*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-5.048 (2005)*

Spatially resolved ion heating measurements during a sawtooth crash on the Madison Symmetric Torus (MST)

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Self-heating of ions during magnetic reconnection is a process important to a number of laboratory and astrophysical plasmas. Measurements have recently been made - for the first time - of the impurity ion temperature (T_C) profile evolution during a fast ($\sim$ 100 μs) reconnection event (sawtooth crash) on the MST reversed field pinch [1]. A new custom-built spectrometer was recently installed on MST to provide localized measurements of T_C with fast time resolution using charge exchange recombination spectroscopy (CHERS) [2]. The profile of T_C rise observed during the crash suggests that the heat source is broad and active throughout the plasma volume. In addition, the time scale for ion heating ($\tau_H \sim 100$ μs) is similar at all measured locations, while the time scale over which T_C returns to its pre-crash value is significantly longer than τ_H at most radii. The bulk ion temperature (T_D) has also been measured at a single point using Rutherford Scattering [3]. Comparisons between these measurements and CHERS results indicate that impurity ions are more strongly heated than bulk ions during a sawtooth crash. A number of theories are being examined to explain the full set of results. These include viscous damping of MHD fluctuations, and acceleration of ions in the mean electric field.

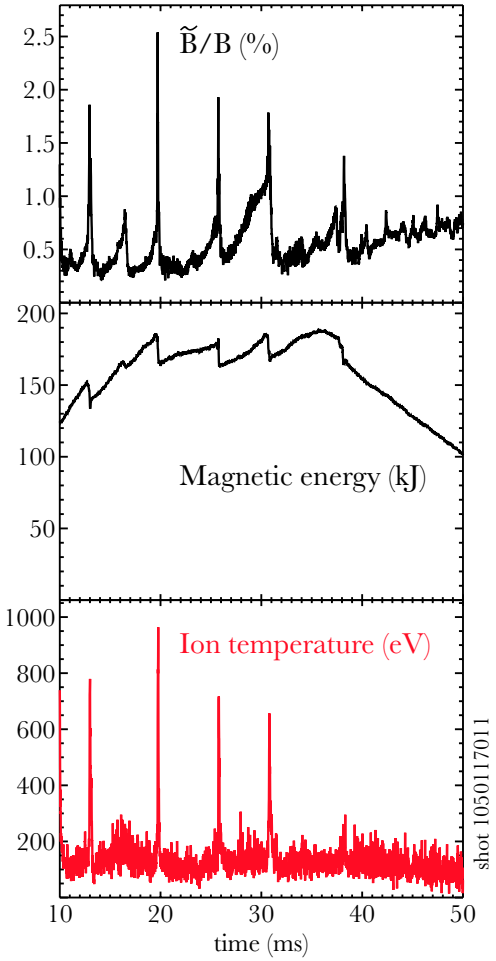

Figure 1: Variation of fluctuation amplitude, stored magnetic energy, and line-average T_C during a single discharge in MST.

Introduction Plasma behavior in MST is characterized by periods of quiescence punctuated

by impulsive change. This can be seen in Fig. 1, where three plasma quantities are plotted as a function of time for a single discharge: magnetic fluctuation amplitude (normalized), stored magnetic energy, and line-average impurity ion temperature (T_C). Each impulse - referred to as a *sawtooth crash* - represents the presence of fast reconnection events in the plasma volume. During the crash (which lasts $\sim$ 100 μs) the fluctuation amplitude and line-average T_C both increase significantly, while the magnetic energy decreases by a few percent. Interestingly, the drop in magnetic energy ($\sim$ 10 kJ) is consistent with the power needed to explain the rise in T_C. What is not well understood is how that energy is transferred to the ions over the short time scale of the sawtooth crash, which is much less than the ion-ion collision time in these plasmas.

Anomalous ion heating associated with increased MHD fluctuation activity and magnetic reconnection has been previously observed on MST [4] as well as other experiments (*e.g.* [5], [6]). A better understanding of the heating mechanisms present during a sawtooth crash would be available from spatially localized measurements of T_i. To capture the temporal structure of the crash, these measurements require fast time resolution. Such a system has recently been developed for MST, employing charge exchange recombination spectroscopy (CHERS).

Ion temperature measurements Values for the impurity ion temperature (and velocity) are obtained from measurements of the Doppler-shifted and broadened profile of an impurity emission line (CVI for these experiments). This emission results from charge exchange between neutral hydrogen atoms injected into the plasma via a diagnostic neutral beam (DNB) and fully-stripped impurity ions present in the plasma *a priori*. An example of typical emission data is shown in Fig. 2. Using an accurate model for the line shape to fit the data (in which a Maxwellian distribution for the impurity ions is assumed), the line width is related to T_C. In addition, because the intersection volume between the DNB and the (poloidal) line-of-sight for the emission measurements is small (sample volume $\sim$ 2 cm; plasma radius = 52 cm), T_C values obtained in this manner are *spatially localized*. The CHERS system currently has 11 different viewing chords, allowing profile measurements of T_C to be made from sets of reproducible discharges.

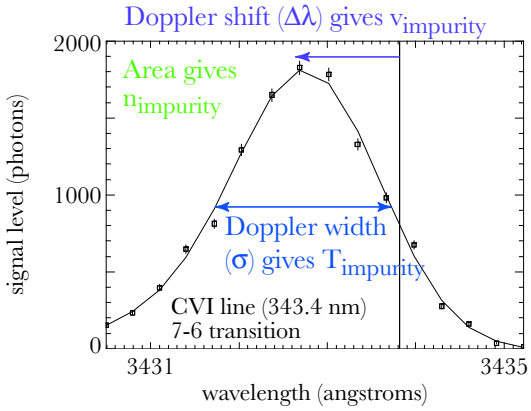

Figure 2: Doppler-shifted and broadened emission resulting from charge exchange between neutral hydrogen (injected with a DNB) and C^{+6}.

Single point measurements of the bulk ion temperature (T_D) are obtained using Rutherford Scattering (RS). This technique involves measuring the energy spectrum of helium atoms injected into the plasma via a neutral beam and subsequently scattered by the plasma majority ions. The width of this spectrum can be directly related to T_D. As the intersection volume between the beam and the energy analyzer collection volume is small, these measurements are also localized, though with poorer radial resolution than CHERS ($\sim$ 7 cm). Nonetheless, these data allow for a valuable comparison between T_C and T_D, which may provide insight into the physics of heating during a sawtooth crash.

Impurity ion temperature measurements during a sawtooth crash T_C data averaged over many similar sawtooth crashes have been obtained at five radial locations (from $r/a = 0$ to 0.75). Results indicate that impurity ion heating is *global* during a sawtooth crash, in that T_C increases significantly at each radius. The rise in T_C begins at approximately the same time for all radii ($\sim$ 200 μs before the crash), and the time scale for heating is comparable at all locations ($\tau_H \sim$ 100 μs). The cooling time scale ($\tau_C \leq$ 1 ms) is longer than τ_H in most cases, except at the edge ($r/a = 0.75$), where $\tau_C \simeq \tau_H$.

Radial profiles of T_C through a sawtooth crash are shown in Fig. 3. Though heating is observed at all radii, it appears to be strongest in the center ($r/a = 0$) and at the edge. In addition, the peak temperature reaches a similar value for all radii outside of the magnetic axis. As indicated above, the edge temperature drops to its pre-crash value quickly following the crash; the rate at which T_C returns to its pre-crash value elsewhere is much longer. These results may be explained by effects of edge ion transport and/or neutral penetration from the walls.

Comparison between impurity and bulk temperature T_D data averaged over multiple sawtooth crashes have been obtained from a single location ($r/a = 0.32$), and the resultant time-history is shown in Fig. 4. Values from each crash were calculated from a moment analysis of the corresponding energy spectrum. T_C data obtained from a nearby location ($r/a = 0.37$) are also plotted in Fig. 4. Results indicate that $\Delta T_C \simeq 2 \times \Delta T_D$, implying that impurity ions are heated more strongly than bulk ions during a sawtooth crash. Curiously, the rate at which T_i re-

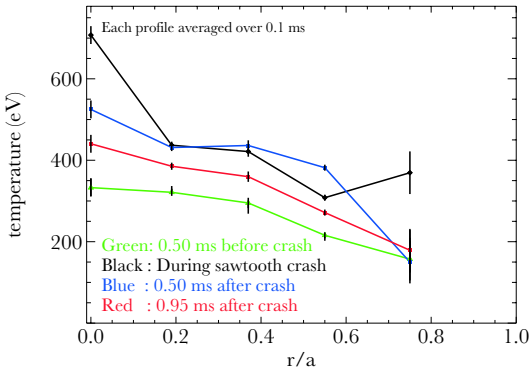

Figure 3: Profile measurements of T_C through a sawtooth crash.

turns to its pre-crash value is similar for both impurity and bulk ions. These results should provide a useful constraint for theoretical modeling of the ion heating.

Summary & Future Work Ion temperature measurements with good spatial and temporal resolution have been made for the first time during a fast reconnection event (*i.e.* sawtooth crash) on MST. Measurements indicate the presence of strong ion heating during the crash, and that the heating occurs over a large fraction of the plasma volume. This heating takes place over a short time scale, relative to the ion-ion collision time. There is also indication that this heating is stronger for impurities than for the bulk.

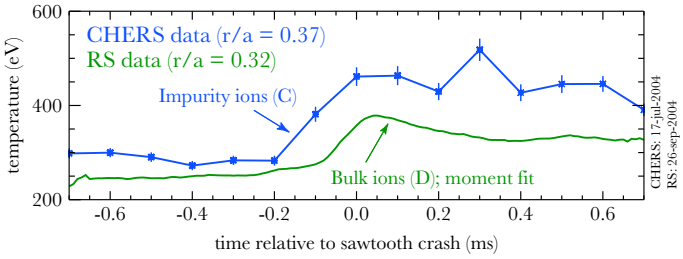

Figure 4: Comparison between T_C and T_D time-histories during a sawtooth crash. Both sets of data are averages over a number of similar discharges.

A number of theories are being developed to explain this heating, including viscous damping of fluctuations and electric field acceleration of ions during the reconnection (though for viscous damping to be effective, large, localized flows are necessary, which have yet to be observed experimentally). To facilitate better comparison with theory, a number of upgrades are currently being performed to the CHERS system. They include: *(1)* addition of a toroidal CHERS view, to allow for measurement of $T_{\|}/T_{\perp}$, an important parameter in many heating theories; *(2)* commissioning of a new long-pulse (20 ms) DNB, which will provide an improvement in the single-shot signal-to-noise and allow for more sawtooth crash data to be collected in a single experimental run; *(3)* studying ion heating during other plasma phenomena - such as in plasmas with reduced relaxation, in which initial observations suggest that anomalous heating may be small - to increase understanding of heat sources and sinks and ion transport in MST.

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