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LETTER TO THE EDITOR

Isotropy of ion heating during a sawtooth crash in a reversed-field pinch

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Abstract. In the Madison Symmetric Torus reversed-field pinch, ions are impulsively heated during a sawtooth crash; the ion temperature more than doubles. Heating appears to be nearly isotropic; the impurity ion temperature measured perpendicular to the magnetic field ($T_\perp$) is approximately equal to impurity ion temperature parallel to the magnetic field ($T_\parallel$) during a sawtooth crash. Ion heating occurs simultaneously throughout the entire plasma volume, with no non-Maxwellian distortion of the ion velocity distribution function.

The mechanism by which ions are heated in a reversed-field pinch (RFP) plasma is not yet understood. This is a fundamental challenge to plasma physics, as ion heating in the RFP exhibits similarities to heating in magnetic reconnection experiments [1] and solar plasmas. To date, all RFPs have been ohmically heated by inductively driving a current through the plasma. From Spitzer resistivity it follows that the electrons should be directly heated, with energy flowing to the ions via collisions. Yet, it has often been observed that the ion temperature is higher than expected from collisional coupling [2–5]; under some conditions $T_i > T_e$, which cannot be accounted for by equipartition. Proposed theoretical explanations include direct ion heating via dissipation of fluctuations by ion parallel viscosity [6, 7], the forward cascade of energy from tearing modes to ion cyclotron resonances [8], viscous thermalization of ions accelerated during fast magnetic reconnection [9], and heating due to absorption by ions of waves emitted by granulations in the electron distribution function which arise from magnetic turbulence [10]. Common to these theories is an expectation that ion heating will not occur isotropically; that is, the velocity distribution function of the ions will be distorted by the heating. Therefore, a key experimental input to these theories is to measure any asymmetry in the ion temperatures perpendicular ($T_\perp$) and parallel ($T_\parallel$) to the confining magnetic field.

On the Madison Symmetric Torus (MST) RFP we observe $T_\perp \approx T_\parallel$ throughout the quiet phase which constitutes most of a sawtooth cycle. During sawtooth crashes, the ion temperature doubles (or more) in 100 μs and magnetohydrodynamic (MHD) tearing mode fluctuations are of large amplitude, but $T_\perp/T_\parallel$ remains approximately equal to one. Furthermore, in MST we also observe that ion heating occurs simultaneously throughout the entire plasma volume. During a sawtooth crash, the radial profile of T_i appears to flatten, with a larger relative increase in T_i in the edge than in the core. There is no obvious spatial localization of the heating mechanism or temporal propagation of a heat pulse. Also, we do not observe any non-Maxwellian distortion of the ion velocity distribution function, even during the rapid ion heating that occurs during a sawtooth crash.

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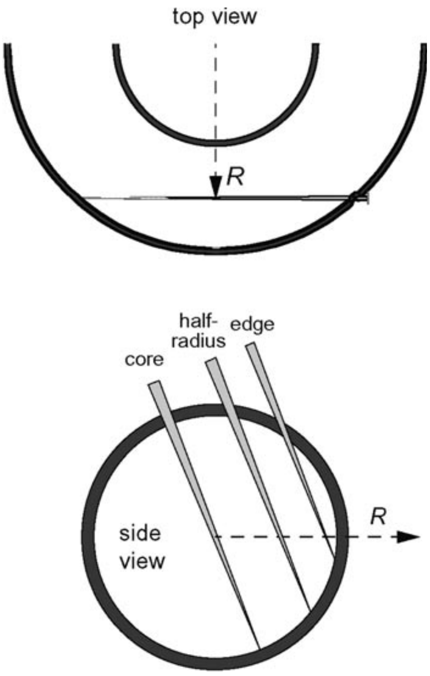

Figure 1. Viewing chords for Doppler spectroscopy on MST. The top view shows the toroidal viewing chord which passes through the central core of the plasma. The side view (below) is illustrative of the radial viewing chord ($r/a = 0$) and half-radius and edge chords.

Impurity ion temperature measurements in MST are made by chord-averaged observation of the Doppler-broadened spectrum of the 227.09 nm line of C^{4+} impurity ions in a hydrogen majority plasma [11, 12]. Since this measurement relies on the passive collection of line emissions, the spatial localization is determined by the C^{4+} emission profile, which is broadly peaked in the plasma core [13]. Therefore, except for viewing chords that intersect only edge plasma, the as-measured impurity ion temperature is representative of the core plasma in MST. The perpendicular temperature is measured with a radial viewing chord (impact parameter $r/a = 0$, figure 1) while the spectrum recorded by a toroidal viewing chord is a convolution of both perpendicular and parallel temperatures. However, a straightforward analysis of the toroidal viewing chord geometry [13] shows that the measured temperature T_ϕ is dominated by $T_\|$. The edge parallel temperature is measured with a viewing chord which intersects the poloidal field lines at the RFP $q = 0$ surface at $r/a \simeq 0.85$.

The data presented here are averaged from a large ensemble of sawtooth events gathered from the flat-top portions of a series of low-current (200 kA) MST discharges. MST is a toroidal magnetic confinement device operated as a RFP, a configuration in which the plasma drives a reversal of the direction of the edge toroidal magnetic field with respect to the core. Ion heating at the sawtooth crash is more dramatic for higher currents and/or deeply reversed discharges, but low-current discharges display all the important ion heating phenomena and allow the collection of a large data ensemble in a relatively short period of time. The sawtooth period for these RFP plasmas is about 4 ms, with variations in the magnetic fluctuation amplitude and mean field as shown in figure 2. In MST, the sawtooth crash coincides with a large increase in MHD fluctuations and the rapid conversion of poloidal flux into toroidal flux, indicative of strong dynamo activity [14]. This dynamo sustains the RFP magnetic field configuration against resistive diffusion and has often been linked to ion heating. As shown in figure 3, strong ion heating takes place in MST during a sawtooth crash. The electron temperature was not

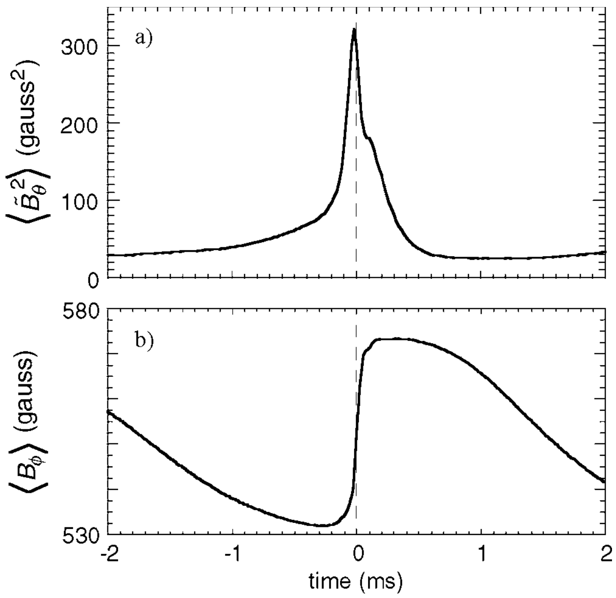

Figure 2. Variation in (a) the magnetic field fluctuation amplitude and (b) the average toroidal magnetic field over a sawtooth cycle in MST from an ensemble average of several hundred sawtooth events. The time of the maximum increase of the toroidal magnetic field defines $t = 0$.

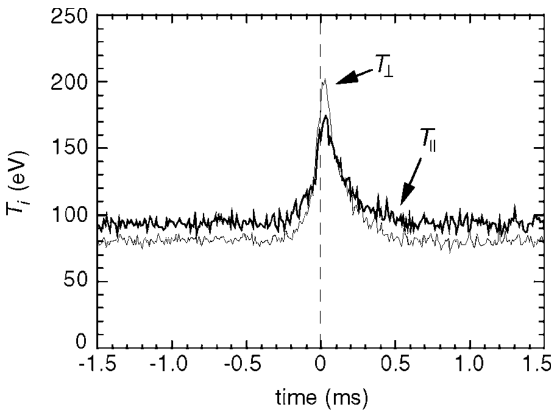

Figure 3. Parallel and perpendicular impurity ion temperatures over a sawtooth cycle. The ions are strongly heated around $t = 0$ when the sawtooth crash occurs and the MHD activity is largest.

measured during this set of discharges, but a temperature of approximately 160 eV has typically been measured under similar conditions [13]. Thus the T_i at the sawtooth crash cannot be explained by electron–ion collisional coupling. The ion temperature between crashes could be due to equipartition if the ion confinement time were several milliseconds (typically, the particle confinement time is about 1 ms in MST). Also of interest is the sudden cooling of the ions after the sawtooth crash. That is, T_i spikes at the crash rather than stepping up to a higher plateau. This behaviour implies an extremely rapid energy transport out of the ions after the sawtooth crash. The mechanisms at work during the rapid heating and rapid cooling are both unknown.

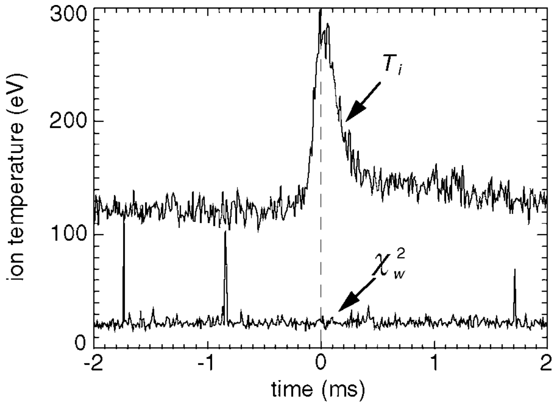

Figure 4. The weighted χ^2_w of the Gaussian fits for the toroidal viewing chord over a sawtooth cycle, illustrating the lack of non-Maxwellian distortion of the ion velocity distribution function, even during strong heating. The radial viewing chord shows similar behaviour. This data is from a set of 300 kA MST discharges, thus T_i is higher than in figure 3.

Referring again to figure 3, both the perpendicular and parallel temperatures rise sharply together with no time lag visible between the two. A difference of about 30 eV occurs during the crash as $T_\perp$ reaches about 200 eV while $T_\parallel$ peaks at about 170 eV. This difference persists for less than 100 μs at which point both temperatures rapidly fall back to their equilibrium values of about 80 eV. The observation that $T_\perp$ slightly exceeds $T_\parallel$ at the sawtooth crash is robust over a variety of discharge conditions. However, the difference in the parallel and perpendicular temperatures could be due to profile changes at the sawtooth (the parallel and perpendicular viewing chords do not weight the impurity emission profile identically). Therefore, within the precision of the measurement, ion heating at the sawtooth crash appears nearly isotropic and occurs very rapidly.

Over the sawtooth cycle, the Doppler-broadened impurity emission spectrum can be fit every 10 μs; a careful visual inspection of each fit during a sawtooth crash reveals no systematic (non-Poisson) deviation of the individual spectral datapoints from a Gaussian fit. This is quantified by calculating the weighted χ^2_w [15] of the Gaussian fits over the sawtooth cycle (figure 4). The lack of any substantial variation in χ^2_w at the crash indicates that the ion velocity distribution function is not distorted during the rapid heating event. In other words, the ion velocity distribution function appears to remain Maxwellian even during the rapid ion heating characteristic of a sawtooth crash. This is an intriguing result, given that the characteristic thermalization time of a ‘bump-on-tail’ distortion of the ion velocity distribution function is $\geqslant$ 100 μs for MST plasma parameters [16]. Thus an ion heating scenario in which ions are anisotropically accelerated and then thermalize does not appear to apply in MST.

Several other measurements confirm the spatial and temporal isotropy of the ion heating mechanism in MST. Figure 5 contains data from viewing chords with core, half-radius and edge impact parameters (see figure 1). Ion heating simultaneous with the core is apparent even in the edge viewing chord. Since C v emission is bright only around the sawtooth crash, the data from the edge chord is not quite good enough to precisely place the ion temperature peak, but the heating ramp prior to $t = 0$ occurs simultaneously to within 10 μs throughout the plasma. (Although not shown in figure 5, this is confirmed by scaling up the edge and half-radius traces such that they peak at the same ordinate value as the core trace.) Note that the core viewing chord records $T_\perp$ while the edge records $T_\parallel$, but this should not seriously affect this conclusion given the lack of a large difference between $T_\perp$ and $T_\parallel$ in the core.

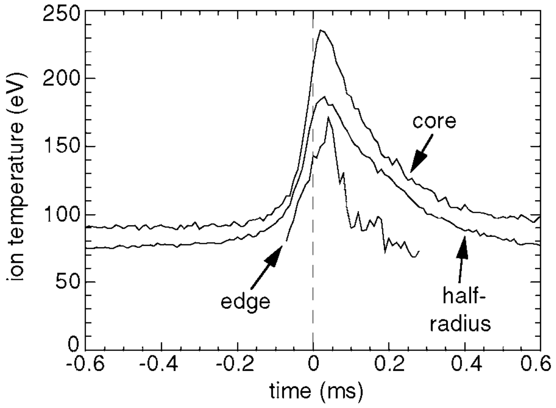

Figure 5. Measurements from core, half-radius and edge viewing chords confirm that ion heating occurs simultaneously across the minor radius during a sawtooth crash.

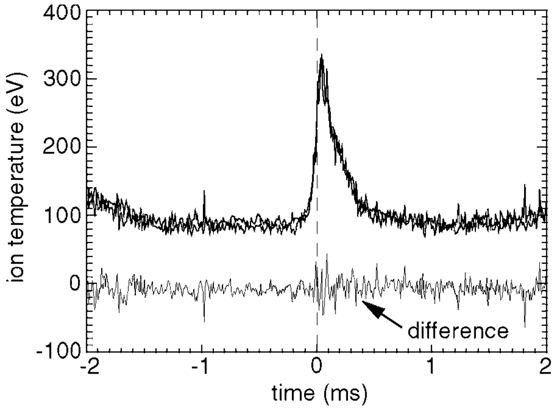

Figure 6. Perpendicular T_i from two toroidally separated viewing chords, and the difference between them, further illustrating the spatial symmetry of ion heating.

As a further check of the spatial symmetry of ion heating, we simultaneously measured the core $T_\perp$ from two radial viewing chords in MST toroidally separated by 84° (figure 6). The traces are identical; there is no toroidal asymmetry in the ion heating. As a sidenote, the data in figure 6 was taken from more deeply reversed RFP discharges, thus the more pronounced ion heating and higher peak T_i at the sawtooth crash. Such discharges in MST exhibit higher levels of MHD fluctuations, indicating a possible correlation between the amplitude of the MHD activity and the level of ion heating. However, while MHD fluctuations may be a necessary condition for strong ion heating, their presence alone may not be sufficient to trigger the ion heating mechanism. Other processes in MST, such as the MHD dynamo [14], are only operative when proper phase alignment is achieved between two or more fluctuating quantities. Such a condition is typically observed only at the sawtooth crash.

The ion heating observations on MST exhibit two major differences from those recorded on the EXTRAP-T2 RFP [17]. First, the equilibrium perpendicular and parallel ion temperatures are similar throughout the sawtooth cycle. This is in contrast to EXTRAP-T2 where $T_\perp / T_\parallel < 1$

throughout the flat-top portion of the discharge. Second, $T_{\parallel}$ is observed to be slightly smaller or equal to $T_{\perp}$ during a sawtooth crash on the MST, whereas on EXTRAP-T2 $T_{\parallel}$ is much larger (sometimes three times larger) than $T_{\perp}$ during periods of an increased magnetic fluctuation amplitude. It is possible that these differences between MST and EXTRAP-T2 are due to the markedly different fluctuation dynamics in the two devices [18]. EXTRAP-T2 is a thin-shell RFP with discharges characterized by a wall-locked mode which strongly affects the dynamics of internal resistive tearing modes associated with the dynamo, whereas MST is a more traditional RFP with a thick conducting shell, rotating tearing modes, and regular sawteeth.

Previous work on MST has shown that the majority protons are also impulsively heated during a sawtooth crash [5], thus similar heating mechanisms are probably at work on both the majority and impurity species. The equilibration time between majority and impurity ions is 40 μs, estimated from the energy relaxation rate for two thermal distributions [19]. Although this is not fast enough to guarantee equilibration during sawtooth crash heating, the evidence suggests that the behaviour of the majority ions is similar to that spectroscopically recorded for the minority ions.

The ion temperature observations on MST imply that the ion heating mechanism is largely isotropic, strongly favouring neither perpendicular nor parallel heating. However, there are at least two possible scenarios which are consistent with our observations, yet still admit the possibility of anisotropic ion heating. The first scenario requires the perpendicular and parallel temperatures to be very tightly coupled by some energy transfer mechanism—so tightly coupled that the lag in energy transfer from perpendicular to parallel is less than 10 μs during sawtooth crash heating. Such a small time lag implies that the energy transfer takes place on an Alfvénic timescale (approximately 1 μs in MST). The coupling mechanism cannot simply be ion–ion Coulomb collisional relaxation, as the characteristic time for proton–proton temperature isotropization or thermalization is $\geqslant 100$ μs [16, 19]. Thus this scenario appears to require the invocation of an as yet unknown, but very fast, energy transfer mechanism to isotropize and/or thermalize the perpendicular and parallel temperatures during a sawtooth crash.

A second possible scenario admitting anisotropic heating requires such dynamics to occur on limited spatial scales. The ion temperature data reported here are spatial averages over a scale length of approximately the minor radius of MST. This average is much larger than, for example, the ion gyroradius or a magnetic island width. So we cannot rule out a turbulent ion heating mechanism that exhibits an anisotropy over small spatial scales, such as a reconnection layer. However, this scenario seems somewhat unlikely, as our measurements indicate no spatial asymmetry or resonant layer localization of ion heating in MST.

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