and then as the plasma discharge proceeds it is ionized and confined. The plasma thus formed will suffer from high power radiation cooling from the central region, resulting in the unfavorable pressure and current profiles, which in turn leading to instabilities. If a carbon dust of 2 μm in diameter, which contains ~ 5×10^{11} carbon atoms, is captured and confined in a ~ 7×10^6 cm^3 plasma of 3×10^{13} cm^{-3} average electron density, it contributes to raise the effective charge Z_{eff} by 6×10^{-7}. Therefore, 10^6 dusts of this size poses a serious problem in obtaining a good plasma performance. In view of its possible importance, we searched for the plasma discharge which showed up large peculiar scattering signals just before the plasma formation. No such an event has been found over ~10,000 shots (1 years operation). This fact, however, does not deny the occurrence of such an event, because the probability of detecting a dust by laser scattering is (scattering volume)/(plasma volume) x (gate width)/(time interval of interest) $\approx 10^{-11}$. Even if 10^6 dusts fall uniformly, the probability of detecting a dust over 10^4 plasma shots is only 1/10.

In order to obtain experimental evidences for/against the above conjectures, we deliberately spread carbon dusts using a setup shown in Fig.2. A 1 cm long thin blade touched normally to a carbon rod of 1 cm in diameter shaves off its thin surface layer when the rod rotates a small angle. By changing the contact pressure of the blade against the rod, the size of the carbon dust was adjusted around 2 μm. One degree rotation is estimated, not measured, to generate ~ 10^5 carbon dusts. The spring effect of the blade works to spread the carbon dusts over an extended region. The results were as follows.

(1) When 10^6 dusts were spread in a 200 ms period in the absence of plasma, the scattering signals of the roughly estimated magnitude indeed appeared as shown in Fig.3. Similar signals appeared on channels 2, 4, 5, 6, 7, 14, 15, 16, 17, 18, 19, 20,21, 22, 23, 25, 26, 27 and 28.

(2) Plasma behavior in response to dust-fall differs for different plasma states. (2-1) When 10^6 dusts were spread in a period of 20 ms on the plasma

in its full performance (plasma current Ip > 150 kA), no noticeable scattering signal appears even on the polychromator which sees the highest region (Z= [17.5, 18.5] cm). This may be due to that the dusts were burn out before reaching the viewing scope of any polychromator. To examine this, we observed the visible light (CII line radiation) from the uppermost region (10 cm in diameter) of the plasma where most of the dusts were expected to hit upon. Even if each dust could not be observed, the uppermost of the plasma was expected to glow in response to the dust-fall. Contrary to our expectation, no noticeable fast signal correlated with the carbon rod rotation was observed. We speculate that the dusts were spread to much more extended region than expected due to, for example, charge-up by plasma radiation. (2-2) On the other hand, when dusts were spread on a very low density plasma, the dust scattering signals were sometimes observed on the polychromators which could see the outside of the plasma as shown in Fig.4. In this case, the signals appeared only on channel 27 at 190 ms. (3) Carbon dusts of $\sim 3\times 10^{6}$ were spread 260 ms before the start of the plasma discharge which evolved as shown in Fig.5 (# 75871). This timing was chosen so that the carbon dusts were located around the center of the vacuum chamber when the plasma begin to discharge. At 20 ms from the start of the discharge, at which time the dusts fell additionally 5 cm, Ip, Te and ne increased enough to ionize the dusts and confine the resultant plasma. If the carbon ions thus generated are completely confined in the normal JIPPT-IIU plasma ($a \approx 23$ cm and average density $n_e = 3\times 10^{13}$ cm^{-3}) , it contributes to raise Z_{eff} by 2, which will be easily noticed in the Bremsstrahlung signal. Plasma current I_p, loop voltage, Bremsstrahlung P_{Brem}, CII and CIV signals of the plasma shots with and without carbon-dust-fall are compared in Fig.5. Both shots were operated with the same condition. Difference in these signals between two cases were clearly noticed in the early phase of the discharge, but it soon disappeared within the shot-by-shot variation, indicating that the most of the impurities present at the startup phase were ejected in less than 30 ms. The enhanced consumption of the 'volt-second' in the early phase probably resulted in a little bit decrease in the plasma current. Contrary to the UFO-fall experiment[11], no current disruption was induced by the dust fall.

Conclusions:

This paper demonstrated occasional dust-falls in a tokamak chamber. Deliberate dust-spreading experiments showed that the plasma is, in general, robust to dust-fall during discharge. The dusts in the central region just before plasma discharge seems to be confined in the early phase but soon ejected. A laser scattering system with much higher detection efficiency and with wider view scope, particularly in the scrape-off region, is necessary for more detail study.

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FIGURE CAPTIONS

Fig.1. (a) Raw scattering signals on the 5th polychromator. (X, Y, Z) denote the spectral channels. Large scattering signals appeared at 350 ms. Similar signals appeared on channels 6, 21, 22, 25 and 27 at different timings. Plasma current I_p is shown for reference.

Fig.2. Schematic drawing of the experimental setup.

Fig.3. Raw scattering signals due to the deliberate dust-fall in the absence of plasma. Similar signals appeared on channels 2, 4, 5, 6, 7, 14, 15, 16, 17, 18, 19, 20,21, 22, 23, 25, 26, 27 and 28.

Fig.4. Raw scattering signals from a low density plasma. A peculiar signal appeared at 190 ms on only channel 27.

Fig.5. Time evolution of I_p, V_{loop}, $T_e(r=0)$, $n_e(r=0)$,P_{Brem}, CII and CIV signals for plasmas with and without dust-fall.

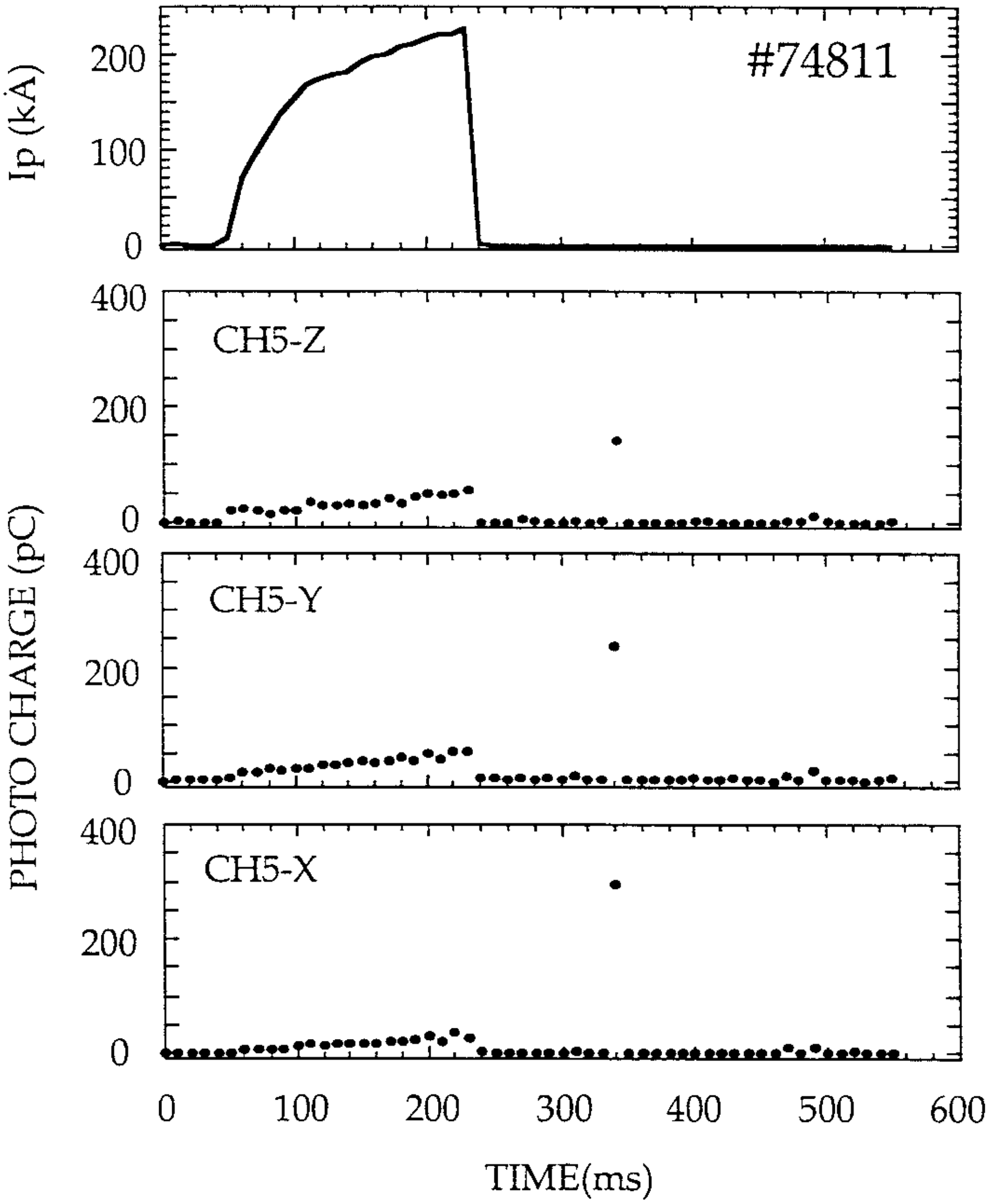

Fig.1 Narihara et al

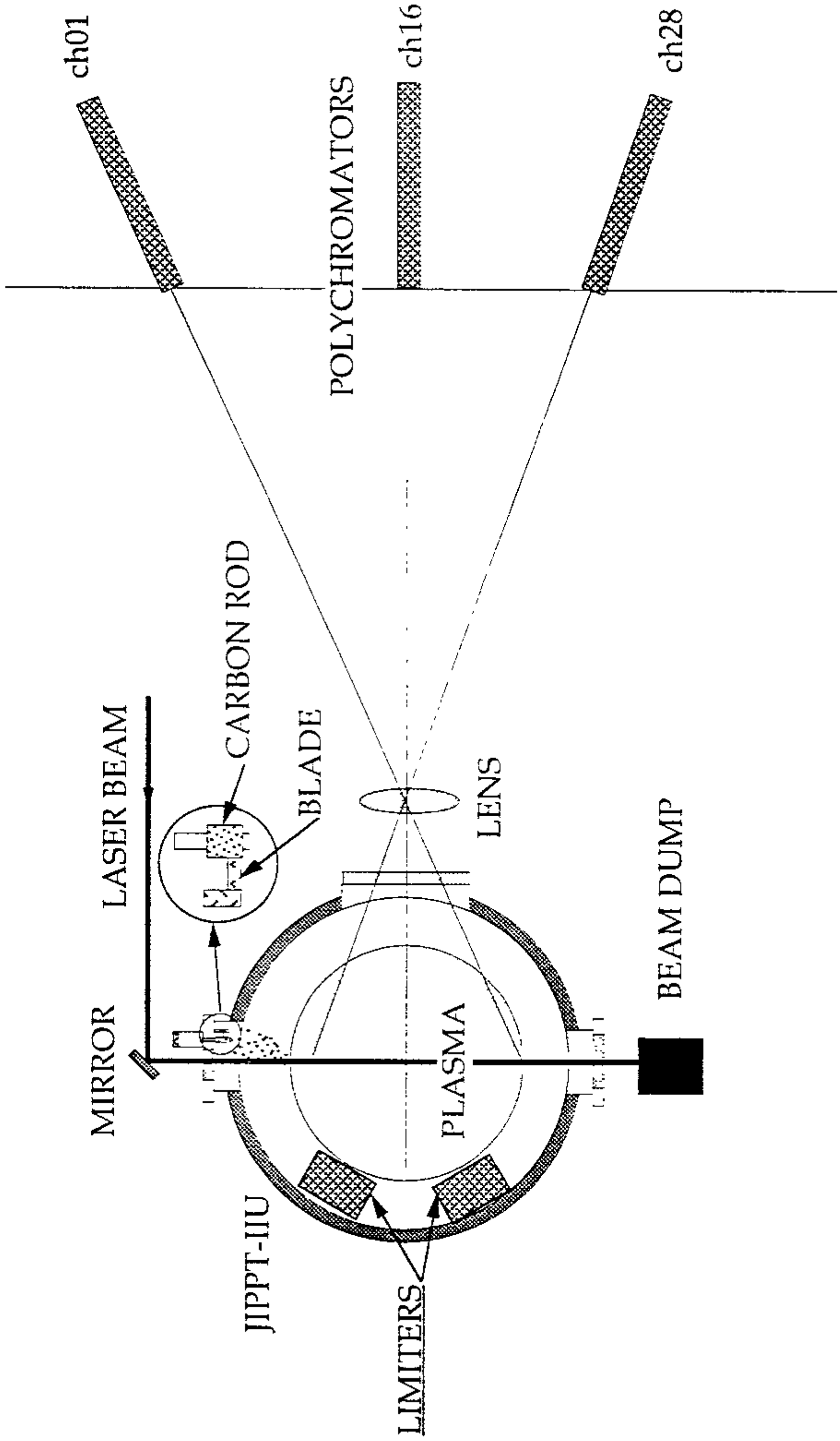

Fig. 2. Narihara et al

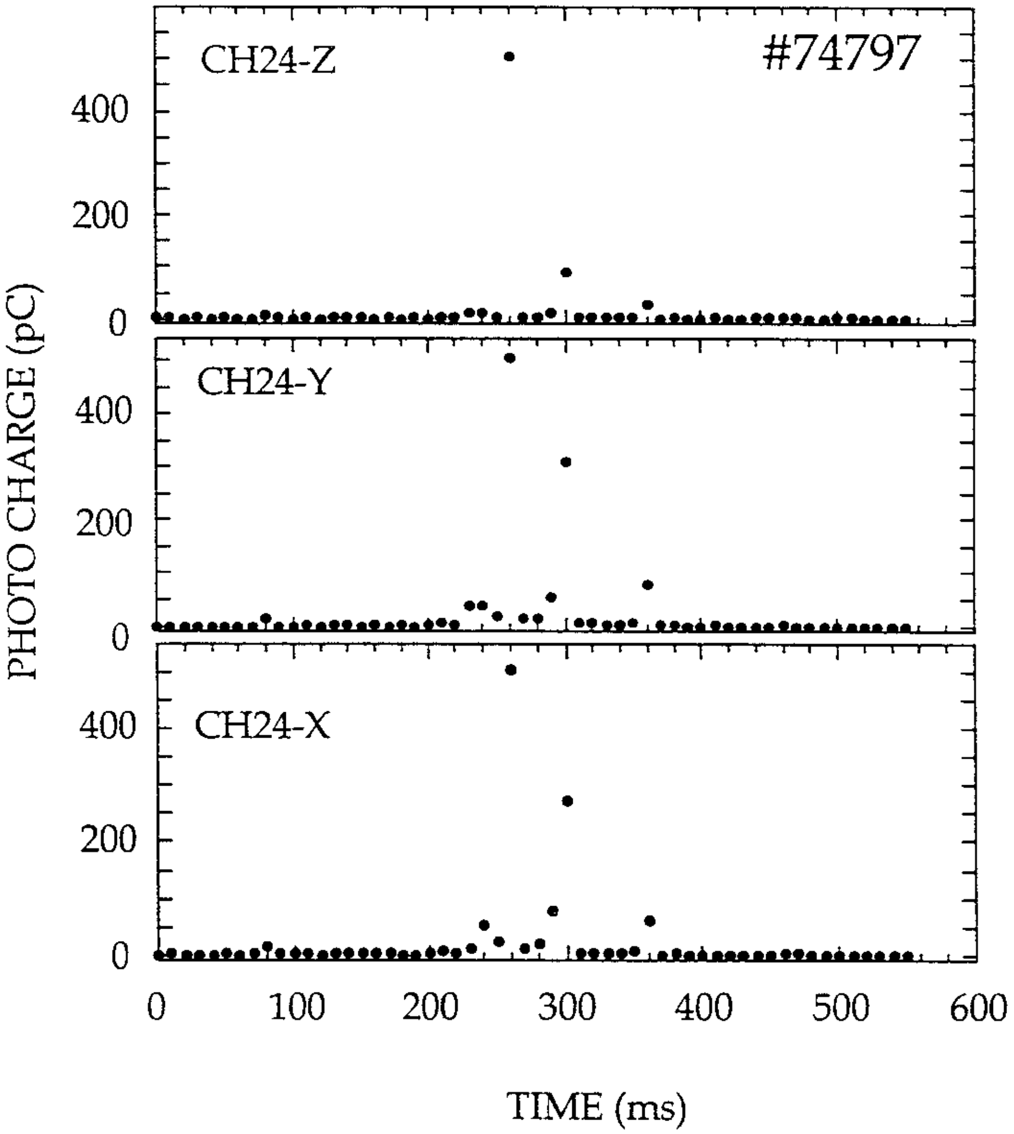

Fig.3. Narihara et al

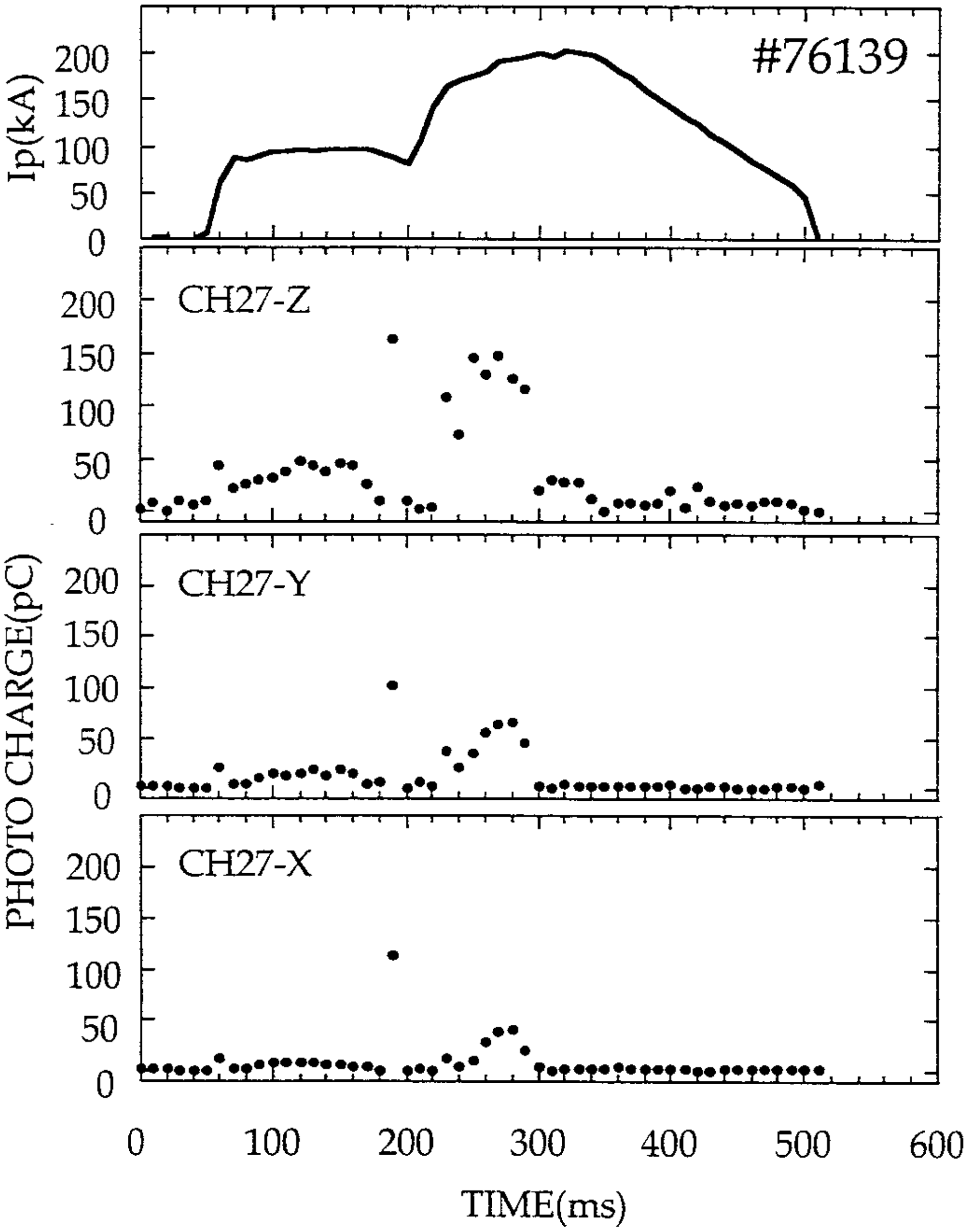

Fig.4 Narihara et al

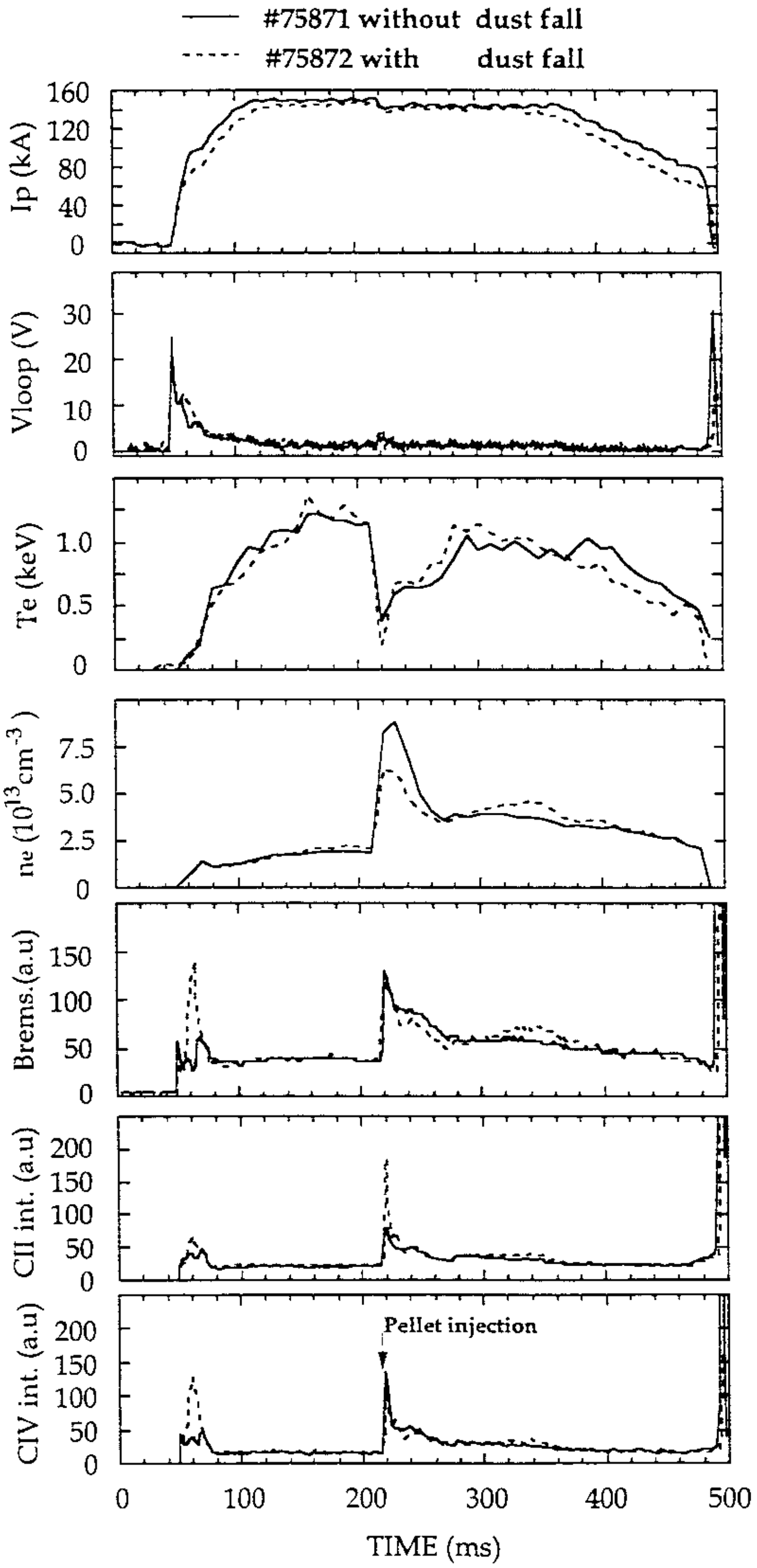

Fig.5 Narihara et al

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