Ion Temperature Increase During MHD Events on the TST-2 Spherical Tokamak

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Abstract. Various types of MHD events including internal reconnection events are studied on the TST-2 spherical tokamak. In weak MHD events no positive current spike was observed, but in strong MHD events, which show a positive current spike, a rapid and significant impurity ion temperature increase was observed. The decrease in the poloidal magnetic energy is the most probable energy source for ion heating. The plasma current shows a stepwise change. The magnitude of this step correlates with the temperature increase and is a good indicator of the strength of each event.

1. Introduction

The spherical tokamak is an attractive candidate for a compact fusion reactor due to its high beta value. On the other hand, the Internal Reconnection Event (IRE) [1], which is characterized by a positive current spike, often causes significant energy loss. Moreover, its classification (*e.g.*, by period, effect on confinement, driving force) have not yet been established. Spherical tokamak is considered to have the feature of reversed field pinch and spheromak configurations as well as the feature of conventional tokamak. In the former, MHD dynamo sustains the configuration, and the dynamo activities are accompanied by strong magnetic fluctuations and by resultant large energy transport. During MHD dynamos magnetic reconnection occurs and causes significant ion heating. Production of high energy bulk ions just after an IRE is reported in the MAST spherical tokamak device [2]. While major disruptions are serious MHD events in conventional tokamaks, a series of IREs occurs instead of a major disruption in spherical tokamaks such as MAST [3]. Various types of MHD events including IREs are studied on the TST-2 spherical tokamak [4]. Some have no positive current spikes, and some IREs are accompanied by a rapid ion temperature increase during a current spike. Effects on other plasma parameters are also presented.

2. Various types of MHD events

During the ramp up phase of the plasma current, large MHD activities are observed in almost all discharges. During a later phase of the discharge, where the plasma current is decreasing gradually or becomes constant, discrete MHD events are often observed. These events are characterized by a change in the plasma current and bursts of magnetic fluctuations with a frequency of 10-20 kHz. Magnetic fluctuations often show an exponential growth with a time constant of a few hundreds of μs (~10^3 τ_A), although the growth phase was not clear in some cases. MHD events with various strengths and various patterns were observed. Figure 1 shows a weak and a strong MHD event. The MHD events are accompanied by changes in other parameters: plasma current I_p, ultra soft X-ray (USXR) emission, hard X-ray emission, electron density, H_α emission and line emissions from impurity ions.

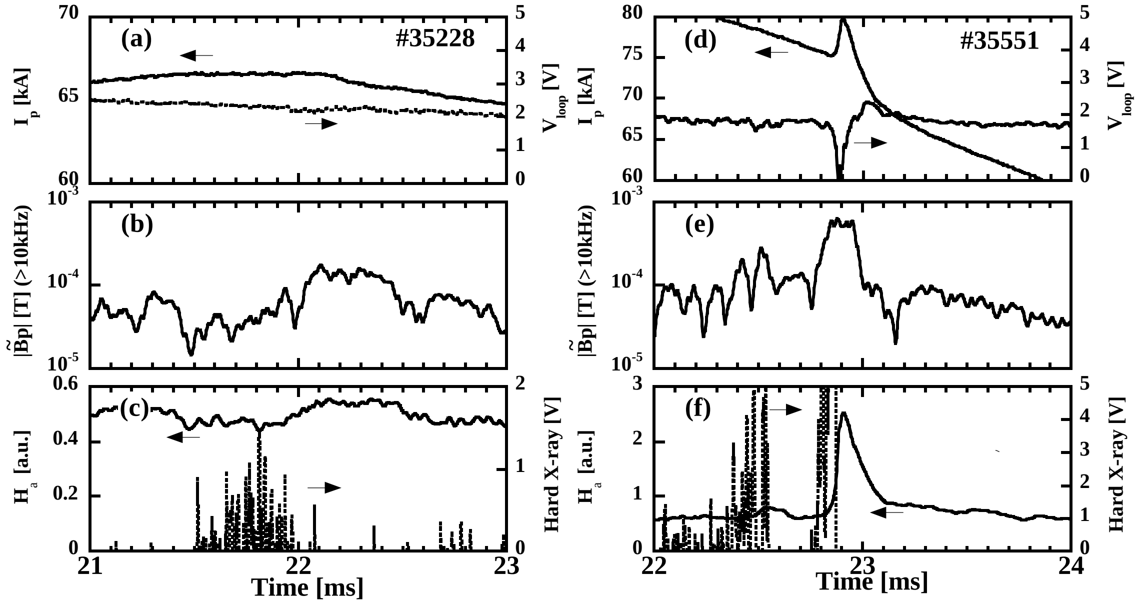

FIG.1. Time traces of the plasma current I_p and the loop voltage V_{loop} (a),(d), the amplitude of poloidal magnetic fluctuations (b), (e), H_α emission and the hard X-ray signal (c), (f) for two discharges, with a weak and a strong MHD event (left and right).

In strong MHD events, I_p has a positive spike and its peak coincides with the peak of magnetic fluctuations. On the other hand, in weak MHD events, changes in plasma parameters are small, but even in such cases we can see some perturbations in I_p (FIG. 1(a)). Before describing strong MHD events, which have positive spikes in I_p, we describe the common time behaviors in the observed MHD events. Firstly, a crash occurs in some line emissions (e.g. CV, OV) and hard X-ray emission is observed. Typically the crash occurs in a time scale of a few tens of μs. In most cases magnetic fluctuations grow during this phase. The hard X-ray emission disappears after the peak of magnetic fluctuations. In contrast, the peak of H_α emission occurs at a slightly later time, which coincides with the peak time of I_p for strong MHD events. These observations suggest that energetic and thermal electrons are lost from the core and hit the wall when magnetic fluctuations grow to large amplitudes, and hydrogen influx from the wall is enhanced as a result.

3. Ion temperature increase during MHD events

Analysis is performed mainly on strong MHD events which show a clear positive spike in I_p. By applying an additional loop voltage the maximum plasma current reaches 100-110 kA, and the current decreases gradually with a few strong MHD events before termination of the discharge. Typical parameters of analyzed plasmas are: major radius R ~ 0.35 m, minor radius a ~ 0.22 m, aspect ratio A ~ 1.6, elongation κ ~ 1.5, toroidal magnetic field B_{T0} = 0.15 T, maximum plasma current I_p ~ 60-80 kA, ion temperature ~ 70 eV and discharge duration ~ 20 ms.

A marked phenomenon during a strong MHD event is that the impurity temperature increases significantly during the events and then decays to the level before the event. A visible spectrometer, which has 11 channels of PMTs and amplifiers with 1/e time response of 10 μs, is used to measure Doppler broadening of impurities. Two horizontal chords with vertical positions z=0, -0.2 m are available. Lines CV (C^{4+}), OV (O^{4+}) and CIII (C^{2+}) showed temperature increases while H_β did not. Since the spectrometer measures the chord integrated emission, the intensity profile should be investigated before discussing the temperature profile. In order to obtain the profile information, plasmas are shifted vertically shot by shot. Temperatures of CV before and well after an MHD event are around 70 eV and the profile is rather flat (FIG. 2(b)). The intensity profile of CV before an MHD event is peaked at the center of the plasma (circles in FIG. 2(a)). After a crash the profile becomes flat for about 0-200 μs (squares in FIG. 2(a)). After the flat period the edge intensity decreases and the profile becomes peaked again. Abel inversion was performed to evaluate the localization of the measurement. When the intensity profile is peaked, CV measurements with z=0 m (notation CV/z=0 is used hereafter) reflect mainly the core information with the normalized radius $\rho<0.3$. When the intensity profile becomes flat, the information with $\rho<0.6$ is obtained. With the chord z=-0.2m, the measurements reflect the outer information $\rho>0.7$.

Figure 3 shows the time evolutions of impurity temperatures for CV/z=0, -0.2, OV/z=-0.2 and CIII/z=-0.2. Four traces from different discharges are plotted. Since the temperature increase is sensitive to the strength of the MHD event, events with similar I_p traces were selected. As described in the next section, I_p step in the decaying trend of I_p (ΔI_p defined in FIG. 3(a)) is a good indicator of the strength of MHD events. Four events have almost the same ΔI_p. The temperatures of CV/z=0, CV/z=-0.2 and OV/z=-0.2 increased to about 400 eV, while the temperature increase of CIII/z=-0.2 is much smaller. The temperature of CV/z=0 decays with a 1/e time constant of 200 μs. During the period indicated by the arrow in FIG 3(c), the CV intensity profile became flatter and the obtained temperature represents the information of a broad region ($\rho<0.6$). At $\Delta t>0.2$ ms, the CV/z=-0.2 intensity decreases and the profile became peaked again. The slower decay of the CV/z=0 temperature compared to the decay of CV/z=-0.2, OV/z=-0.2 temperatures suggests cooling from the outer region of the plasma.

Bulk ion (hydrogen) temperature was not available. The temperature relaxation time between impurity and hydrogen ions is estimated to be about 10 μs before the event, and therefore the impurity temperature reflects the bulk ion temperature. On the other hand, the relaxation time is 30-250 μs during and after the event due to the decrease in density and increase in temperature. The lower value is calculated assuming that the hydrogen temperature does not change, and the higher value is calculated assuming that the hydrogen temperature increase is the same as the impurity temperature. Since the higher value is almost the same as the decaying time constant, it is possible that the bulk ion temperature increase is not as high as the increase of the impurity ion temperature.

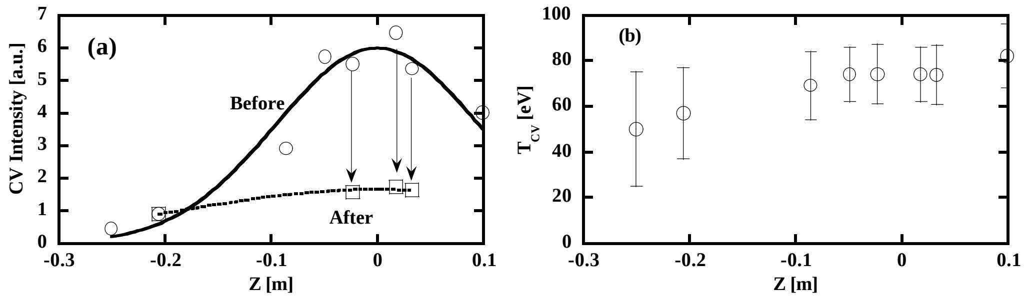

FIG. 2. Profiles of the temperature and the intensity measured from CV ($C4^+$, 227.1 nm) line emission. Plasmas are shifted vertically and z in the figures represent the relative position of the measurement chord from the center of the plasma.

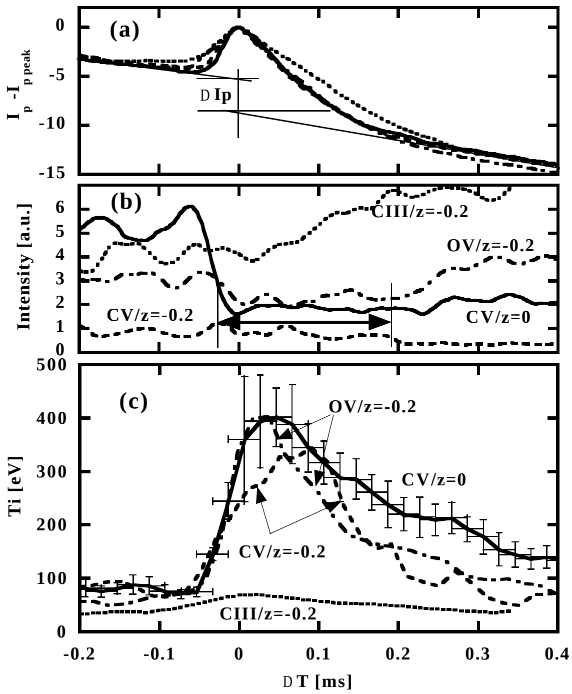

FIG. 3. Time evolutions of the plasma current (a), the intensities (b) and temperatures of CV (z=0, -0.2 m), OV (z=-0.2 m) and CIII (z=-0.2 m) during an MHD event.

4. Effect of MHD events on other plasma parameters

The strength of MHD event can be measured by ΔI_p (defined in FIG. 3(a)), and the effects on plasma parameters depend on ΔI_p. However, when the positive spike in I_p is very small, ΔI_p was not identified (*i.e.*, ΔI_p ~0). In addition, in weak MHD events there is no positive spike in I_p and ΔI_p ~0. Therefore ΔI_p can be used only for relatively strong MHD events. Figure 4 shows the changes in various plasma parameters before and after an MHD event as functions of ΔI_p for discharges with I_p~60-80 kA. The temperature increases of CV (z=0, -0.2 m) increase with ΔI_p (FIG. 4(a)). Significant energy and particle losses are suggested from the USXR emission (FIG. 4(a)) and from the line integrated electron density NL with a chord passing near the center of the plasma (FIG. 4(c)). H_α emission increases with ΔI_p. It should be noted that USXR and H_α emissions are affected by the events even for the cases ΔI_p ~0.

The energy source for the impurity temperature increase is discussed for the case of strong MHD events with ΔI_p ~10 kA. During the magnetic reconnection, magnetic energy can be converted to the kinetic energy. The poloidal magnetic energy is estimated to be about 330 J based on the equilibrium reconstruction for a plasma with I_p~90 kA. Since the plasma size does not change significantly the energy scales as $I_p^2 L_i$ where L_i is the internal inductance. If we assume that L_i did not change, the energy decrease due to ΔI_p ~10 kA is about 100 J. The energy decrease can be larger if L_i decreases after an MHD event. The ion energy increase due to the temperature increase is about 130 J assuming that the hydrogen temperature is the same as the impurity temperature, and that the ion energy loss due to reconnection is negligible.

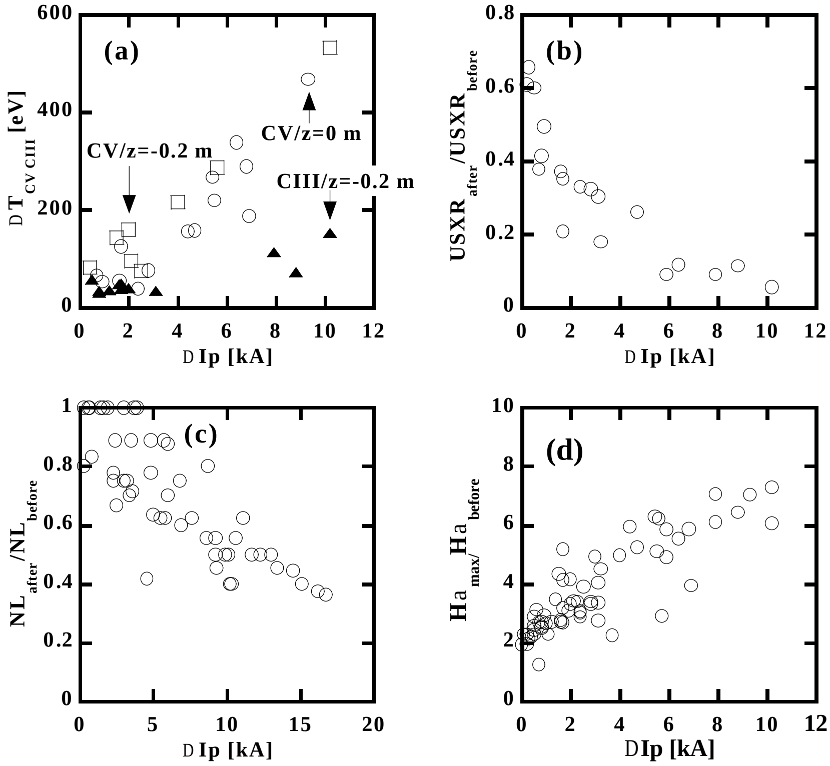

FIG. 4. Changes in plasma parameters: impurity temperature (a), ultra soft X-ray emission (b), line integrated electron density NL and H_a emission. Ratios of parameters before an MHD event to the minimum or maximum values just after the MHD event are shown as functions of DI_p.

The lack of the hydrogen temperature measurement and the density profile measurement cause uncertainty in this factor. In conclusion, the estimated poloidal magnetic energy decrease is not inconsistent with the ion temperature increase, but detailed profile measurements are required.

5. Conclusions

MHD events in the current sustainment and decaying phases of TST-2 plasmas were investigated. Strong MHD events (IREs) are characterized by a positive spike in the plasma current and by a stepwise decrease in the trend of the plasma current. During these strong MHD events the impurity temperatures increase rapidly to a level several times higher than the original level. The amount of poloidal magnetic energy decrease is not inconsistent with the ion temperature increase. The effect on plasma parameters depends on the magnitude of the stepwise change in the plasma current.

References

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