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ECE AND X-RAY IMAGE RECONSTRUCTIONS
OF SAWTOOTH OSCILLATIONS ON TFTR

BY

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ECE and X-ray image reconstructions of sawtooth oscillations on TFTR

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Abstract

High resolution ECE and X-ray image reconstructions have been made simultaneously during the sawtooth crash in the fast rotating plasma on TFTR. The X-ray tomography is found not to represent flux surfaces but to show metal impurity behavior. The experimental results show that the reconnection process causes the sawtooth crash, even when the crash time is 20 times faster than the Kadomtsev reconnection time. New features are observed during the sawtooth crash, such as an oval shaped hot spot and a cooler region between the island and the hot spot.

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Periodic crashes of the central electron temperature, called sawtooth oscillations, are a common feature of tokamak discharges. On small tokamaks in low temperature ohmic heated plasmas, the tomographic analysis of the sawtooth crash¹ was consistent with the Kadomtsev model.² On large tokamaks in high temperature plasmas,³ however, the comparison between the experiment and the theory has been inconclusive. In this paper, we report on the evolution of the electron temperature contours and the impurity behavior during the sawtooth crash using simultaneous ECE (electron cyclotron emission) imaging and X-ray tomography on TFTR. The significant findings are; (1) metal impurities escape from the broken flux surface with a slower velocity than that of the electron heat conduction, (2) X-ray emission contours do not always represent flux surfaces, and (3) a fast reconnection process is comprehensively documented. New features of the sawtooth crash are also revealed from the high resolution image reconstruction.

We apply the ECE and X-ray image reconstruction techniques to a typical fast TFTR sawtooth crash in a plasma with major radius of 2.45 m, minor radius of 0.80 m, toroidal magnetic field of 4.8 T at R=2.45 m, plasma current of 1.6 MA, heated by co-tangential (in the direction of plasma current) NBI of 12.5 MW, and counter-tangential NBI of 4.5 MW. This plasma has a central ion temperature of 17 keV, central electron temperature of 6.8 keV, volume averaged density of $\langle n_e \rangle = 3.2 \times 10^{19} \text{ m}^{-3}$, density peakedness of $n_{e0} / \langle n_e \rangle = 1.9$, and the fast ion beam density is 20 % of the electron density at the center. For effective documentation, we sample sawtooth crashes whose crash time is short in terms of impurity transport but is longer than the plasma rotation period. The same features are observed in other fast TFTR sawtooth crashes.

The electron temperature profile on the mid-plane of the plasma is measured with a 20 channel grating polychromator.⁴ The polychromator data is cross-calibrated to a Michelson interferometer.⁵ The data is collected with a 2 μs time resolution covering R=220-340 cm with spatial resolution of 6 cm. The poloidal resolution is 11°. The data from the inside and outside major radii are used for a full rotation (66 μs), and an interpolation between both sides is carried out, so that the time resolution is better than 33 μs .⁶ In addition, two soft X-ray cameras separated by 75° view the plasma, one vertically and the other horizontally, through 125 μm thick Be filters with 20 and 60 silicon-diode detectors, respectively.^{7,8} The X-ray emission is de-

scribed by the Fourier series of order of M and the Bessel function expansions of order of L .⁹ The data are taken in a quarter rotation using two cameras, so the time resolution is $17 \mu\text{s}$. Here, $L = 10$ and $M = 7$ are chosen giving a radial resolution of 9 cm and the poloidal resolution of 13° . The image reconstruction techniques using rotation have been reported previously.⁶ The reconstruction errors due to the noise and the rigid rotation assumption have been examined using numerical simulations.⁶

The ECE and X-ray signals for sawtooth oscillations are shown in Fig. 1. The ECE and X-ray images with the inversion surface superimposed are shown at the times indicated by the letters, in Figs. 2-4. Here, the inversion surface is obtained from the electron temperature profile as in the previous report.¹⁰ The time evolution of the ECE image, which is considered to represent the evolution of flux surfaces, is shown in Fig. 2. The sawtooth crash time is defined to start at time D and finishes at time K in Fig. 1, so that the crash time is estimated to be $400 \mu\text{s}$, which is longer than the central temperature decay time of $200 \mu\text{s}$ (from D to G in Fig. 1). The crash time is 10 times faster than the Kadomtsev time.² Figure 2 clearly shows a growing crescent shaped island and a shrinking hot spot, as expected from a full reconnection process.² The same process is also observed for a faster sawtooth crash having the central temperature decay time of $37 \mu\text{s}$. The crash time is $180 \mu\text{s}$, which is 20 times faster than the Kadomtsev time. This fast reconnection has been of strong interest in the plasma physics community.¹¹

We now compare images from ECE and X-ray reconstructions at a time midway through the sawtooth crash (Fig. 3) and at the end of the crash (Fig. 4). In Figs. 3 and 4, the "ECE (perturbation)" is the residual of the averaged signal over one cycle of the rotation subtracted from the raw signal, and it is more sensitive to the presence of perturbations. We also compare the images when the hot spot is on the weak field side (larger major radius side) and on the strong field side (smaller major radius side) in Fig. 3. Here, we note that the fine structure in the X-ray image is an artificial effect introduced because of the limited number of Fourier components.

The high resolution image reconstructions find three important features; (1) the hot spot pushes out more on the weak field side, (2) a "cool region" between the hot spot and the island grows gradually, (3) the shape of the hot spot is oval and radially elongated before the crash phase. Theoretically, the pushing out of the hot spot on the weak field side can be explained as a

combination of finite pressure and toroidal effects.^{10,12} The “cool region” is not due to the heating of the island, because the temperature of the island does not change (Fig. 1). The “cool region” becomes an $m=1/n=1$ cold bubble after the crash, which sometimes generates successor oscillations on TFTR. The oval shaped-hot spot is commonly seen in NBI heated plasmas and RF heated plasmas, but it has not been theoretically predicted.¹²

The X-ray emission at the center decreases 75% during the sawtooth crash (the line integrated emission drops by 30%), which cannot be explained by the drop of the central electron temperature (10%) and density (10%). The detected X-ray spectrum is shown in Fig. 5(d). Before the sawtooth crash, the total Z_{eff} is 2.8 with a contribution from metals of ~ 0.7 . X-ray pulse height analysis (PHA),¹³ which looks horizontally in the midplane, shows that the line averaged ΔZ_{eff} , the contribution from the metal impurities (iron, nickel and chromium) to the Z_{eff} , decreases 27%, as shown in Fig. 5(a). Time histories of the ΔZ_{eff} and the X-ray emission correlate very well. The intensity of the K_{α} resonance line of the helium-like iron ion, FeXXV, which is measured by a bent-crystal spectrometer,¹⁴ decreases 47%, as shown in Fig. 5(b). The observed drop of the electron temperature and density should reduce the FeXXV line emission by 11%, as calculated by the MIST code.¹⁵ Thus, the line averaged iron ion density must decrease $\sim 36\%$. The ratio of measured X-ray emission to calculated bremsstrahlung, based on measured temperature and density, is called the enhancement factor,¹⁶ and is a good indicator of impurity content. In Fig. 5(c), it is observed that the enhancement factor profile becomes peaked between sawtooth crashes ($t=4.1s$), and flattens after the sawtooth crash ($t=4.2s$). These results show that the drastic X-ray drop at the sawtooth crash is due to the escape of the metal impurities, which have accumulated in the central region between crashes. The accumulation mechanism may be the high Z ion pinch effect.¹⁷ Just before the end of the sawtooth crash (Fig. 4[I]), the X-ray emission in the hot spot is higher than in the island, although the electron temperature at the hot spot is equal to that at the island. These results indicate that the high X-ray emission in the hot spot is mainly due to the metal impurities.

Just after the crash (Fig. 4[J]), a crescent shaped hot-spot-like feature remains in the X-ray image. This was also observed in JIPP T-II, where it was interpreted as a kink flow along the $q=1$ surface.¹⁸ On TFTR, however, the ECE electron temperature contours, which represent flux surfaces better

than the X-ray emission contours do, show a cooler "cold bubble" region. This result implies that the impurity transport time is much longer than the electron heat conduction time, from the broken flux surface (X-point). Time scales can be estimated as follows: particles and heat escape through the X-point along the field line, at the electron thermal velocity v_e for the conduction and at the ambipolar velocity v_i for the convection; and each time scale is described by $\tau_\alpha \approx (\pi R/v_\alpha)(q/\delta q)$, ($\alpha = e, i$), where δq is the range on change during the crash time of the reconnection layer on q -value and the suffix e and i indicate the electron heat conduction and the ion convection, respectively. For $\delta q/q = 0.1$, we have $\tau_e \approx 1\mu s$ and $\tau_i \approx 100\mu s$, which explains the time lag of impurity contours against the temperature contours.

The present experimental results lead to the following physical picture of the sawtooth crash. Since particles are frozen to the field line, the result that both impurities and heat escape through the X-point from the inside to the outside of the inversion surface imply that field lines from inside and outside of the $q = 1$ surface are reconnected during the sawtooth crash. The hot electrons escape to the outside and the cold electrons are drawn to the inside due to the ambipolar effect. Thus, the temperature of the reconnection region inside the original $q = 1$ surface is lower than the island, as is observed in this experiment. The existence of the "cool region" implies that the island is not completely stochastic but that it has established flux surfaces.

In summary, simultaneous high resolution ECE and X-ray image reconstructions have been made during the sawtooth crash in the fast rotating plasma with NBI heating on TFTR. The shrinking circular hot spot and the growing crescent shaped island are revealed in the electron temperature contours, which are considered to be the best representation of flux surfaces. The results suggested that the X-ray emission describes the behavior of the metal impurities, the impurity convection is slow in comparison with the electron heat conduction, and the X-ray contours are found not to represent flux surfaces. The crescent shaped "hot spot" in the X-ray emissivity is identified as the metal impurity behavior. Finally, the experimental results show that the sawtooth crash is a full reconnection process for the TFTR sawteeth.

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Figures

FIG. 1. The ECE signal from the grating polychromator and the X-ray signals from the horizontal camera during a sawtooth oscillation. Here, minor radii are measured from the magnetic axis, and the negative sign indicates the high field side on the ECE signals. The parameter of the X-ray channel indicates the height of the X-ray chord.

FIG. 2. Series of ECE images during the sawtooth crash. The number on the center indicates peak electron temperature in keV. The contour step size is 300 eV. The bold circular line indicates the inversion radius which is obtained from the ECE signals. The numbers on the right of the figures indicate the reconstruction time in seconds.

FIG. 3. Reconstructions of the X-ray, the ECE and the perturbation of ECE at a time midway through the sawtooth crash, when the hot spot is on the low field side (F) and on the high field side (G). The contour step size is 300 eV on ECE(total) and 60 eV on ECE(perturbation).

FIG. 4. Reconstructions of the X-ray, the ECE and the perturbation of ECE, at the end of the crash. The contour step size is 300 eV on ECE(total), and is 60 eV in (I) and 30 eV in (J) on ECE(perturbation), respectively. The plasma makes half rotation from (I) to (J).

FIG. 5. (a) Time evolution of Z_{eff} due to the metal impurities (iron, nickel and chromium) which is measured by the pulse height analysis (PHA) X-ray spectrometer. The PHA data are averaged for 50 ms. The solid line is the X-ray emission from the central chord. (b) Time evolution of FeXXV (0.185nm) line emission which is measured by the crystal spectrometer. (c) Time evolution of the enhancement factor profile between the first sawtooth crash ($t=3.9s$) and the second sawtooth crash ($t=4.2s$). (d) X-ray spectrum measured by the PHA. The unit of the intensity is $3 \times 10^{11} keV/keV-cm^2-s$.¹³ The three peaks are K_{α} lines of metal impurities. The measured continuum (dotted line) is about four times higher than the calculated bremsstrahlung from a pure deuterium plasma.

FIG. 1

FIG. 2

FIG. 3

Fig. 4

FIG. 5

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