

## Abstract

The energization of plasma ions during magnetic reconnection is observed in many laboratory and astrophysical plasmas. Whether it takes the form of thermal heating, bulk acceleration, or a distortion of the distribution function, the mechanism is often anomalous. In the MST reversed-field pinch, the impulsive reconnection may energize the ions in more ways than one. It is well known that the sudden (~100 μs) drop in energy in the equilibrium magnetic field during reconnection is accompanied by a large increase (x2-3) in the ion temperature. A critical outstanding question has been whether or not this heating is isotropic with respect to the mean magnetic field, which is addressed here with localized spectroscopic measurements of the impurity ion (C<sup>+6</sup>) temperature. It is observed that the parallel heating shows a strong density dependence that the perpendicular heating does not. The reconnection also generates a large burst of d-d fusion neutrons that cannot be explained by the measured increase in temperature. The presence of a high energy tail in the ion distribution function would explain this observation, and simple calculations show that such a tail could be generated by the large inductive electric field associated with the change in magnetic flux.

## Reconnection in MST

- The impulsive, periodic reconnection is characterized by a large increase resonant magnetic tearing modes, an increase in neutron flux, and anomalous ion heating (fig. 1)
- During the reconnection, the energy in the equilibrium magnetic field decreases (fig. 2) and the power in magnetic fluctuations increases (fig. 3)
- The ion heating is stronger for the impurity than for the bulk ions (fig. 4)
- The electron temperature in the core drops and scales inversely with density (fig. 5)

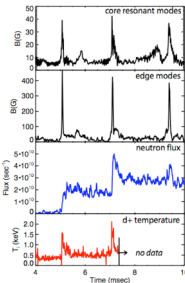


Fig 1. Sawtooth behavior in various signals during an MST discharge.

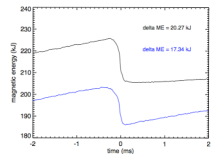


Fig 2. The change in energy stored in the equilibrium magnetic field for low density (black) and high (blue).

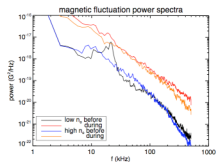


Fig 3. Spectra before and during reconnection for high (~1.2e13cm<sup>-3</sup>) and low (~0.8e13cm<sup>-3</sup>) density plasmas.

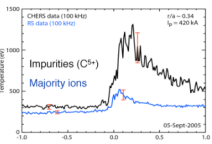


Fig 4. A comparison of the bulk ion (Rutherford Scattering) and impurity ion heating (CHERS).

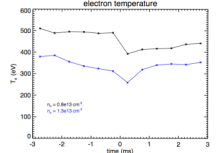


Fig 5. Thomson Scattering electron temperature data (J. Reusch).

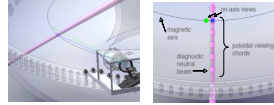
## CHERS

- Localized charge exchange emission from C<sup>+6</sup> ions is Doppler broadened and shifted,

$$kT_e = m \left( \frac{c\sigma}{\lambda_0} \right)^2 \quad \frac{z\lambda_0 - 2\sigma\lambda}{\lambda_0} = \sigma = 0.3 - 1.5 \text{ Ang.}$$

$$v_e = \frac{c\Delta\lambda}{\lambda_0} \quad \frac{\lambda - \lambda_0}{\lambda_0} = \Delta\lambda = 0.01 - 0.6 \text{ Ang.}$$

- MST has two complementary sets of viewing chords: poloidal (right) and newly installed toroidal (left)



## Ion Heating

Parallel ion heating is strongly density dependent, perpendicular is not

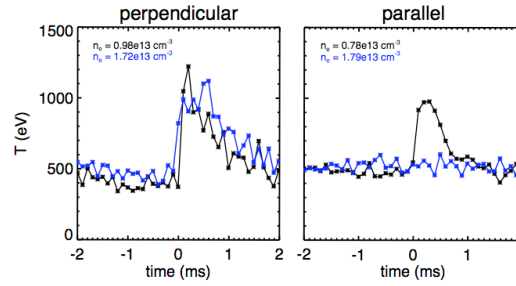


Fig 6. CHARGE Exchange Recombination Spectroscopy measurements of the C<sup>+6</sup> ion temperature in the core of MST both perpendicular (left) and parallel (right) to the magnetic axis during a reconnection event.

Parallel ion heating is strongly density dependent in both the core and edge

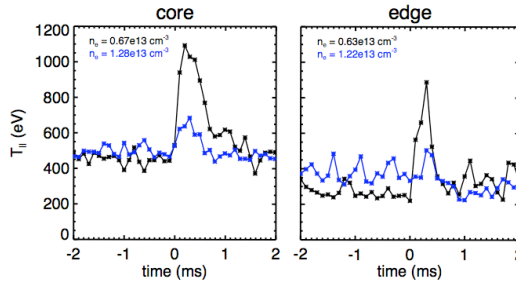


Fig 7. CHERS measurements of the C<sup>+6</sup> parallel ion temperature in the core (left) and the edge (right) during a reconnection event.

## Theory

### Ion heating:

- The dissipation of MHD fluctuations by parallel viscosity can heat the ions in the parallel direction (Gimblett, 1990). A gradient in the tearing mode flows  $-v_e/\rho_e$  is required (Svidzinski, 2008).
- ICRH from a turbulent cascade of tearing modes can explain stronger heating of impurities (Tangri, 2008).
- The observed mass dependence of the heating efficiency can be explained with a stochastic heating model (Fiksel, 2009).

### Non-Maxwellian energization:

- The enhanced resistivity due to impurities or magnetic trapping of electrons permits ion runaway (Furth and Rutherford, 1972). A high-energy tail in the parallel direction is observed with an NPA on MAST (Helander, et. al., 2002)
- A model in which a kinetic electron instability excites waves that damp on ions is used to explain an observed high energy tail perpendicular to B on RFX (Costa, et. al, 1999)
- A non-Maxwellian, power law (Kappa) velocity distribution may exist in the solar wind (Scudder, 1992)

## Non-Maxwellian Ions

### Observation

- The measured neutron flux cannot be explained by the fusion of Maxwellian ions
  - fusion neutrons should scale  $\sim n^2$ ; an inverse relation is observed
  - a tripling of temperature in this regime would result in a  $10^4$  increase in neutron flux

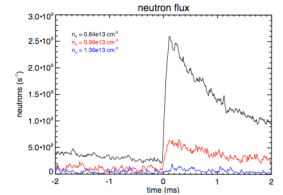


Fig 7. Measured neutron flux increase at a reconnection event is larger at lower density.

### Interpretation

- Because the d-d fusion cross-section is such a steep function of energy, a small number of fast ions can produce more neutrons than the bulk
- A large electric field (~50 V/m) is measured during the reconnection event (~100 μs), which can accelerate ions. A thermal ion could accumulate 15 keV in 4-5 events

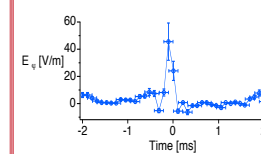


Fig 8. Measured electric field in the core of MST at a reconnection event (W. Ding).

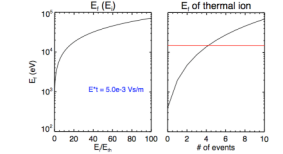


Fig 9. Calculation of the final energy of a test d<sup>+</sup> ion due to electric field acceleration, neglecting friction, vs. initial energy (left) and number of events (right).

- The measured neutron flux can be explained by a combination of thermal fusion and fast ion fusion

- 1% at 15keV before the event, 3% after
- fast ions are known to be well-confined in MST

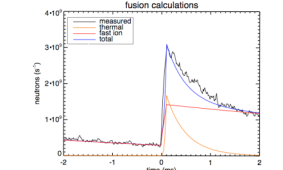


Fig 10. A comparison of the measured neutron flux with a model containing both thermal and fast ion fusion.

## Conclusions

- Magnetic reconnection in MST appears to energize plasma ions through both anomalous thermal heating and a non-maxwellian distortion, possibly ion runaway.
- Existing theories can explain features of the heating, but there is no all encompassing theory.
- The parallel heating of impurity ions is strongly density dependent, in both the core and the edge; the perpendicular is heating is not. This is a new constraint on theory.
- Measurements of neutron flux during reconnection are consistent with the presence of a ~1% population of fast ions with  $E \sim 10$ keV, which could be generated by the inductive electric field.

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