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Statistical analysis of variations in impurity ion heating at reconnection events in the Madison Symmetric

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Abstract

The connection between impurity ion heating and other physical processes in the plasma is evaluated b studying variations in the amount of ion heating at reconnection events in the Madison Symmetric Torus (MST). Correlation of the change in ion temperature with individual tearing mode amplitudes indicates that the edge-resonant modes are better predictors for the amount of global ion heating than the core-resonant modes. There is also a strong correlation between ion heating and current profile relaxation. Simultaneous measurements of the ion temperature at different toroidal locations reveal, for the first time, a toroidal asymmetry to the ion heating in MST. These results present challenges for existing heating theories and suggest a stronger connection between edge-resonant tearing modes, current profile relaxation, and ion heating than has been previously thought.

Key Topics

Plasma temperature
Plasma heating
Toroidal plasma confinement
Magnetic reconnection
Temperature measurement

Magnetic reconnection is a process that reconfigures the magnetic field in the plasma in such a way tha energy stored in the magnetic field is redistributed throughout the plasma, often resulting in an increase in the kinetic or thermal energy of the plasma particles. Magnetic reconnection occurs in a variety of settings, including magnetospheric substorms,[1] magnetar flares,[2] and many laboratory plasmas. The heating that frequently accompanies reconnection is of broad interest, also occurring in both astrophysical and laboratory settings. The sun provides many valuable examples of heating as a result of reconnection, such as in the corona and chromosphere.[3–5] Ion heating has been observed in laboratory plasmas, including plasma merging experiments,[6] the magnetic reconnection experiment (MRX),[7] and sawtooth crashes in Reversed Field Pinch (RFP) plasmas.[8–11]

One particular RFP experiment in which ion heating has been observed and studied is the Madison Symmetric Torus (MST).[12] MST produces toroidally shaped plasmas with a major radius R = 1.5 m and minor radius r = 0.52 m. When ion heating was first studied in MST, it was shown to come and go with th magnetic fluctuations in the plasma that are now thought to drive reconnection.[13] Later, heating was shown to occur for both majority and impurity ions, but that the impurities are usually heated more strongly. With localized measurements of the ion temperature, ion heating was shown to occur where reconnection occurs; enhancing the link between reconnection and heating.[14] The heating in MST is also known to be anisotropic such that the perpendicular ion temperature is larger than the parallel ion temperature at reconnection events.[15] The mass dependence for heating of majority ions has been studied;[16] and most recently, the charge and mass dependency of impurity ion heating has been investigated.[17]

Despite many laboratory experiments and simulations, the mechanism for transferring energy to the ion from the magnetic field is still unknown, and no single theory has proved conclusive. There have been four main theories proposed to explain ion heating in RFPs. One theory suggests that the magnetic fluctuations in the plasma cascade to higher and higher frequencies until they reach the ion-cyclotron frequency at which ions absorb the fluctuations' energy and are heated.[18,19] A second possible heating mechanism is the energetic, localized outflows produced by the magnetic modes that cause reconnection.[20–22] Viscous damping of these flows may heat the ions. A slight variation of this theory is that there is viscous damping of neoclassical parallel flows to transfer energy from the magnetic fluctuations to the ions and give rise to the observed anisotropy of ion heating.[23–25] Stochastic ion heating is a theory in which the cross-field radial transport of ions results in random changes in the ion perpendicular E × B drift velocity and leads to perpendicular heating of the ions. The radial transport is caused by magnetic stochasticity that is generated by multiple tearing instabilities in the plasma.[16] The final theory suggests that the ions are heated by resonant emission from electrons following stochastic fields.[26]

The C^{+5} ion temperature for a single MST plasma discharge is shown in Fig. 1. Each spike in the temperature is a discrete reconnection event. Traditionally, studies of ion heating in MST have utilized the average ion temperature behavior for an ensemble of similar sawteeth. However, as seen in Fig. 1, the change in temperature is not constant for the four reconnection events, but varies from event to event. This variation is believed to be the result of real differences in the plasma as the amount of random error in a temperature measurement (due to Poisson counting statistics) is not large enough to account for the range of variation seen in the change in temperature. The variability in the amount of ion heating presents an opportunity for new analysis techniques that examine what other parameters in the plasma are changing with the variations in the amount of ion heating. Such analysis can test relationships between parameters that current heating theories predict and may suggest new heating mechanisms.

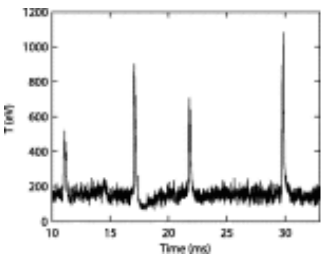


FIG. 1.

The behavior of the C^{+5} impurity ion temperature for a MST plasma. The temperature increases at each reconnection event.

In this paper, we perform correlation studies to relate the change in impurity ion temperature at individua events with various other plasma parameters to determine which factors are most connected with the amount of ion heating at individual events. Correlation of the temperature change with the change in stored magnetic energy gives additional compelling evidence that the magnetic field is indeed the energ source for heating the ions. Correlations of the temperature change with various magnetic tearing mode amplitudes indicate that the amplitude of the magnetic modes resonant throughout the core of the plasma do not determine the global change in ion temperature as well as the modes resonant in the edge of the plasma. The relative unimportance of the core modes is further supported by the lack of a strong correlation between the change in ion temperature and the number of modes active in the core. One of the strongest predictors of the amount of ion heating at individual events is the amount of toroida flux produced as a result of the relaxation of the current profile. The strong relationship between ion heating, edge resonant mode amplitudes, and current profile relaxation is not well addressed by any current heating theory.

A second possibility allowed for by the variation in ion heating is a rotating, toroidal asymmetry to the heating. No current heating theory makes any predictions for the toroidal structure of the ion heating, although all of the theories would allow for spatial nonuniformity. In this paper, we show for the first time that the amount of ion heating is not toroidally uniform around MST, but that there is an asymmetry. The asymmetry is not static, but moves around in such a way that variations in the amount of heating measured at a single location are expected. The structure of the asymmetry is such that a single locatio measures the largest ion temperature when the location lies between the X-point of the largest edge-resonant tearing mode and the position of the maximum constructive interference of the core-resonant modes. Like the correlation results, this structure suggests that the edge-resonant modes may play an important role for the amount of ion heating, not only in the edge, but throughout the entire plasma.

A brief description of the spectroscopic diagnostics used to measure the impurity ion temperature and of the analysis techniques used for the correlations will be given in Sec. II. The results of correlating the change in ion temperature with various plasma parameters are presented in Sec. III. In Sec. IV, measurements are presented of a toroidal asymmetry to the ion heating. Section V discusses both the correlation results and the toroidal asymmetry structure in light of the current heating theories. Finally, a summary of the main results of this work is presented in Sec. VI.

Doppler spectroscopy is a noninvasive technique that has been used successfully in physics and astrophysics to determine kinematic properties of individual atomic species, such as the temperature of ions in a plasma. Two diagnostics on MST use Ion Doppler Spectroscopy to measure the temperature of several impurity ion species in MST. Both diagnostics use high optical throughput spectrometers to analyze light collected by fiber optic bundles along a line of sight.[27,28] The temperature measurements are the weighted average of the temperature along this line of sight. If the light emission profile is very broad, then the weighted average is nearly a true line average. One of the spectrometers has the ability to make localized measurements of the ion temperature using CHarge Exchange Recombination Spectroscopy (CHERS),[28] but these measurements are inherently noisier, making them difficult to work with on an individual event basis. This work used only line-integrated values for the ion temperature, measuring the C^{+4} emission line at 227 nm and the C^{+5} emission line at 343.3 nm. The emission profile for both of these ions is broad at the plasma currents for which the measurements were used. At higher currents, the emission becomes more hollow (especially for C^{+4}) causing the temperature in the edge to be weighted more heavily. The temperature measurements chosen for this analysis were taken along a line of sight that lies in a single poloidal plane and passes through the center of the plasma, at an angle of 75° above the outboard midplane.

Using information from individual reconnection events for the analysis of this work required compiling a large data ensemble from which to extract statistically meaningful results. For the correlation part of the analysis, an ensemble of over 3000 reconnection events was compiled from data taken on MST over the past 10 years. Only data from standard RFP plasmas where the plasma was rotating in the lab frame were included in the ensemble. For each event, the change in the ion temperature was found as this gave the most straightforward measure of the amount of heating that occurred at each event. Strictly speaking, the ion temperature responds to both heating and energy transport but the temperature rise at the reconnection event is large and rapid enough that variations in the amount of temperature rise are likely dominated by variations in the heating term.

The change in the C^{+4} and C^{+5} ion temperatures at individual reconnection events was correlated with a variety of plasma parameters. For each correlation, the coefficient of determination (r^2) was calculated to quantify what fraction of the variation in the change in ion temperature is accounted for by that particular parameter. An r^2 value of one corresponds to a perfect linear relationship where all of the variation in the dependent variable is explained by the independent variable of the relationship. This section aims to present the most interesting results of the correlation analysis and any immediate physical consequences of the results. Further interpretation of the results will be discussed in Sec. V.

A. Change in magnetic energy

If the energy stored in the magnetic field is indeed the energy source for heating the ions, then a reconnection event where more magnetic energy is released should also have a larger change in ion temperature. Plotting the change in ion temperature against the absolute change in magnetic energy found from the alpha model[29] showed this to be the case (Fig. 2). The red triangles correspond to C^{+4} ions and the blue squares correspond to C^{+5} ions. The location of a single dot gives the change in temperature and the change in magnetic energy for that reconnection event. The data span a large range in plasma current, plasma density, and toroidal magnetic field strength so variations in the change in magnetic energy are partly due to the setup of the plasma and partly due to variations in the relaxatio mechanisms at work in the plasma.

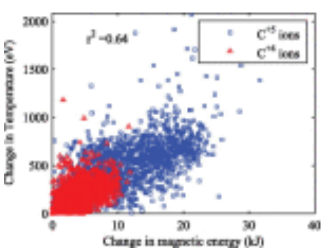


FIG. 2.

The change in temperature for two carbon impurity ions plotted against the absolute change in magnetic energy for over 3000 reconnection events.

The magnetic energy has long been identified as the energy source for the ions because the magnetic energy drops at a reconnection event by a sufficiently large amount (see, e.g., Ref. 14). Figure 2 makes this link stronger by demonstrating that the variations in the change in temperature at individual events are strongly correlated to variations in the amount of magnetic energy released. This indicates that the heating mechanism is fairly robust in that the amount of ion heating scales with the decrease in magneti energy despite varying conditions in the plasma.

B. Change in mode amplitude

The magnetic fluctuations in MST, which are thought to be associated with reconnection at tearing mode resonant surfaces, also correlate strongly with the change in ion temperature. The magnetic field in MST can be Fourier decomposed into different modes that are resonant in different regions of the plasma (se Fig. 3). Conventionally, each mode is designated by a pair of mode numbers, (m, n), where m is the poloidal mode number and n is the toroidal mode number. Modes that are resonant in the edge of the plasma are denoted by m = 0 and n = 1–4. Modes that are resonant in the core of the plasma are designated by m = 1 and n = 5–14. The mode amplitude is measured by a set of 64 coils distributed toroidally along the inner wall of the MST vessel. During a reconnection event, the mode amplitude for a modes will increase suddenly, much like the ion temperature. An initial estimate of the amplitude before the crash can be subtracted from the peak amplitude during the crash to give the change in mode amplitude.

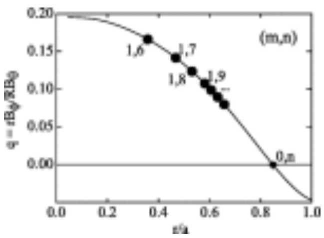


FIG. 3.
$q\ (= rB_{\phi}/RB_{\theta})$ profile for a typical MST discharge at Ip = 400 kA, ne = 10^{19} m^{-3}. Reprinted from S. Gangadhara, Phys. Plasmas 15, 056121 (2008). Copyright 2008 AIP.

Of all the mode amplitudes, the change in the edge localized m = 0, n = 1 mode amplitude at an event correlated most strongly with the change in ion temperature. This is shown in Fig. 4 where the correlatio of the n = 1 mode with the change in ion temperature is compared to two examples of core mode correlations using the n = 6 and n = 9 modes. When the mode amplitude is larger, the transport losses in the plasma are almost certainly greater, yet the change in ion temperature is greater for larger mode amplitudes. This implies that the heating mechanism for the ions must be stronger when the n = 1 mode is larger to enable a rise in temperature despite the increased losses. The importance of the n = 1 mode is also shown in Table I, which lists the r^2 values for each mode number. The data show that the edge-resonant mode amplitudes are much better predictors of the amount of ion heating than the core modes The significance of the edge-resonant modes in MST for ion heating has been previously suspected when it was demonstrated that ion heating does not occur in the absence of the m = 0 modes.[14] It is particularly interesting that the edge-resonant modes are the best predictor of ion heating throughout the entire plasma and not just in the edge region. Our measurement of temperature samples the entire plasma volume and the emission profiles for most of these plasmas weight the contribution from regions around core-resonant modes more strongly than the edge region.

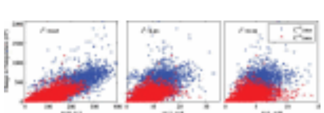


FIG. 4.
The change in temperature for two impurity carbon ions is plotted against the change in mode amplitude for one edge mode (n = 1) and two core modes (n = 6 and n = 9).

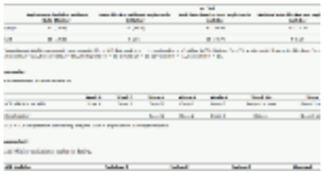


Table I.

A table summarizing the r^2 values for the change in carbon ion temperature with various changes in mode amplitudes.

The importance of the m = 0 modes for global ion heating is further suggested by the lack of any correlation of the change in ion temperature with the number of core modes active. More modes actively causing reconnection in the core of the plasma might be hypothesized to cause more line-integrated ion heating, but the low r^2 value (see Table II) instead indicates that the change in ion temperature is nearly independent of the number of core modes active. Why the edge modes are better indicators of the global ion heating is not immediately apparent and will be discussed further in Sec. V.

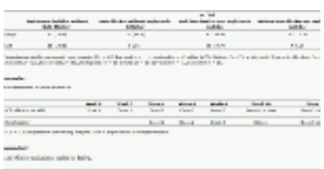


Table II.

A table summarizing the r^2 values for the change in carbon ion temperature with all parameters examined. The mean value and standard deviation for each parameter are also listed.

C. Global plasma parameters

The global ion heating was examined with several global parameters of the plasma: the plasma current, the line-averaged plasma density, and the soft x-ray (SXR) emission from the plasma. The r^2 values for all of the parameters examined are summarized in Table II.

The circuit that drives the toroidal plasma current is the source for the energy stored in the magnetic field and so some degree of correlation with the amount of ion heating is expected. Based on the plot (Fig. 5) of the change in ion temperature versus the plasma current, the maximum amount of ion heating possible at an event increases with current, but the amount of heating still varies widely at any given plasma current. The current determines the total amount of stored magnetic energy, but not necessarily the amount of magnetic energy that will be released and channelled to impurity ion thermal energy at an individual event.

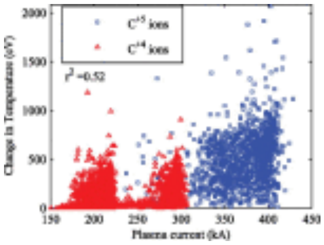


FIG. 5.
The change in temperature for two impurity carbon ions plotted against the average plasma current value during the reconnection event.

Plasma density in MST is measured with a CO2 laser interferometer. The extremely low r^2 value (see Table II) indicates that in the context of multiple widely varying plasma parameters, the amount of ion heating is independent of the plasma density. A linear decrease of the change in ion temperature with density does become apparent when other parameters, such as the change in magnetic energy and the change in mode amplitude, are kept constant. This indicates that although the observed temperature response may vary somewhat, the total amount of energy being deposited in the ions is nearly independent of density as noted in previous studies.[14,15]

The measured SXR emission is a function of the electron density, electron temperature, and the impurity content of the plasma. The SXR emission from the plasma is measured using a photodiode with a thin beryllium foil filter. A higher SXR level typically indicates that the electrons in the plasma are hotter. Based on the r^2 value, the change in ion temperature does correlate with the SXR level before a reconnection event perhaps indicating that the heating mechanism favors higher electron temperatures.

D. Other relaxation activities

Anomalous ion heating is not the only activity that occurs primarily at reconnection events. The change in ion temperature was correlated with several of these transport activities to see if any of them varied with the variation in the amount of ion heating. A strong correlation between ion heating and any of these activities might indicate a synergistic mechanism. In this line of analysis, we chose to use easily measured global characteristics available at every reconnection event to qualitatively represent the overall effect of more complicated local processes that normally require statistical analysis over many events to fully quantify.

Electron heat transport is the loss of electron energy during a reconnection event and is indicated in our analysis by the amount of sudden decrease in SXR emission during an event. While the ions in the plasma experience a net increase in energy during a reconnection event, the electrons in the plasma actually experience an overall loss in energy because electron losses win out over whatever heating of the electrons may occur at the reconnection event. This transport has been studied extensively in MST.[30,31] The correlation of the change in ion temperature with the change in SXR emission yields an r^2 value of 0.55, reflecting a significant correlation between these two activities.

Momentum transport is the cause for the sudden ceasing of the rotation of the plasma at a reconnection event; and in our analysis, we represent this by the change in the toroidal phase velocity of the core-resonant m = 1, n = 6 magnetic fluctuation. This process has also been studied extensively in the past and is strongly affected by the nonlinear interactions between different tearing modes in the plasma.[32–3 The change in ion temperature does not vary consistently with the change in toroidal velocity at a reconnection event ($r^2 = 0.33$) and so it seems that the momentum transport process operates in coincidence with ion heating, but independently from it.

Current profile relaxation due to fluctuations, sometimes referred to as the RFP dynamo, is another feature of reconnection events in the RFP. The fluctuations suppress current along the poloidal magneti field in the edge of the plasma resulting in a sudden increase in toroidal flux.[35,36] We used the change i toroidal flux as a proxy for the amount of current profile relaxation occurring throughout the plasma during an individual reconnection event. The change in temperature correlated strongly with the change in toroidal flux (Fig. 6). In fact, the correlation between the change in ion temperature and the change in toroidal flux was the strongest of any considered in this analysis indicating that the amount of current profile relaxation is a very good predictor of the amount of ion heating. This may be pure coincidence, but the high level of correlation suggests that the current relaxation and ion heating processes may be directly linked. It is worth noting that the rate of change of toroidal flux (which is proportional to the edge poloidal electric field) also correlates strongly with the amount of temperature rise seen at an event. Hence, the connection between the current relaxation and ion heating may alternatively be thought of as a connection between the strength of the inductive electric field and ion heating.

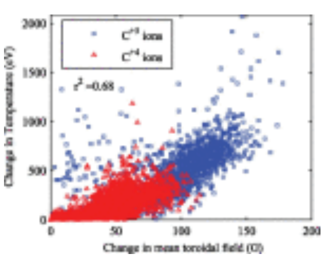


FIG. 6.
The change in temperature for two impurity carbon ions plotted against the change in mean toroidal fiel which is used as an estimate of the level of dynamo activity.

No heating theories have addressed whether the ion heating should be toroidally asymmetric in an RFP, but the nature of the theories certainly allow for inhomogeneity. For a given reconnection event, one region in the torus may be heated more strongly than the rest of the plasma. If this hot spot is not fixed i toroidal location, but is free to move about from event to event, then temperature measurements at a single toroidal location would sometimes measure the hot spot and sometimes a cooler spot. The change in ion temperature at any given fixed location would then be seen to vary from event to event because of the rotating asymmetry.

To assess whether such an asymmetry exists required a dedicated experiment on MST. Two different experiments were performed, but the basic setup for each experiment was the same. For these experiments, four fiber optic bundles were installed at four different toroidal locations on MST. The poloidal positions and viewing angles were the same for all fibers so that the only difference in the ion temperature due to location would be from the toroidal positioning of the fibers. In the first experiment, the fibers were placed at 105°, 240°, 300°, and 320° (as illustrated in Fig. 7). In the second experiment, the fibers were placed at 105°, 120°, 240°, and 320°. The spectrometers were set so that each view measured the same C^{+4} line emission at 227 nm. The experimental setup allowed for simultaneous measurements of the ion temperature at four different toroidal locations at each reconnection event.

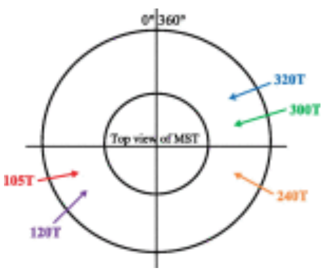


FIG. 7.
Top-down view of MST showing the toroidal positions of the four fiber optical bundles used to measure the asymmetry of the ion heating.

Magnetic fluctuations are an important part to all existing heating theories; and since these fluctuations are inherently asymmetric, they are a natural place to begin examining asymmetries in the amount of ioı heating. The magnetic modes discussed in Sec. III B were used to examine the toroidal asymmetry of the ion heating. Each mode number has a specific amplitude (examined previously) and phase. The phase of the n = 1 mode is defined in such a way that the phase angle indicates the toroidal location of the X-point of reconnection due to that mode. The X-point and the O-point of the n = 1 mode are illustrated in Fig. 8(b), where the X-point is shown at 180° toroidally. It has been shown previously that the m = 0 modes are able to couple to the m = 1 modes via three-wave coupling,[32,37] causing a constructive interference pattern in the m = 1 modes known as the slinky pattern.[38] The toroidal position of maximum constructive interference is labeled as the slinky position. The slinky structure is illustrated in Fig. 8(a) with the slinky position indicated by the vertical line. Correlating the slinky position at the crash with the n = 1 phase at the crash reveals a tight relationship and a constant offset between these two structures (see Fig. 9). According to these measurements, the slinky location at the reconnection event is nearly always approximately 150° beyond the location of the n = 1 X-point.

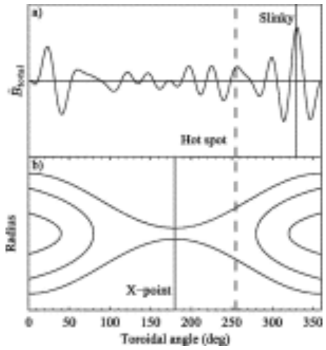


FIG. 8.
An illustration to show how the slinky position, n = 1 phase, and the toroidal location of heating align during a sawtooth crash. (a) shows the slinky for a standard plasma composed of m = 1 modes with n = 6–14. (b) shows the magnetic flux contours of the n = 1 mode. The heating occurs between the X-point and slinky location and is marked by the dashed vertical line.

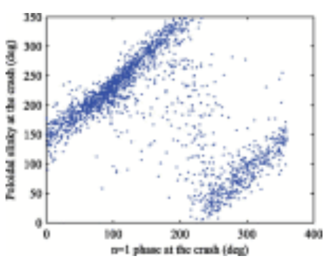


FIG. 9.
The slinky position at a sawtooth crash correlated with the n = 1 phase at the crash.

Since both the position of the n = 1 X-point and the slinky vary for individual reconnection events, if there is an associated asymmetry to the ion heating, then the ion temperature measured at a fixed location should depend on the position of these two magnetic structures. Our measurements show that this is indeed the case. There is a large amount of variation in the measured ion temperature at a single slinky position, likely due to differences caused by the heating mechanism. To remove those variations, we calculated the average temperature for all events where the slinky position was within 15° of twelve distinct locations. The resulting dependence of the five different temperature measurements on the location of the slinky is shown in Fig. 10. The data are plotted as a function of the slinky position relative to the measurement location. Hence, an angle of zero degrees in Fig. 10 means the slinky position coincides with the measurement location. The ion temperature at a reconnection event is observed to be the largest for all views when the slinky is positioned to the right of the measurement location. Because the slinky position and n = 1 phase are linked, the maximum temperature correspondingly occurs when the n = 1 X-point is to the left of the measurement location. The position of maximum heating appears to be centered between the location of the slinky and the location of the n = 1 X-point. The asymmetry is clearly linked to the coupled m = 0 modes and m = 1 modes, but whether it is the n = 1 X-point or the slinky that is responsible for the effect on ion temperature is still unclear.

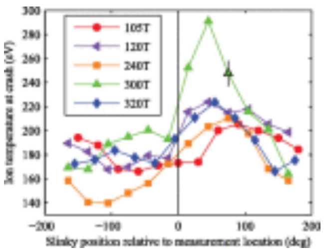


FIG. 10.

The average C^{+4} ion temperature at the sawtooth crash at five different toroidal locations as it varies wit the slinky position relative to the location of the measurement. The error for each point was calculated tc be the standard deviation divided by the number of events. A typical error bar is shown.

A toroidal asymmetry related to the n = 1 X-point and O-point location has been previously observed in the electron temperature during a reconnection event in MST. It was shown that the m = 0 modes directl affected both the edge and the core electron temperature.[39] The electron losses were inferred to be higher at the O-point during the reconnection event (meaning the X-point was relatively hot compared tc the O-point). The ion and electron asymmetries do not line up, as the maximum ion temperature is slightly shifted from the X-point location.

The different ion temperature measurements presented in Fig. 10 all show a preference for larger heating when the measurement location is centered between the slinky location and the n = 1 X-point. However, not all measurements yield the same degree of dependence on the location of these magnetic structures. Measurements taken near 300° show the largest dependence on slinky position while those near 100° show very little dependence. This indicates that in addition to the asymmetry produced by the magnetic structures, there is another asymmetry related to the absolute position of the measurement on the machine. The reason for this is not clear. However, both types of asymmetry are repeatable features of these plasmas and are not the result of differences in measurement apparatus (spectrometers, filters, etc.). The observed pattern is also preserved when the direction of the plasma current is reversed (see Fig. 11). In such a case, the position of the slinky and n = 1 X-point are swapped in Fig. 8, but the maximum heating still occurs between the two locations and is still most apparent at large toroidal angles. One potential explanation for the difference between measurements at different toroidal angles i a difference in emission profiles at different toroidal angles. If the temperature asymmetry is larger at some radii than others, differences in emission profile could make this more apparent at some toroidal locations than others. This possibility could be explored in future experiments.

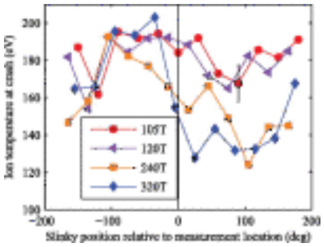
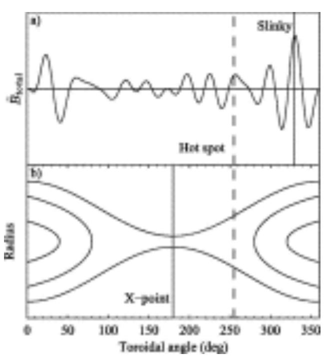


FIG. 11.

The average C^{+4} ion temperature at the sawtooth crash at four different toroidal locations as it varies with the slinky position relative to the location of the measurement. The plasma current direction for this data is reversed as compared to the data in Fig. 10. The error for each point was calculated to be the standard deviation divided by the number of events. A typical error bar is shown.



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An illustration to show how the slinky position, n = 1 phase, and the toroidal location of heating align during a sawtooth crash. (a) shows the slinky for a standard plasma composed of m = 1 modes with n = 6–14. (b) shows the magnetic flux contours of the n = 1 mode. The heating occurs between the X-point and slinky location and is marked by the dashed vertical line.

In Sec. III, the change in amplitude of the edge-resonant modes was shown to be a better predictor of the amount of global ion heating than the core-resonant modes. In the ion-cyclotron heating theory, the m = 0 modes could enter as the moderator of m = 1 mode coupling and they may enhance the magnetic energy cascade to the ion cyclotron frequency at which point the ions are heated. A fluctuation spectrum broadened by the m = 0 could also be a part of the theory that connects ion heating to electron heat transport since a broader m = 1 spectrum leads to a more stochastic magnetic field. In the stochastic ion heating theory, a similar role for m = 0 modes could be accommodated. The viscous damping theory is the only theory not to involve the m = 0 modes in an obvious way unless the m = 1 velocity fluctuations are altered significantly by the presence of the m = 0.

If the main role of the m = 0 modes is to broaden, the m = 1 spectrum and/or facilitate the cascade to higher frequencies, then one might expect the amplitude of the high n modes or the number of core-resonant modes to correlate with the heating more strongly than the m = 0 amplitude. In this sense, our result that the opposite is true is actually quite unexpected. The experimental results appear to argue fo a more direct connection between m = 0 and ion heating, one that perhaps includes m = 1 modes but does not depend so strongly on the magnetic fluctuation amplitude of the higher n modes as the key lin to ion heating. It should be noted that events of a somewhat different nature with large m = 0 amplitude and small m = 1 amplitude have been observed in enhanced confinement discharges in MST and the io temperature rise is small and limited to the edge in such cases.[14] Hence, the tie between global ion heating and the m = 0 mode amplitude appears to somehow still involve the presence of the m = 1 modes.

The viscous heating theory has been virtually ruled out because the flows must be very large and extremely localized to produce the observed amounts of ion heating. Such flows have not been observe in MST despite deliberate efforts to measure them.[36] The toroidal asymmetry results provide another reason to question this theory. Assuming both that the velocity fluctuations have maximum constructive interference at the same toroidal angle as the magnetic field and that the viscous heating theory is correct, then each view should measure larger changes in temperature when the slinky is aligned with the measurement location. Instead, there is an offset between slinky position and the location of maximum heating.

Another key result of the correlation analysis is that the variation in ion heating correlated very strongly with the level of current profile relaxation in the plasma, exhibited some degree of correlation with the amount of electron heat transport, and showed very weak correlation with momentum transport. This is somewhat perplexing because of all of these, the existing theory for momentum transport at a reconnection event very explicitly involves m = 0 modes and m = 1 mode coupling. Hence, it is strange that ion heating correlates strongly with m = 0 mode amplitude, but weakly with momentum transport. One of the existing ion heating theories does explicitly connect the process of ion heating to radial electron heat flux, but no theory makes a strong connection between ion heating and the strongest correlator, the increase in toroidal flux. The strength of the correlation between ion heating and current profile relaxation motivates thinking about new models for ion heating.

The inspiration for one possible model that could connect ion heating to current profile relaxation comes from tokamak experiments. In some tokamak experiments, such as Alcator,[40,41] Versator II,[42] and ASDEX,[43] a non-Maxwellian electron distribution has been observed. When a critical value for the ratio of the drift velocity to the thermal velocity has been reached, a “slide-away” regime of the electrons appears. In this regime, it has been theorized that high frequency current-driven modes can be excited. Some of these modes produce waves at the ion-cyclotron frequency and the ions can absorb the wave energy.[41] In MST, there is an experimentally verified strong electric field in the core of the plasma that has the ability to accelerate both fast ions[15] and fast electrons. The fast electrons may be accelerated t an energy at which they can produce the waves necessary for heating the ions in the plasma.

The strong correlation between ion heating, toroidal flux generation, and m = 0 mode amplitude may all be linked via a strong electric field in the plasma. The m = 0 modes have a direct effect on the current profile in the edge (dominantly poloidal current) and hence on the toroidal flux. There is some evidence that the presence of the m = 0 modes greatly enhances the relaxation action of core-resonant m = 1 modes as well, which are responsible for the redistribution of current in the center of the plasma. The global effect of this combination of processes is a broad inductive electric field profile at the reconnection event, which could accelerate electrons which then damp on ions via waves. Momentum transport, though also a consequence of the modes, does not relate directly to the electric field strength and so should not correlate as strongly with ion heating. The soft x-ray emission might be an indication of how many electrons are in the tail of the electron distribution and this may account for the modest correlation between SXR emission and ion heating. This heating mechanism does not use collisions to transfer the energy from the electrons to the ions and so could be consistent with the observed weak correlation between the ion heating and the plasma density.

The variability in the change in impurity ion temperature at reconnection events was used to gain further physical insight into the process of ion heating in MST. Correlating the change in ion temperature with the change in magnetic energy showed that a larger release of magnetic energy does correspond to a proportionally larger increase in ion temperature. The change in ion temperature also increases with a larger change in the m = 0, n = 1 tearing mode amplitude indicating an importance of the edge-resonant modes for global ion heating. The edge-resonant modes correlate more strongly with the heating than the core-resonant modes and the number of core-resonant modes active at the event does not correlate with the change in ion temperature. The increase in the toroidal flux correlates very strongly with the change in ion temperature implying perhaps a direct connection between the relaxation of the current profile and ion heating.

First measurements of a toroidal asymmetry to the ion temperature were also presented. This asymmetry is not static and so can contribute to the variability in the temperature rise observed at a fixed location on any given event. The asymmetry in ion temperature is strongly linked to the location of the edge-resonant n = 1 mode X-point and the slinky position where core-resonant m = 1 tearing modes constructively interfere. However, which structure is responsible for the toroidal asymmetry of the ion temperature remains to be determined. Also unknown is whether the asymmetry results from an asymmetry in the ion heating or an asymmetry in the ion energy losses.

These experimental results are challenging to accommodate within existing ion heating theories. There is a need for new or revised theories that better incorporate the importance of the m = 0 modes for ion heating and the possibility of a non-collisional heating mechanism in the presence of the strong inductive electric field that accompanies sudden changes in the current profile brought about by the fluctuations. Low noise, radially localized measurements of the ion temperature and more accurate transport models that include the exchange of energy between different ions would also help to clarify the relationship between the observed variations in ion temperature and the nature of the heating process.

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