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Citation: Phys. Plasmas 20, 056501 (2013); doi: 10.1063/1.4804958
View online: http://dx.doi.org/10.1063/1.4804958
View Table of Contents: http://pop.aip.org/resource/1/PHPAEN/v20/i5
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PHYSICS OF PLASMAS 20, 056501 (2013)

Charge-to-mass-ratio-dependent ion heating during magnetic reconnection in the MST RFP[a)]

S. T. A. Kumar,[1,2,b)] A. F. Almagri,[1,2] D. Craig,[3] D. J. Den Hartog,[1,2,c)] M. D. Nornberg,[1,2] J. S. Sarff,[1,2] and P. W. Terry[1,2]
[1]*Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[2]*Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[3]*Wheaton College, Wheaton, Illinois 60187, USA*

(Received 21 December 2012; accepted 26 March 2013; published online 14 May 2013)

Temperature evolution during magnetic reconnection has been spectroscopically measured for various ion species in a toroidal magnetized plasma. Measurements are made predominantly in the direction parallel to the equilibrium magnetic field. It is found that the increase in parallel ion temperature during magnetic reconnection events increases with the charge-to-mass ratio of the ion species. This trend can be understood if the heating mechanism is anisotropic, favoring heating in the perpendicular degree of freedom, with collisional relaxation of multiple ion species. The charge-to-mass ratio trend for the parallel temperature derives from collisional isotropization. This result emphasizes that collisional isotropization and energy transfer must be carefully modeled when analyzing ion heating measurements and comparing to theoretical predictions. © *2013 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4804958]

I. INTRODUCTION

Ion heating and acceleration during magnetic reconnection have been observed in many laboratory[1–4] and astrophysical plasmas.[5–7] In spite of extensive theoretical and experimental efforts, the underlying mechanism of conversion of magnetic energy to particle thermal energy is not clearly understood. Multiple mechanisms might be active during magnetic reconnection, each important for different aspects of the heating and acceleration processes. In this paper, we describe an experimental observation which may help further refine our understanding of the mechanism of impurity ion heating during magnetic reconnection. Line-averaged spectroscopic measurements of various charge states of impurity ions are made during magnetic reconnection events in a toroidal magnetized plasma. It is found that the increase in ion temperature during magnetic reconnection, measured predominantly in the direction parallel to the equilibrium magnetic field, increases with the charge-to-mass ratio of the ion species. This trend can be reproduced by a model in which ions are heated only in perpendicular direction, and the parallel temperature evolves solely through collisional isotropization. This observation brings out the importance of considering collisional isotropization in understanding the ion heating mechanism, as well as indicating that the mechanism of impurity ion heating during magnetic reconnection events favors the perpendicular degree of freedom.

II. EXPERIMENTAL SETUP

Experiments are carried out in the Madison Symmetric Torus (MST)[8] reversed field pinch, which is a toroidal plasma confinement device with a major radius of 1.5 m and a minor radius of 0.5 m. In MST, the magnetic field lines are purely toroidal at the core and become more poloidal toward the outer regions of the plasma as shown in Fig. 1. The pitch of the helical magnetic field lines varies dramatically from the core to the edge, enabling long wavelength spatial perturbations known as tearing modes to resonate and grow at many locations in the plasma. These multiple coupled resonant modes grow, overlap, and lead to magnetic reconnection and field line stochasticity. The instability intensifies and relaxes cyclically throughout the plasma discharge, producing a quasi-periodic chain of magnetic reconnection events.[9]

For the experiments reported in this paper, deuterium plasmas of toroidal plasma current ~400 kA, line-averaged central electron density $n_e \sim 0.8 - 1 \times 10^{19}\,\mathrm{m}^{-3}$, and central electron and ion temperatures ~400 eV are formed. Plasma-wall interaction liberates impurities into the plasma. In MST, the dominant impurities are aluminum, carbon, oxygen, and nitrogen. Ionization balance of these impurities mainly depends on the electron temperature (through electron impact excitation) and neutral density (through charge-exchange loss). Measurements reported in this paper are made at the edge of the plasma (impact parameter, r/a ~ 0.92) where electron temperature is relatively lower (~50–100 eV) and neural density is relatively higher, leaving these impurities predominantly at their lower charge states. Doppler broadened line-averaged emissions of various atomic transitions, as tabulated in Table I, are measured using an ion Doppler spectrometer.[10] Gyro-radii of these ions are less than the distance between the measurement location and the wall. So it is unlikely that the ion gyro radius clipping affects our temperature measurements. As the viewing chord passes through the edge of a radially thin emission shell, these measurements are somewhat localized. It can be shown (see Appendix) that this edge chord measurement is sensitive only to the

[a)]Paper BI2 2, Bull. Am. Phys. Soc. **57**, 22 (2012).
[b)]Electronic mail: stkumar@wisc.edu
[c)]Invited speaker.

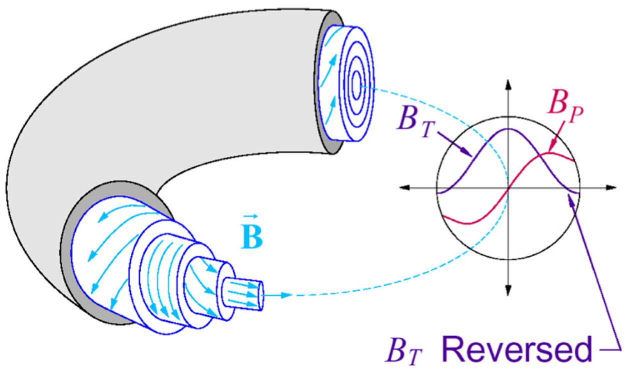

FIG. 1. Schematic of the MST magnetic geometry. Spectroscopic measurements reported in this paper are made at the edge of the plasma, viewing vertically at an impact parameter of r/a ∼0.92, predominantly parallel to the magnetic field lines.

temperature parallel to the magnetic field lines. During a reconnection event, the electron temperature decreases and the neutral density increases (due to increased plasma-wall interactions), causing the emission shell of these lower charge states to move inwards to a slightly higher ion temperature region. This shift could result in an apparent increase in ion temperature in the measurement. However, the movement of emission shell for the ions reported here is found to be less than the spatial resolution of this measurement, having negligible effect on the interpretation of the data presented in this paper.

Temperature evolution of one of the ions (C^{+4}) is shown in Fig. 2 for reference. The data are averaged over a large number of similar magnetic reconnection events. The error bars include both statistical and instrumental uncertainties. Increase in temperature is calculated by subtracting average temperature away from the event from the peak temperature at the event. Similar measurements have been done for the other impurity species as well. The increase in ion temperature of these ion species versus their charge-to-mass ratio is plotted in Fig. 3. It is apparent that the parallel ion heating at the reconnection event increases with the charge-to-mass ratio of the ion species. The decrease in magnetic energy stored in the plasma, which is the energy source for the ion heating, is similar for all reconnection events used for this analysis.

TABLE I. Impurity ion species, atomic transition wavelengths and their charge-to-mass ratio (Z/μ, where Z is the ionic charge and μ is the ratio of the ion mass to the proton mass.).

Impurity ion species	Wavelength (Angstrom)	Charge-to-mass ratio (Z/μ)
Al^{+1}	3587.0	0.037
Al^{+2}	3601.0	0.074
C^{+2}	2982.0	0.166
C^{+4}	2271.0	0.33
N^{+2}	3367.0	0.143
N^{+3}	3478.0	0.214
O^{+2}	3047.0	0.125
O^{+3}	3064.0	0.188
O^{+4}	2941.0	0.25

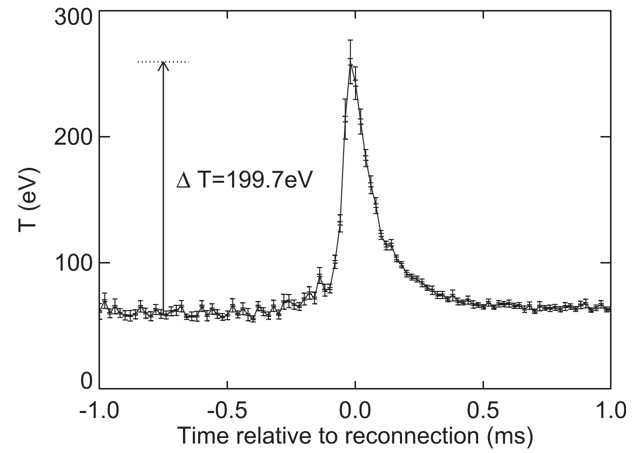

FIG. 2. Measured time evolution of C^{+4} temperature (predominantly parallel to equilibrium magnetic field) during magnetic reconnection.

III. DISCUSSION

It is well known that magnetic reconnection in MST results in significant ion heating.[2,11–13] It is also known that the ultimate energy source is the equilibrium magnetic field created by inductively driving current in the plasma. At the reconnection event, the stored magnetic energy decreases significantly, and this decrease in magnetic energy in MST is well correlated with the increase in ion temperature.[14] For reference, the decrease in magnetic energy for the typical plasma parameters reported in this paper is ∼20 kJ. The heating occurs in a time scale (∼0.1 ms) much shorter than the electron-ion collision time (∼10 ms). Also, the electron temperature is much less than the ion temperature. Hence the heating is very clearly non-collisional.

Several theoretical models have been put forward to explain the ion heating mechanism. There are three models which are extensively discussed in relation to the observations in the reversed field pinch: viscous damping of the flows generated at reconnection,[15–17] stochastic heating,[14,18] and cyclotron damping of magnetic fluctuations[19,20] Viscous damping of flows requires high flow velocity (on the order of ion thermal velocity) and strong velocity gradient (on the order of ion gyro radius) to result in any significant ion

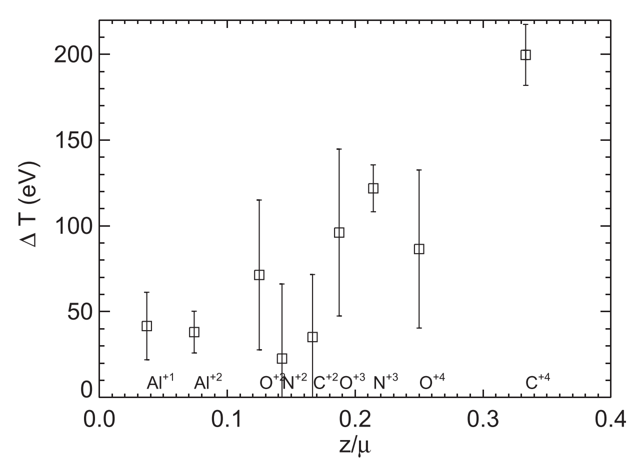

FIG. 3. Increase in temperature of various ion species versus their charge-to-mass ratio.

heating, which have not yet been observed experimentally. Previous experimental measurements of the bulk ion temperature showed a mass dependence that suggested a stochastic heating mechanism[14] However, impurity ion temperatures suggest a mass and charge dependence. The ion cyclotron damping model examines the role of turbulent magnetic fluctuations in heating the ions. In MST, the magnetic fluctuations exhibit a turbulent cascade, with the total fluctuation power increasing strongly during the reconnection event,[21] as shown in Fig. 4. Magnetic fluctuations gyro-resonate with the ion species and the fluctuation power is damped to the ions at their resonant cyclotron frequencies. Cyclotron heating is expected to produce anisotropic temperatures with a particular charge-to-mass ratio scaling. Heating is in the perpendicular degree of freedom. In the absence of a parallel heating mechanism, the increase in parallel temperature is solely due to collisional isotropization. A significant anisotropy in the ion temperature during reconnection is, therefore, expected. The heating rate is proportional to $\tilde{B}_{ci}^2 Z^2/\mu$ where $\tilde{B}_{ci}^2$ is the magnetic fluctuation power at the ion cyclotron frequency, Z is the ionization state of the species, and μ is the ratio of the ion mass to the proton mass.[22] Ions with lower charge-to-mass ratio will resonate at lower frequencies where the heating power is higher.

There are some previous experimental evidences of ion heating from MST which favor the ion cyclotron damping mechanism. For example, Scime *et al.*[2,11] have observed that the anomalously high ion temperature during magnetic reconnection is well correlated with structure in the magnetic fluctuations spectra. In other experiments in MST, significant temperature anisotropy has been observed in impurity ion heating during magnetic reconnection, indicating a heating mechanism which favors the perpendicular degree of freedom.[3,13] Tangri *et al.*[19] observed that the impurity heating rates in MST are consistent with ion cyclotron damping expectations.

For MST plasmas, heating from ion cyclotron damping should decrease with the charge-to-mass ratio since the fluctuation power is higher at lower frequency, despite the heating rate scaling as Z^2/μ. However, our experimental observation is the inverse. As shown in Fig. 3, the increase

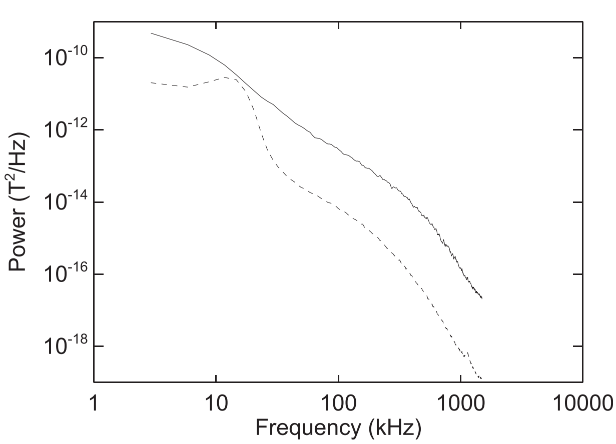

FIG. 4. Power spectra, at (solid line) and away from (dotted line) the reconnection event, of magnetic fluctuations ($\tilde{B}_\theta$) measured using magnetic pickup coil at the edge of the plasma.

in temperature increases with the charge-to-mass ratio. This could possibly be due to the measurements being most sensitive to the component of the temperature parallel to the equilibrium magnetic field whereas cyclotron damping heating is solely in the perpendicular direction. Increase in the parallel temperature, in the absence of a separate parallel heating mechanism, would solely be due to collisional isotropization.

To investigate this possibility, a simple collisional isotropization model is used in which the ion temperature is evolved according to[13]

$$\frac{dT_{\perp,z}}{dt} = \frac{1}{kn_z}\left(C_{\perp,zD}(T_D - T_{\perp,z}) + \sum_i m_i J_{\perp,zi}\right) - \frac{T_{\perp,z}}{\tau} + Q_\perp, \tag{1}$$

$$\frac{dT_{||,z}}{dt} = \frac{2}{kn_z}\left(C_{||,zD}(T_D - T_{||,z}) + \sum_i m_i J_{||,zi}\right) - \frac{T_{||,z}}{\tau} + Q_{||}, \tag{2}$$

where subscripts z and D represent impurity ions and deuterons, n_z is the density of impurity ion species, C operators represent collisional equilibration between the deuterons and impurity ions and the J operators represent the collisional isotropization of the impurity on all other impurity species (see Appendix A of Ref. 6 for definitions of C and J terms). $Q_\perp$ and $Q_{||}$ represent heating in perpendicular and parallel directions, respectively. Energy is transported through collisional isotropization and equilibration processes (first two terms in the equations) as well as the anomalous transport ($\frac{T}{\tau}$), where τ is the ion energy confinement time.

For modeling the ion cyclotron damping, the *ad-hoc* heating term is assumed to be purely in the perpendicular direction ($Q_{||} = 0$) with a magnitude $Q_\perp \propto \Delta\tilde{B}_{ci}^2 Z^2/\mu$, consistent with the theory.[22] Here, $\Delta\tilde{B}_{ci}^2$ is the difference in fluctuation powers at and away from the reconnection event, at the cyclotron frequency of the ion species. This value is obtained from the poloidal magnetic fluctuation ($\tilde{B}_\theta$) power spectra measured at the edge of the plasma (Fig. 4). Heating is applied only for a small duration around the reconnection event as shown in Fig. 5(b). The first four ionization states of all major impurities (B, C, N, O, and Al) are included in the model. Subscript i in the summation represents all ions in the model. Densities of impurity elements are assumed to be 2% of the electron density at r/a ~0.92 ($n_e \sim 0.5 \times 10^{19}/\mathrm{m}^3$) and the ionization balance of these impurities are calculated using a collisional radiative model (The Atomic Data and Analysis Structure (ADAS) (Ref. 23)). Time evolution of main ion (deuterium) temperature at the edge of the plasma is not available. Therefore, the deuterium temperature measured in the core by Rutherford scattering[24] is used, scaled to a lower value appropriate for the edge region [Fig. 5(a)]. The main ion temperature is assumed to be isotropic ($T_{D_{||}} = T_{D_\perp} = T_D$). All impurity ions are assumed to have same initial temperature. Therefore, inter-species equilibration (other than deuteron-impurity equilibration) is ignored. The heating term and the confinement time are the two main variables in the code. Various combinations of these two parameters can reproduce the experimentally observed charge-to-mass ratio dependence of the parallel temperature

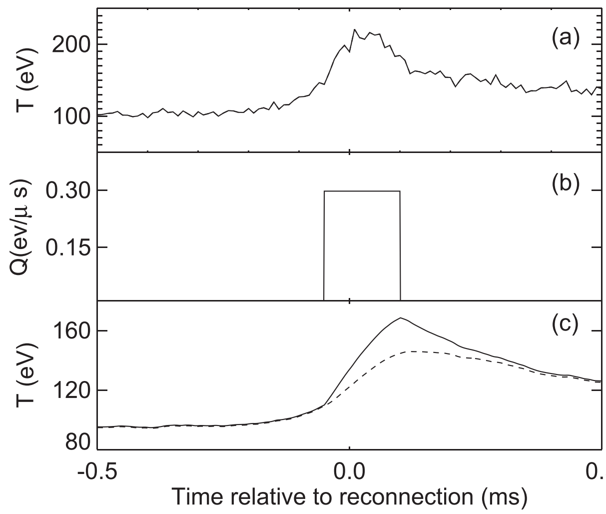

FIG. 5. (a) Normalized version of the main ion temperature evolution during reconnection event measured using Rutherford scattering diagnostic. (b) *Ad-hoc* perpendicular heating term used in the model for C^{+4} ion. (c) Modeled time evolution of perpendicular (solid line) and parallel (dashed line) C^{+4} ion temperatures.

increase. For the model results presented here, we used an ion energy confinement time of 1 ms.

Time evolution of the modeled parallel and perpendicular ion temperatures for C^{+4} is shown in Fig. 5(c). Increase in temperature is calculated in a similar way to the experimental data (see Fig. 2). Figs. 6(a) and 6(b) show the change in parallel and perpendicular temperatures, respectively, at the reconnection event for all ions, as a function of their charge-to-mass ratio. It can be seen that the parallel and perpendicular ion heating depends on the charge-to-mass ratio differently. While the perpendicular heating decreases with charge-to-mass ratio, as expected from the cyclotron damping mechanism, the parallel heating has an inverse trend, similar to what is observed in the experiment. Even though the species with low charge-to-mass ratio gain more perpendicular heating, their poor collisional isotropization results in a reverse trend in the parallel direction. The increasing anisotropy toward lower charge-to-mass ratio is a testable

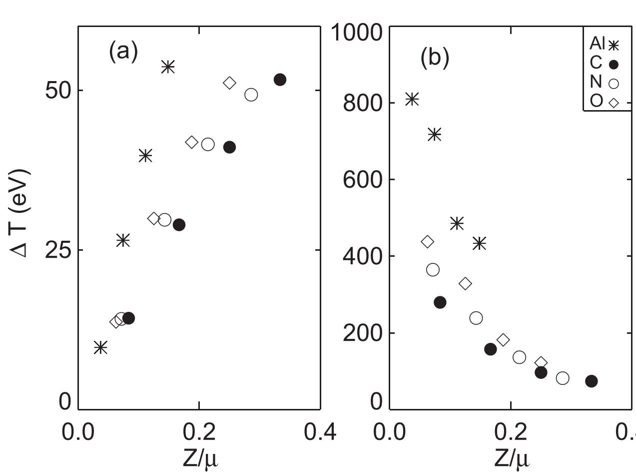

FIG. 6. Change in ion temperature in parallel (a) and perpendicular (b) directions for a perpendicular heating consistent with the ion cyclotron model.

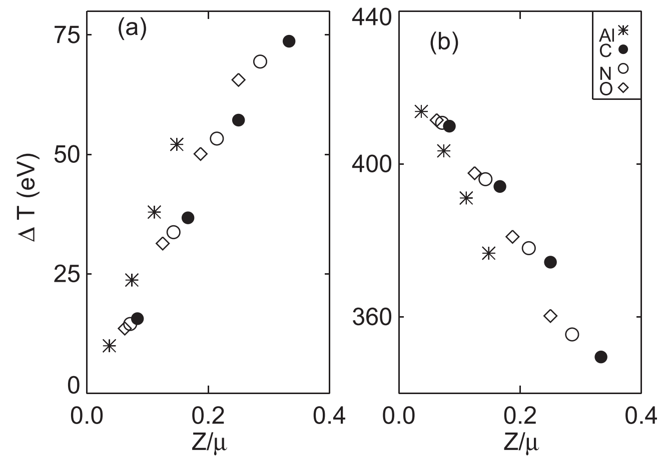

FIG. 7. Change in ion temperature in parallel (a) and perpendicular (b) directions for a constant perpendicular heating of 3 eV/μs for all ions.

prediction which could be investigated in future. It can be seen that the model reproduces the trend reasonably well even though the absolute values are different. The model shows that the increase in ion heating with charge-to-mass ratio for the parallel temperature is consistent with the cyclotron damping model.

Even though the experimental observations are found to be consistent with the cyclotron damping mechanism, the model does not rule out the possibility of other mechanisms. There are two main features of the model which should be highlighted:

1. The experimentally observed charge-to-mass ratio trend of the parallel temperature, and an inverse trend in the perpendicular temperature similar to that shown in Fig. 6(b), can also be reproduced with a constant heating term for all the species, instead of $Q_\perp \propto \tilde{B}_{ci}^2 Z^2/\mu$, as shown in Fig. 7. This observation implies that a charge-to-mass ratio trend in either parallel or perpendicular increase in temperature during magnetic reconnection may not necessarily indicate a charge-to-mass ratio dependent heating mechanism.
2. A charge-to-mass ratio dependent heating solely in the parallel direction ($Q_\perp = 0, Q_\| \propto Z/\mu$) could reproduce the experimentally observed trend in the parallel temperature. However, this mechanism results in an anisotropy in the temperature, $T_\| > T_\perp$, which is inconsistent with previous anisotropy observations ($T_\| < T_\perp$) (Refs. 3 and 13). A heating predominantly in the perpendicular degree of freedom is, therefore, required.

IV. CONCLUSIONS

This paper reports an experimental observation of charge-to-mass ratio dependent ion heating during magnetic reconnection. The observed trend is the inverse of what is expected from ion cyclotron damping—a heating mechanism which is expected to produce a charge-to-mass ratio scaling. However, a simple model which incorporates collisional isotropization suggests that the observed dependence of the parallel temperature increment on Z/μ may arise from a combination of predominantly perpendicular heating (with or without Z/μ dependence) and collisional isotropization. The collisional relaxation of such anisotropic heating occurs much more slowly for low Z/μ ions than for high Z/μ ions. The simple collisional isotropization model employed in this work neither captures all of the physics nor explains all of the observed features, but it clearly highlights the importance of considering collisional isotropization in understanding the ion heating during magnetic reconnection.

ACKNOWLEDGMENTS

Authors would like to thank R. M. Magee for assisting us with a collisional isotropization code. This work was supported by the US Department of Energy under cooperative agreement DE-FCO2-05ER54814 for MST and by National Science Foundation -PHY0821899.

APPENDIX: CALCULATION OF $T_\perp$ AND $T_{||}$ MIX ALONG THE VIEWING CHORD

In spectroscopic measurement of ion temperature from thermal broadening, the measurement is sensitive only to the component of thermal velocity parallel to the viewing chord. For the measurements reported in this paper, the viewing chord passes through the edge of the RFP plasma where field lines are predominantly in the poloidal direction. The angle θ that the field lines make with the viewing chord is shown in Fig. 8. In order to calculate the component of velocity parallel to the viewing chord, velocity space coordinates are formed with the viewing chord making an angle θ with the $v_{||}$, as shown in Fig. 9. Here, $v_{||}$ and $v_\perp$ are thermal velocities parallel and perpendicular to the field lines, respectively. From Fig. 9, it can be shown that

$$v_{\text{measured}} = \sqrt{x^2 + y^2} = \sqrt{y^2 \tan^2\theta + y^2} = y\sqrt{\tan^2\theta + 1}.$$

From the equation of the ellipse,

$$x^2/v_\perp^2 + y^2/v_{||}^2 = 1,$$

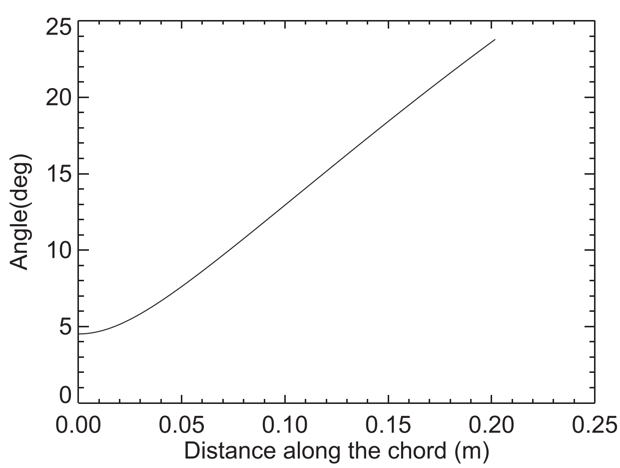

FIG. 8. Variation of the angle (θ) between the magnetic field and the viewing chord.

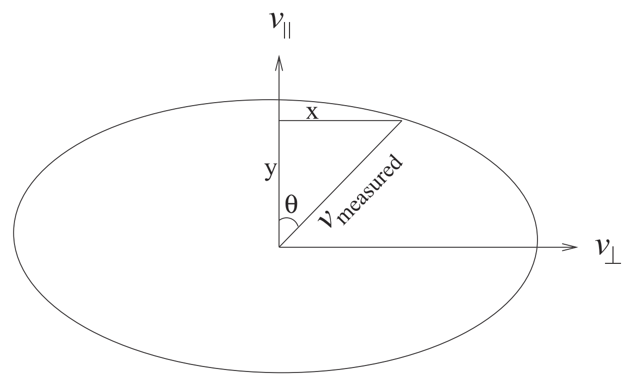

FIG. 9. At a point along the chord, sight line makes an angle θ with $v_{||}$.

$$y^2 \tan^2\theta/v_\perp^2 + y^2/v_{||}^2 = 1,$$

$$y = \sqrt{\frac{1}{\tan^2\theta/v_\perp^2 + 1/v_{||}^2}}.$$

Therefore,

$$v_{\text{measured}} = \sqrt{\frac{\tan^2\theta + 1}{\tan^2\theta/v_\perp^2 + 1/v_{||}^2}}.$$

From which temperature measured at each point along the chord can be calculated as

$$T_{\text{measured}} = \frac{\tan^2\theta + 1}{\tan^2\theta/T_\perp + 1/T_{||}},$$

where $T_\perp$ and $T_{||}$ are local temperatures in the perpendicular and the parallel direction to the magnetic field line, T_{measured} is the "mixed" temperature measured in our experiment. It can be seen that for small angles, the $T_\perp$ and $T_{||}$ mix along the viewing chord is negligibly small.

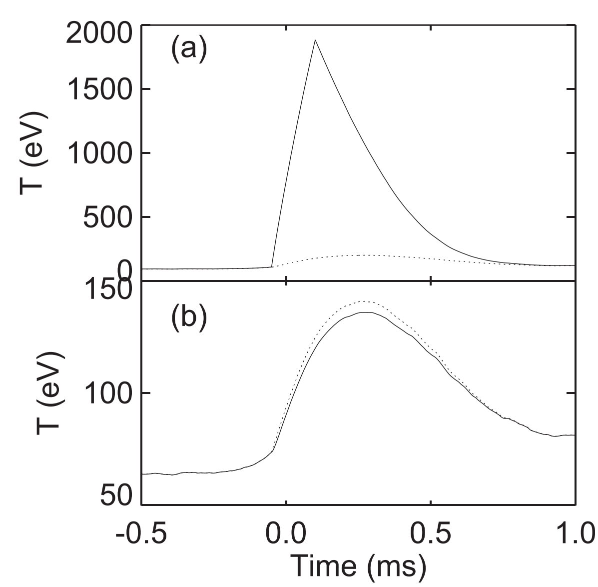

FIG. 10. (a) Model predicted perpendicular (solid) and parallel (dotted) temperatures. (b) Chord averaged parallel (solid) and mixed (dotted) temperatures.

In order to calculate the effect of this mixing in the chord averaged value, a parabolic radial profile of ion temperature is assumed and the variation of ion temperature along the viewing chord is calculated. Parallel and perpendicular temperatures along the chord are then obtained by multiplying the model predicted local $T_\perp$ and $T_{||}$ with the normalized ion temperature profile along the chord. The chord averaged temperature is then calculated as

$$T_{\text{averaged}} = \frac{1}{L}\int_0^L T_{\text{measured}} d\ell,$$

where L is the half length of the chord. Chord averaged parallel and the mixed temperatures for a case of large anisotropy are shown in Fig. 10. It can be seen that the $T_\perp$ mixing in our measurement is negligibly small even at large anisotropy.

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