Ion energization during magnetic reconnection in MST

S. Munaretto, S.T.A. Kumar, S. Eilerman, M.D. Nornberg, D.J. Den Hartog
University of Wisconsin-Madison, Madison, Winsconsin 53706, USA

Ion energization during magnetic reconnection events is a phenomena widely observed both in astrophysical [1, 2, 3] and in laboratory [4, 5, 6] plasmas, but still not clearly understood. In the Madison Symmetric Torus (MST) [7], a Reversed Field Pinch (RFP) experiment with $R = 1.5$ m and $a = 0.5$ m, several studies were performed to characterize the conversion of magnetic energy into ion kinetic energy. Ion heating and acceleration during magnetic reconnections in MST has been studied both for impurities and majority ions. A common point of all the observations besides the correspondence between the magnetic reconnection and the ion energization is the non-collisional nature of the heating mechanism [4, 8]. The ions gain energy on a time scale of ~ *0.1* ms that is much shorter than the electron-ion collision time (~ *10* ms) and the ion temperature often exceeds the electron temperature. Several theoretical models have been proposed to explain the ion energization mechanism, but up to now there is not a general explanation for all the observations. The purpose of this paper is to relate the experimental observations of ion energization on MST.

Impurity ion temperature is measured through the Charge Exchange Recombination Spectroscopy [9, 10]. Since the magnetic field in the core is purely toroidal, with this technique it is possible to measure the parallel (T_{par}) and perpendicular (T_{perp}) temperature separately [10]. There is clear evidence of C^{+6} temperature anisotropy during magnetic reconnection events as seen in figure 1 [8]. Here the average C^{+6} ion temperature (T_C) time evolution of similar events is shown for discharges with electron density of about $n_e \sim 10^{19}$ m^{-3}. The time $t = 0$ is selected as the time when the maximum change of magnetic flux during reconnection events happens.

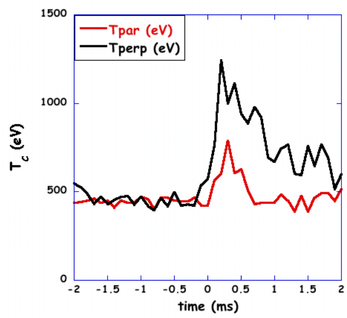

Figure 1: Time evolution of the C^{+6} T_{perp} (black line) and T_{par} (red line) during a magnetic reconnection (t=0).

At times far away ($t > 2$ ms) from the reconnection events $T_{C,\ perp} = T_{C,\ par}$, while at the sawtooth crash the increase in the perpendicular temperature is higher than in the parallel.

This observation implies the perpendicular degree of freedom is favoured for the reconnection heating mechanism, but then collisions redistribute the thermal energy. Moreover increasing the electron density increases the anisotropy [8]. This inverse dependence may be related to a decrease of the relative impurity content in the plasma.

The impurity ion heating during reconnection has also a dependence from their charge-to-mass ratio [11]. It has been observed collecting line-averaged spectroscopic measurements of several charge states of impurity ions at the edge of the plasma (*r/a ~ 0.92*). The ion temperature is calculated from the thermal broadening, therefore it is sensitive only to the component parallel to the line of sight. In this case the line of sight goes through the edge, where the magnetic field is poloidal; the perpendicular component of the temperature is negligible with respect to the parallel one. The result of the measurements is reported in figure 2, where the increase in the temperature (ΔT) of different ion species is reported as function of their charge to mass ratio (Z/μ). The temperature increase is calculated as the difference between the peak and the average temperature away from the reconnection event. It approximately increases with charge to mass ratio.

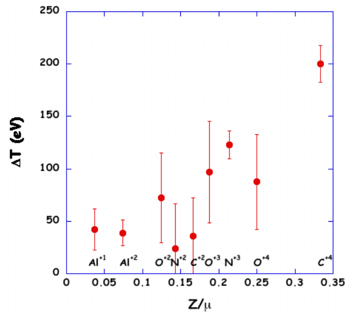

Figure 2: Increase of the parallel ion temperature at a magnetic reconnection event as function of Z/μ, where Z is the ionic charge and μ the ratio of the ion mass to the proton mass.

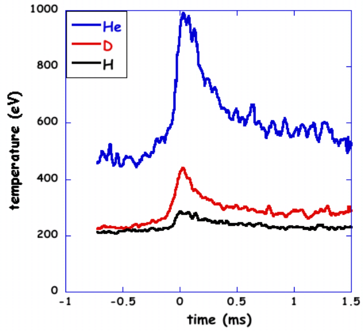

Figure 3: Comparison of the time evolution of majority ion temperature during a magnetic reconnection (t=0) in case of hydrogen, deuterium and helium plasmas.

Both the anisotropy and the charge to mass ratio dependence of the ion heating suggest that ion cyclotron damping may contribute to it. A model to describe the heating in the perpendicular direction carried to the parallel direction through collisional isotropization was proposed by *Cranmer et al.* and *Tangri et al.* [3, 12]. In this model ions with lower Z/μ resonate at lower frequencies, where in MST the magnetic energy fluctuation is higher. This suggests a decreasing heating with the charge to mass ratio, that is the inverse of the experimental observation, but since T_{par} is measured, the opposite Z/μ dependence of the collisional isotropization mechanism dominates. It means that the model can explain the experimental observations, but they are not a sufficient constraint for it.

The majority ion temperature in MST is measured through the Rutherford Scattering diagnostic [13]. The geometry of the diagnostic system is such that only the ion temperature perpendicular to the magnetic field can be measured. In figure 3 is reported the increase of the bulk ion temperature in case of three different majority ions. Again the time *t = 0* is selected as the time when the maximum change of magnetic flux during reconnection events happens [14]. It is clear that the heating is stronger for greater mass.

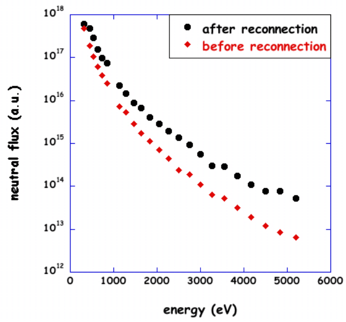

Figure 4: Energy spectra of the neutron particle flux before (diamonds) and after (circles) a reconnection event.

Fiksel et al. [14] explain the mass dependence of the majority ions assuming as main energization mechanism the stochastic ion heating. They proposed the heating being due to a large cross-field radial transport of ions through a strong fluctuating radial electric field, which causes fast random changes in the ion perpendicular $E \times B$ drift velocity.

Magnetic reconnection in the RFP also leads to the formation of a high-energy tail in the ion distribution function. The energetic ion distribution is measured using two different Neutral Particles Analizers [15, 16] that allow the detection of atoms with energies up to 45 keV.

In figure 4 is reported the neutral particle flux observed shortly before (diamonds) and after (circles) a reconnection event. The slope of the neutral flux agrees with a Maxwellian ion distribution with a small power-law component. It is evident the presence of a higher flux of neutrons after the reconnection event, that suggest the presence of suprathermal ions. The presence of the suprathermal deuterium population is then corroborated by scintillator measurements of D-D fusion neutrons, which highlighted that the neutron production in MST is dominated by fast ions produced during the magnetic reconnection events. The energy of these fast ions has been measured being as high as 25 keV [17]. Moreover the acceleration mechanism energizes not only the thermal ions, but also the fast ions (with energies from 15 to 25 keV) introduced through neutral beam injection. The time evolution of the neutral flux at several energies during the injection of neutrals is shown in figure 5.

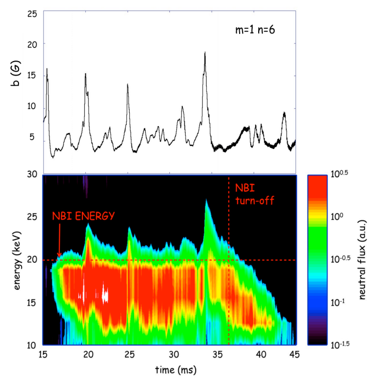

Figure 5: Time evolution of the neutral flux at several energies during the injection of neutrals with energy of 20 keV in correspondence to the magnetic modes evolution.

At the moment it is not clear which mechanism is responsible for the production of fast ions. A possible candidate is the electric field acceleration. During magnetic reconnection in MST a large parallel electric field is induced. The balance between ion acceleration and frictional drag is affected by the presence of impurities that let the deuterons experience up to 3/4 of the applied field [8]. Another possible candidate is the Fermi acceleration mechanism, in a way already used to explain both Earth's magnetosphere and solar flares [18]. The proximity of the tearing mode resonant surfaces leads to the formation of small regions of private flux embedded in the magnetic topology, called magnetic islands. The particles that are trapped in the islands can gain energy as the islands begin to contract through reflections.

Summarizing, several experimental observations of both majority and impurity ions have been obtained characterizing ion energization during magnetic reconnection. All the measurements have been explained singularly, using several possible mechanisms, but no one of these models is exhaustive.

This work is supported by the US Department of Energy under cooperative agreement DE-FCO2-05ER54814 for MST and by National Science Foundation CMSO-PHY0821899

References

[1] E.R. Priest et al, Nature 3**93**, 545 (1998)
[2] P. Sturrock et al, Astrophys. J. **521**, 451 (1999)
[3] S.R. Cranmer et al, Astrophys. J. **518**, 937 (1999)
[4] E. Scime et al, PRL **68**, 2165 (1992)
[5] S.C. Hsu et al, Phys. Plasmas **8**, 1916 (2001)
[6] S. Gangadhara et al, Phys. Plasmas **15**, 056121 (2008)
[7] R.N. Dexter et al, Fusion Technol. **19**, 131 (1991)
[8] R.M. Magee et al, PRL **107**, 065005 (2011)
[9] D.J. Den Hartog et al, Rev. Sci. Instrum. **77**, 10F122 (2006)
[10] R.M. Magee et al, Rev. Sci. Instrum. **81**, 10D716 (2010)
[11] S.T.A. Kumar et al, Phys. Plasmas **20**, 056501 (2013)
[12] V. Tangri et al, Phys. Plasmas **15**, 112501 (2008)
[13] J.C. Reardon et al, Rev. Sci. Instrum. **72**, 598 (2001)
[14] G. Fiksel et al, PRL **103**, 145002 (2009)
[15] E.D. Mezonlin et al, Rev. Sci. Instrum. **78**, 053504 (2007)
[16] J. Reusch et al, Rev. Sci. Instrum. **83**, 10D704 (2012)
[17] S. Eilerman et al, Rev. Sci. Instrum. **83**, 10D302 (2012)
[18] J.F. Drake et al, Nature **443**, 553 (2006)