Reduction of Ion Heating During Magnetic Reconnection by Large-Scale Effective Potentials

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Ion heating due to magnetic reconnection is an important process with applications to diverse plasmas, but previous simulations and observations have measured heating less than half of theoretical predictions. Using kinetic particle-in-cell simulations, we show that this heating reduction is due to the presence of large scale parallel electric fields creating an effective field aligned potential which reduces the velocities of counterstreaming ions created by Fermi reflection. This potential arises to contain hot exhaust electrons, and an analytic form suitable for observations is derived.

Introduction: Magnetic reconnection is a universal plasma process which converts stored magnetic energy into particle energy. The process is believed to be important in many astrophysical, solar, geophysical, and laboratory contexts. One of the principle questions in understanding reconnection is how it converts magnetic energy into ion thermal energy.

Ion thermal energy often makes up a large fraction of the released magnetic energy during magnetic reconnection\cite{1-14, 19}. In the exhaust region of reconnection, ion heating has often been found to take the form of interpenetrating beams which ultimately isotropize due to instabilities\cite{2, 7-9, 11, 12, 17, 18}. These interpenetrating beams can be generated through Fermi reflection due to contracting magnetic field lines, with a predicted counterstreaming velocity equal to twice the outflow velocity $v_{\text{out}}$ in the case of antiparallel reconnection\cite{3}. These beams are associated with an ion temperature increase (or increment) of $\Delta T_i \approx 0.33 m_i v_{\text{out}}^2$. However, solar wind observations have measured ion beam velocities significantly less than $v_{\text{out}}$, and this difference was attributed to beam instabilities\cite{7}. Direct measurements of the ion increment have yielded $\Delta T_i \approx 0.13 m_i v_{\text{out}}^2$\cite{3}. Ion heating during asymmetric magnetopause reconnection has been measured as $\Delta T_i \approx 0.13 m_i v_{\text{out-th}}^2$, where $v_{\text{out-th}}$ is the predicted outflow velocity based on asymmetric inflowing plasma conditions\cite{13}.

A possible clue to this disparity lies in the presence of low amplitude, long range parallel electric fields and associated effective parallel potentials in magnetic reconnection exhausts\cite{5}. This parallel electric field is a fundamental component in electron pressure balance and acts to trap electrons within the exhaust\cite{9, 10}. However, the effect of this parallel electric field on ion dynamics and the resultant ion heating has not been explored.

We have performed a systematic kinetic particle-in-cell (PIC) simulation study of ion heating during magnetic reconnection over a range of inflowing parameters. As with the observations, we find that the ion heating is substantially less than that predicted by the basic Fermi reflection model of ion acceleration. Instead of beam instabilities as postulated previously, the large-scale effective potential slows the counterstreaming ions which reduces ion heating. The magnitude of this potential is consistent with a simple analytic form dependent on upstream and exhaust values. A modified Fermi bounce theory including the effect of this potential accurately predicts the ion increments measured in the simulations. A major finding is that, through this potential, electron dynamics can modify the nature of ion heating.

Simulations: We use the parallel PIC code P3D\cite{20} to perform simulations in 2.5 dimensions of collisionless antiparallel reconnection. Magnetic field strengths and particle number densities are normalized to $B_0$ and $n_0$, respectively. Lengths are normalized to the ion inertial length $d_0 = c/\omega_{pi0}$ at the reference density $n_0$, time to the ion cyclotron time $\Omega_{i0}^{-1} = (eB_0/m_i c)^{-1}$, and velocities to the Alfvén speed $c_{A0} = \sqrt{B_0^2/(4\pi m_i n_0)}$. Electric fields and temperatures are normalized to $E_0 = c_{A0} B_0/c$ and $T_0 = m_i c^2_{A0}$, respectively. The coordinate system is a generic “simulation coordinates,” meaning that the reconnection outflows are along $\hat{x}$ and the inflows are along $\hat{y}$. Simulations are performed in a periodic domain with a system size of $L_x \times L_y = 204.8 d_0 \times 102.4 d_0$. Simulation parameters are given in Table I.

The initial conditions are a double current sheet\cite{15}. A small magnetic perturbation is used to initiate reconnection. Each simulation is evolved until reconnection reaches a steady state, and then for analysis purposes

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TABLE I. Initial simulation parameters. Electron to ion mass ratio \( m_e/m_i \), speed of light \( c \), grid spacing \( \Delta_s \) and upstream conditions: Reconnection (in-plane) magnetic field \( B_r \), density \( n \), Electron and ion temperatures \( T_e \) and \( T_i \).

| Run | \( m_e/m_i \) | \( c \) | \( \Delta_s \) | \( B_r \) | \( n \) | \( T_e \) | \( T_i \) |
|-----|-------------|---------|-------------|---------|-----|--------|--------|
| 301 | 25          | 15      | \( .05 \)    | 1.0     | .2  | .25    | .25    |
| 305 | 25          | 15      | \( .05 \)    | 1.0     | .2  | 2.25   | .25    |
| 325 | 25          | 15      | \( .05 \)    | 1.0     | .2  | .0625  | .3125  |
| 901 | 25          | 30      | \( .05 \)    | 2.236   | .2  | 2.25   | .25    |
| 603 | 25          | 15      | \( .05 \)    | 2.236   | .2  | .25    | 1.25   |
| 707 | 100         | 30      | \( .025 \)   | 1.0     | .2  | .0625  | .3125  |
| 691 | 25          | 15      | \( .05 \)    | 2.236   | .2  | 1.25   | .25    |
| 692 | 25          | 15      | \( .05 \)    | .447    | .2  | 0.05   | 0.05   |
| 693 | 100         | 30      | \( .025 \)   | 1.0     | .2  | .25    | .25    |
| 694 | 25          | 15      | \( .05 \)    | 1.0     | .2  | .0833  | .0833  |
| 695 | 25          | 15      | \( .05 \)    | 1.0     | .2  | .25    | .0833  |

During this steady period the simulation data is time averaged over 100 particle time steps, which is typically on the order of 50 electron plasma wave periods \( \omega_{pe}^{-1} \).

**Method:** To quantify the effects of the parallel potential on the ion temperature, the average ion heating is determined by averaging over the width and the length of the exhaust (the boxed green hashed region illustrated in Figure 1) and then subtracting off the inflowing temperatures. In Figs. 1b-c, within around 10 \( d_i \) of the \( x \)-line at \( x \approx 155 \), the ion temperature \( T_i \equiv \frac{\text{Trace}[\mathbf{T}_i]}{3} \) is dominated by \( T_{i\parallel} \). Farther downstream in the exhaust, \( T_{i\parallel} \) increases substantially and broadens in the inflowing direction. In a cut along \( y \) at the right hand edge of the hashed region in Fig. 1b, \( T_{i\parallel} \) dominates everywhere but the midplane region.

To calculate an effective thermal energization per particle, for each \( x \) location a cut along \( y \) is taken and \( P_i \) and \( n \) are averaged in the exhaust region to determine \( \langle n T_i \rangle \) and \( \langle n \rangle \), with \( \langle T_i \rangle \equiv \langle n T_i \rangle / \langle n \rangle \). The inflowing ion temperature \( T_{i\uparrow} \) is determined by spatially averaging a typical inflow region, and the ion temperature increment is then \( \langle \Delta T_i \rangle \equiv \langle T_i \rangle - T_{i\uparrow} \). A plot of the resultant ion temperature increments as a function of \( x \) are shown in Figure 1. These increments stabilize to spatially uniform values around 25 \( d_i \) downstream of the \( x \)-line (dashed green vertical line). The values used for the statistical study \( \Delta T_i \) are shown as the black dashed horizontal lines.

In this study the principle mechanism investigated for ion heating is outlined by Drake et. al. 2009 [3]. In the reference frame moving with the reconnect field lines (i.e. frame where \( \mathbf{E}_\perp = 0 \)) the cold ion population enters the reconnection exhaust with a parallel velocity equal to the field line velocity in the stationary frame of \( v_0 \). The ions reach the midplane and undergo an elastic Fermi-like reflection, and then proceed to travel back out along a field line. The reflected population mixes with new cold incoming ions creating counter-streaming beams and a temperature increment of:

\[
\Delta T_i = \langle \Delta T_{i\parallel} \rangle + 2\langle \Delta T_{i\perp} \rangle / 3 = \frac{1}{3} m_i \omega_{pi}^2 v_0^2.
\]  

In order to test this prediction it is necessary to determine the field line velocity \( v_0 \). Figure 2a shows a horizontal slice at the midplane of \( v_0 \approx -c E_z/B_y \) as well as the ion outflow velocity \( v_{ix} \). Farther away from the x-line the ion velocity asymptotes to the field line velocity, with the horizontal dashed line being the value \( v_0 \) chosen for this case of the statistical study.
In order to maintain electron pressure balance along the magnetic field, a large-scale, although relatively small magnitude, parallel electric field arises (Fig. 1d). This $E_i$ fills the entire exhaust and points away from the midplane, which slows down inflowing ions leading to a reduced ion beam velocity and a reduce $\Delta T_i$. This parallel electric field can be written in terms of electron force balance as:

$$eE_\parallel = -\nabla_b T_{e\parallel} - T_{e\parallel} \nabla_b \ln n + (T_{e\parallel} - T_{e\perp}) \nabla_b \ln B,$$

where $\nabla_b = (\mathbf{B}/B) \cdot \nabla$.

We characterize the impact of this electric field on the ions by introducing an effective parallel potential $\phi$, where $\phi \equiv \int \mathbf{E} \cdot d\mathbf{l}$, and $d\mathbf{l}$ is the distance along a magnetic field line. In Figure 3b, $\phi$ is plotted along the solid black field line shown in Fig. 1d. $\phi$ and $l$ are chosen to be zero at the midplane.

The equation for $\phi$ can be simplified because the three terms on the right hand side of Eq. 2 play a role in three distinct regions. Moving along a field line from the inflow region, $T_{e\parallel}$ first rises just inside of the separatrices. Then, associated with ion dynamics, the density rises as the ion outflow is accelerated and the second term becomes dominant. By the time $B$ changes relatively close to the midplane, the electron temperature is nearly isotropic and the third term plays little or no role. The simplified form of $\phi$ is:

$$e\phi \approx e\phi_{up} \equiv (T_{e\parallel} - T_{e\parallel up}) + T_{e\parallel} \ln \frac{n}{n_{up}},$$

where “up” denotes upstream or inflowing conditions. This approximation for $\phi$ is plotted as the blue line in Figure 3b, and matches well with the integrated $E_\parallel$ deduced from the simulation.

Figure 3c. Since increased $\Delta T_i$ represents counterstreaming beams and a temperature increment of $\Delta T_i = m_i v_i^2 / 3$. Determining $v_d$ first requires an estimation of the propagation speed of $\phi$ outwards along a magnetic field line. A clue to this speed is the strong correlation of $\phi$ and ion parallel temperature $\Delta T_{i\parallel}$ as they vary along field lines, as shown in stack plots for three different field lines in Fig. 3b. Since increased $T_{i\parallel}$ represents counterstreaming beam formation, $\phi$ propagates to a good approximation with the ion parallel beaming speed $v_d$. Conservation of
upstream ions that would enter the exhaust with a speed insufficient to pass through the potential. We therefore restrict our investigation to reconnection with smaller ion temperatures such that no significant number of ions are reflected by the potential.

To quantify an average value of \( \Delta \phi \), we select the field line that passes through the midplane 10 \( d_e \) downstream of the x-line; an example is identified by the black field line in Figure 1d. \( \Delta \phi \) is chosen as the difference of the potential between its near-midplane maximum and the location along the field line where the density and electron temperature reach their inflowing values. The value of \( \phi \) at these two locations is demarcated by the horizontal dot-dashed lines in Figure 3.

Using the \( \Delta \phi \) measured in the set of simulations, the two principle claims of the paper, expressed in Eqs. 3 and 5, can be verified. To systematically test the approximate form of the potential in Eq. 3, the parallel electron temperature and density are averaged by the same method previously outlined for the ion temperature to determine \( \Delta T_{e||} = T_{e||ex} - T_{e||up} \) and \( n_{ex} \), with \( \text{“}ex\text{”} \) denoting exhaust values. These quantities are used to calculate

\[
\epsilon \Delta \phi_{pe} = \Delta T_{e||}(1 + \ln \frac{n_{ex}}{n_{up}}) + T_{eup} \ln \frac{n_{ex}}{n_{up}} \tag{6}
\]

which is plotted against the measured \( \Delta \phi \) in Figure 3, showing good agreement.

Lastly, in Figure 3 we compare the simulations ion heating with the new heating prediction in Eq. 5. Figure 3 is plotted with the same limits as Figure 2 to emphasize the dramatic effect of including the potential into the ion heating calculation. The spread in the data is markedly reduced and all of the points now straddle a line with a slope of 1. Most revealing is the change in position of the \( T_e/T_i = 9 \) simulations which are denoted by filled black triangles in Figs. 2 and 3. These simulations have anomalously large \( \Delta \phi \) which significantly reduces the ion beam velocity and thus the ion temperature increments.

**Conclusions:** In a systematic kinetic PIC simulation study of ion heating, we find that the temperature increment is well below the \( \Delta T_i = m_i v_0^2 / 3 \) predicted by Fermi reflection. This temperature reduction is due to the presence of large scale effective parallel potentials \( \phi \) that slow the ions passing through the exhaust, leading to a reduction in ion beam velocities and ion heating. The scaling of \( \Delta T_i \) in the simulations is consistent with this theory. An important conclusion is that electron dynamics can substantially modify the nature of ion heating, i.e., the very high \( T_e \) cases in this study showed markedly reduced \( \Delta T_i \) owing to a very large \( \phi \).

A question remains as to why previous observational studies measure an ion increment \( \Delta T_i \sim m_i v_0^2 \), even though such a scaling is not implied by Eq. 5 due to the presence of the \( \Delta \phi \) term inside the radical. This \( \Delta \phi \) term depends on both \( \Delta T_{e||} \) and \( T_{eup} \) in Eq. 6. The \( \Delta T_{e||} \) term has been shown to scale with \( m_i v_0^2 \) using \( v_0 \approx c_A \). Any deviation from the \( m_i v_0^2 \) scaling, therefore,
can only be caused by the $T_{\text{exp}}$ term. As long as the electron heating is sufficiently strong, the $\Delta T_e$ term should dominate, recovering the both observational scaling and the scaling of the unfilled triangles in Fig. 2b.

Determining $\phi$ from observations directly is problematic because the weak $E_j$ is difficult to measure experimentally. However, $\phi$ can be estimated directly from Eqs. 4 or 5 using measured outflow velocities and either ion beam speeds or $\Delta T_e$. As a consistency check, $\phi$ can also be estimated from Eq. 6 using the electron parallel temperature increment and the exhaust compression ratio.

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