Spatially Resolved Measurements of Ion Heating during Impulsive Reconnection in the Madison Symmetric Torus

S. Gangadhara, D. Craig, D. A. Ennis, D. J. Den Hartog, G. Fiksel, and S. C. Prager

University of Wisconsin, Madison, Wisconsin and Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, Madison, Wisconsin 53706, USA

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The impurity ion temperature evolution has been measured during three types of impulsive reconnection events in the Madison Symmetric Torus reversed field pinch. During an edge reconnection event, the drop in stored magnetic energy is small and ion heating is observed to be limited to the outer half of the plasma. Conversely, during a global reconnection event the drop in stored magnetic energy is large, and significant heating is observed at all radii. For both kinds of events, the drop in magnetic energy is sufficient to explain the increase in ion thermal energy. However, not all types of reconnection lead to ion heating. During a core reconnection event, both the stored magnetic energy and impurity ion temperature remain constant. The results suggest that a drop in magnetic energy is required for ions to be heated during reconnection, and that when this occurs heating is localized near the reconnection layer.

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Magnetic reconnection occurs in many laboratory and astrophysical plasmas. During reconnection, magnetic energy can be converted into kinetic or thermal energy. Hence, particle energization and heating are often observed in settings where reconnection is present, e.g., in the solar corona [1,2] and Earth's magnetosphere [3]. Ion heating associated with MHD fluctuation activity and magnetic reconnection is also observed in a number of laboratory experiments. These include magnetic fusion devices such as the tokamak [4], the reversed field pinch (RFP) [5–9], the spheromak [10,11], and the spherical tokamak [12,13], as well as high energy density plasmas [14] and basic plasma experiments designed specifically to study reconnection [15,16]. Magnetic reconnection (and subsequent heating) often occurs in impulsive events, both in nature (e.g., solar flares and magnetospheric substorms) and in laboratory plasmas (e.g., sawtooth crashes in the tokamak [17] and the RFP [18]).

A correlation between ion heating and magnetic reconnection has been observed in many experiments, and in low temperature plasmas dedicated to reconnection studies the direct relationship between reconnection and heating has been explored [15,16]. However, for high temperature plasmas, which may contain multiple reconnection sites, the relationship between the spatial distribution of the heating and the spatial location of reconnection has not been established. Most measurements in high temperature plasmas have relied on line-of-sight techniques—such as passive Doppler spectroscopy—that provide line-integrated measures of ion temperature. Such measurements cannot resolve simultaneously the heating in both space and time.

In this Letter, we present fast, spatially resolved spectroscopic measurements of the impurity ion temperature during three kinds of impulsive reconnection events in the Madison Symmetric Torus (MST) RFP [19]. During the first type of event reconnection is limited to the edge, the drop in stored magnetic energy is modest, and ion heating is limited to the outer half of the plasma. In the second kind of event many coupled reconnection sites exist throughout the plasma, the drop in stored magnetic energy is larger, and ion heating occurs at all radii. In both cases the ion temperature rise occurs on a fast time scale, of order of the reconnection time, and in both cases the drop in magnetic energy is sufficient to explain the observed rise in ion temperature. In the third type of reconnection event reconnection is limited to the core, the stored magnetic energy remains approximately constant, and no ion heating is observed at any radial location. The results suggest that a drop in magnetic energy is required for ions to be heated during reconnection, and that when this occurs heating is concentrated near the reconnection layer. Consequently, the large-scale heating observed during a global reconnection event arises from the presence of many heating layers distributed throughout the plasma volume.

Plasma behavior during reconnection is established by ensemble averaging the data from many similar reconnection events. In Fig. 1, the ensemble-averaged amplitudes of tearing mode fluctuations responsible for reconnection are shown for an edge and global reconnection event, as is the evolution of the stored magnetic energy. The magnetic fluctuation data are determined from Fourier decomposition of coil data at the plasma boundary. The stored magnetic energy is calculated from an equilibrium model [20]. During an edge reconnection event (lasting ~40 μs), edge-resonant fluctuations with poloidal mode number $m = 0$ are excited first, followed by modest growth of core-resonant $m = 1$ modes later in time [Fig. 1(a)]. Conversely, during a global reconnection event (lasting ~100 μs) $m = 1$ modes are excited first [Fig. 1(b)], and nonlinearly couple to excite edge-resonant $m = 0$ fluctuations, the largest having toroidal mode number $n = 1$. The

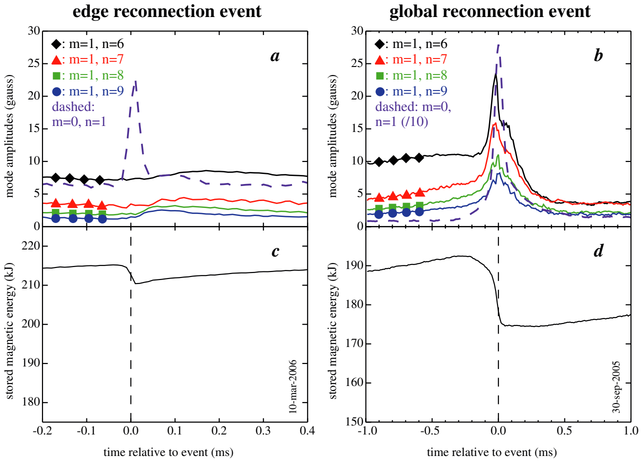

FIG. 1 (color online). Tearing fluctuation activity (a),(b) and volume-integrated stored magnetic energy (c),(d) in an edge and global reconnection event. Data are averaged over a number of similar events. In (b), the $m = 0$, $n = 1$ amplitude is divided by 10.

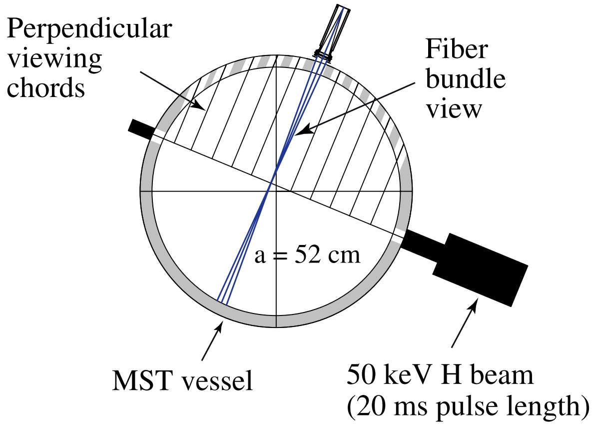

FIG. 2 (color online). Vertical cross section of MST showing the position of the beam and the views used to make CHERS emission measurements.

increase in $m = 0$ mode amplitude is substantially larger for a global event than for an edge event (by a factor of $\sim$10), and the change in stored magnetic energy is correspondingly larger as well [Fig. 1(c) and 1(d)]. In general, edge events have a smaller effect on plasma parameters than global events, and are primarily observed during periods of enhanced confinement [21,22].

Impurity ion temperature data were obtained from localized measurements of impurity ion emission using charge exchange recombination spectroscopy (CHERS) [23]. The use of CHERS to measure impurity ion parameters was first demonstrated by Fonck *et al.* [24] and by Isler and Murray [25]. On MST, a CHERS system has been developed to study ion fluctuations and fast ion dynamics during impulsive reconnection events. The system has a 10 μs time response, and has been optimized to accommodate both the MST temperature range (typically 300–500 eV, though up to 2 keV in high current plasmas) and the high level of competing background emission from the plasma.

Results described in this Letter were obtained from measurements of C VI emission ($\lambda \simeq 343.4$ nm) stimulated by charge exchange between C^{+6} ions and neutral hydrogen atoms injected radially into the plasma via a diagnostic neutral beam. A cross section of MST showing the position of the beam and the optical views available for the CHERS measurement is given in Fig. 2. The radial resolution for these measurements is $\simeq$2 cm. Data are collected using two fiber bundles (to allow for real-time background subtraction); for each discharge, the bundles are placed at a single viewport, providing measurements from a single radial location. The collected light is dispersed and recorded in a custom-built, high-throughput spectrometer [26]. Values for the local C^{+6} ion temperature (T_C) are extracted from nonlinear fits to the data. Within the spatial ($\sim$2 cm) and temporal (10 μs) resolution of the measurements, the ion velocity distribution remains Maxwellian throughout a reconnection event (regardless of the type of event), and there is no significant change in the ion flow. Thus, a Maxwellian velocity distribution is used in the modeling, and effects of spin-orbit coupling are included [27].

Ensemble-averaged results for the impurity ion temperature during an edge reconnection event have been obtained at five radial locations, ranging from $r/a = 0$ to $r/a = 0.75$, and are shown in Fig. 3. Error bars were estimated by assuming the data noise is dominated by Poisson photon counting statistics. Measurements were made in plasmas with a toroidal current of $\simeq 420$ kA and a line-average plasma density of $\simeq 0.7 \times 10^{19}$ m^{-3}. An increase in the ion temperature is observed only for the two outermost measurement locations, suggesting that ion heating is *limited to the edge* for an edge reconnection event. The heating is largest at $r/a = 0.75$, the position closest to the resonance surface for $m = 0$ tearing fluctuations (near $r/a \sim 0.8$ in these plasmas). Radial profiles of T_C

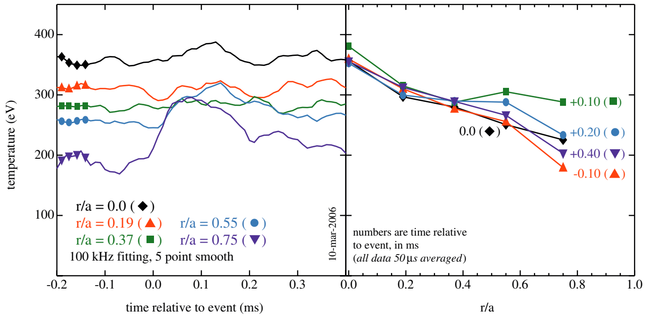

FIG. 3 (color online). Left: Average values for the impurity ion temperature through an edge reconnection event, measured at five plasma radii. Right: Radial profiles of the impurity ion temperature through an edge reconnection event. Each point represents an average of T_C data over a 50 μs time window.

have been constructed from the time-resolved data, and the results for five time points are also shown in Fig. 3. Prior to the event, a slightly peaked profile is observed. At the time of the event, T_C increases first at $r/a = 0.75$. The temperature increase then propagates inward towards $r/a = 0.55$. The temperature inside this radius is unaffected, and thus a slightly hollow T_C profile results. Following the event, cooling occurs over ~0.5 ms.

Ensemble-averaged results have also been generated during a global reconnection event and are shown in Fig. 4. Error bars were again estimated by assuming the data noise is dominated by Poisson photon counting statistics. Measurements were made in plasmas with a toroidal current of $\simeq 390$ kA and a line-average density of $\simeq 10^{19}$ m^{-3}. T_C is observed to increase at all measured locations, and the temperature increase begins at approximately the same time relative to the event at all radii ($\simeq 200$ μs before the event, and at the same time as the mode amplitudes begin to increase—see Fig. 1). In addition, the time scale for heating is comparable at all radii, and is of order the reconnection time (~100 μs), which is much faster than transport time scales. These observations indicate that ion heating occurs over a *broad radial extent* during a global reconnection event. Radial profiles of T_C at five time points are also shown in Fig. 4. A slightly peaked temperature profile is observed prior to the event. At the time of the event, heating is nearly uniform and is substantial, causing a factor of 2 or more increase in T_C. Peak temperatures occur shortly after the event, with the largest increase off-axis, between $r/a = 0.19$ and $r/a = 0.37$. Many $m = 1$ modes are resonant in this region, suggesting that the heating mechanism may be strongest in regions of maximum reconnection. Following the event, the edge plasma cools rapidly, on a similar time scale to the heating and comparable to the cooling rate observed after an edge reconnection event, while the plasma core cools on a much slower time scale (~1 ms).

Results shown in Figs. 3 and 4 suggest that during reconnection events ion heating occurs near resonant surfaces. This heating only occurs, however, when there is a substantial drop in the magnetic energy, and not all reconnection events result in such a drop. In Fig. 5, a reconnection event is shown in which core-resonant $m = 1$ modes are active but edge-resonant $m = 0$ modes are not. Although the core-resonant modes grow to similar amplitude in both core and global reconnection events [compare Fig. 5(a) to Fig. 1(b)], no change is observed in either the stored magnetic energy or the on-axis impurity ion temperature [Fig. 5(b)]. Profile measurements of T_C obtained from a number of similar core reconnection events indicate that this result remains true at all radial locations.

A number of mechanisms have been proposed to explain ion heating during magnetic reconnection, including resonant heating resulting from a turbulent cascade of tearing fluctuations to cyclotron frequencies [7,28], and collisional viscous damping of flows associated with tearing fluctuations [29–31]. Simulations indicate that cross-field flows would have to be comparable to the thermal ion sound speed and vary strongly over a gyroradius scale for perpendicular viscosity to be effective in heating the ions [32]. Such large and localized flows have yet to be observed experimentally. Parallel viscosity is responsible for damping neoclassical parallel flows [33,34], as well as cross-field compressional flows [29,31], and may therefore play an important role in transferring energy from fluctuations to the ions, since the parallel viscosity coefficient is significantly larger than the perpendicular viscosity coefficient [35]. The effects of parallel viscosity in MST are

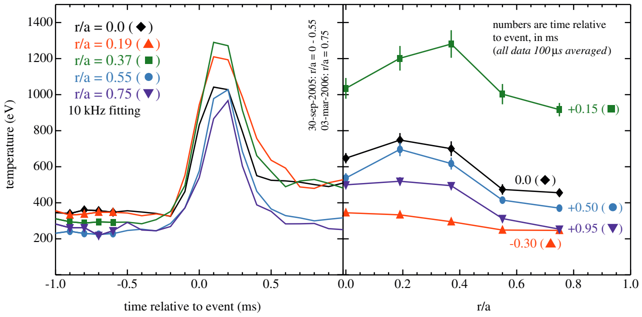

FIG. 4 (color online). Left: Average values for the impurity ion temperature through a global reconnection event, measured at five plasma radii. Right: Radial profiles of the impurity ion temperature through a global reconnection event. Each point represents an average of T_C data over a 100 μs time window.

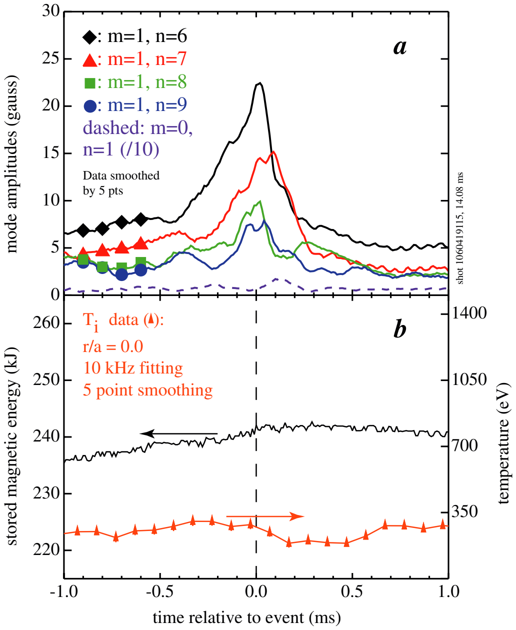

FIG. 5 (color online). Tearing fluctuation activity (a), volume-integrated stored magnetic energy [(b),solid line], and on-axis impurity ion temperature [(b), triangles] in a single core reconnection event. In (a), the $m = 0$, $n = 1$ amplitude is divided by 10.

currently being studied using calculated tearing mode flow profiles. The role of cyclotron damping in heating ions remains an open question, and is under theoretical investigation. Earlier measurements of the fluctuation power spectrum during global reconnection events in MST indicated energy loss at $\omega = \omega_{ci}$ [7]. However, ion heating by cyclotron waves is expected to be anisotropic, and no such anisotropy was observed in previous line-integrated results for $T_{\|}$ and $T_{\perp}$ [9]. As a consequence of MST's magnetic topology, current CHERS measurements yield a mix of both parallel (on-axis) and perpendicular (in the edge) ion temperature. Additional views are being designed to provide complete localized measurements of $T_{\|}$ and $T_{\perp}$, so that the effects of cyclotron damping may be accurately assessed. Any mechanism that is used to explain ion heating during edge and/or global reconnection events must also explain the absence of heating during core reconnection events.

In summary, spatially resolved measurements of the impurity ion temperature evolution during three types of impulsive reconnection events in MST have been obtained using charge exchange recombination spectroscopy. Results indicate that during an edge reconnection event—when the drop in stored magnetic energy is modest—the ion temperature only increases in the outer half of the plasma, and that this increase is strongest near the location of reconnection. Conversely, during a global event—when the drop in stored magnetic energy is large—ion heating is observed simultaneously at all radial locations, indicating that the heating occurs over a broad radial extent. Heating is also large in this case, causing the impurity ion temperature to increase by a factor of 2 or more. For both types of event, the drop in magnetic energy is adequate to explain the increase in ion thermal energy. In addition, the time scale for heating is of order of the reconnection time, while the time scale for cooling is generally longer, and likely determined by energy transport. The correspondence between the heating and reconnection locations and the heating and reconnection time scales implies that the observed heating is directly related to reconnection. However, not all impulsive reconnection events lead to ion heating. During a core reconnection event, both the stored magnetic energy and the impurity ion temperature remain constant. A drop in stored magnetic energy is therefore required for ions to be heated during reconnection. Future work is focusing on the influence of nonlinear coupling between core and edge reconnection sites in triggering such a drop.

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