Non-collisional Ion Heating and Magnetic Turbulence in the RFP

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Abstract: strong non-collisional ion heating occurs during sawtooth-like magnetic reconnection events in Madison Symmetric Torus, where ions are transiently heated to as high as 3 keV, often exceeding the electron temperature. The free energy source for this ion heating is the mean magnetic energy. Measured magnetic fluctuations exhibit an exponential spectral density consistent with dissipative nonlinear turbulent cascade, originating from unstable MHD tearing fluctuations, believed to be related to the observed non-collisional ion heating. Our key results are 1) achieved high ion temperature plasma through a non-collisional heating and then sustained by parallel current profile control helping to establish MST's record energy confinement time of 12 ms, 2) the resulting ion heating has a square-root of the mass dependence where heavier ions heat up to higher temperature 3) the high frequency magnetic turbulence is anisotropic in wave number, most of the power is in the perpendicular wave number, and 4) we observe a dissipative cascade in $k_\perp$ with $k_{dis} = 0.22 cm^{-1}$.

1. Introduction

Non-collisional ion heating occurs during sawtooth-like magnetic reconnection events in MST Reversed Field Pinch (RFP) plasma. The ions are rapidly heated to as high as 3 keV, often exceeding the electron temperature [1]. The energy source for this ion heating is the plasma mean magnetic energy. This transient ion heating has been utilized to enhance plasma beta and energy confinement in MST by timing the application of current profile control just after a reconnection event. Magnetic turbulence cascade is thought to be related to the observed non-collisional ion heating, which is not well understood. Magnetic fluctuations are measured over a broad range of scales down to the ion gyroradius, 0.5 cm, with 10 MHz bandwidth. The measured magnetic turbulence exhibits anisotropy with respect to the mean magnetic field, a feature expected for MHD turbulence in magnetized plasmas. These fluctuations reveal an exponential spectral density consistent with dissipative nonlinear turbulent cascade, originating from unstable MHD tearing fluctuations. The tearing modes in MST are measured by a toroidal array of 32 magnetic coils. The 32 signals are then Fourier decomposed into toroidal and poloidal modes. The tearing modes fall into two groups, low n (1,2,3,4) with m=0 and high n (5,6,7,8,9,..) with m=1 The non-collisional ion heating [2] and anisotropic magnetic turbulence [3] are also observed in astrophysical plasmas, heightening interest in these observations. MST provides an exceptional laboratory setting to examine this ion heating mechanism and magnetic turbulence.

MST is equipped with two neutral-beam-based ion temperature diagnostics. Rutherford scattering, a rare diagnostic in plasma research worldwide, monitors the majority Deuterium ions, while charge-exchange-recombination spectroscopy (CHERS) monitors the minority Carbon ions. Both of these CHERS and Rutherford measurements are sampled at a 1 MHz rate. MST is also equipped with a set of insertable multi-coil magnetic probes. The probes measure the equilibrium as well as high frequency poloidal and toroidal components of fluctuations. Two coil measurements at a toroidal and poloidal separation of 5 mm provides the wave vector both in the parallel $k_{//}$ and the perpendicular $k_\perp$ directions relative to the mean field. The mean magnetic field signals are sampled at 200 kHz rate while the fluctuating component are sampled at 10 MHz rate. Ion temperature measurements are typically made in high plasma current discharges, 400 to 500 kA, some of the probes data are made in lower, 250 kA, plasma current discharges when probes are inserted past r/a ~ 0.95. The plasma density and plasma profiles such as field reversal parameter F and pinch parameter θ are nearly the same.

2. Ion heating

The free energy source of the observed ion heating is the energy released from the internal mean magnetic field by reconnection event. The presence of the m=0, n=1 mode is a essential for ion heating to occur. Reconnection events that do not have (0,1) mode do not result into ion heating. The (1,0) mode is the product of nonlinear coupling of high n tearing modes. The (0,1) mode is a critical ingredient in many phenomena in MST plasmas. Reconnection events that do not have (0,1) mode do not release the magnetic energy and do not result into ion heating. Figure 1 shows the change in deuterium ion temperature, the change in the (0,1) mode amplitude, and the change in the mean magnetic energy during a reconnection event. The time axis is relative to a reconnection event where 0.0 is the time of the reconnection event, negative time is before, and positive time is post the reconnection event. Figure 2a displays the increase in the ion temperature for plasmas with different majority ions. Figure 2b shows the change in the mean magnetic energy for the three different cases. We note that the three different cases are similar in most respects. Even though the available source of energy is the same in all three cases the heating is stronger for heavier ions. Both plots in figure 1 and 2 are the averages of many reconnection events. We therefore conclude that the efficiency with which the magnetic energy is converted to ion thermal energy scales with the ion mass as seen in figure 3 [4]. The mechanism responsible for ion heating remains to be determined, despite a number of proposed theoretical models. A theoretical model based on stochastic ion heating in a randomly varying electric field predicts $\sqrt{M}$ scaling in the range of parameters when the field decorrelation time exceeds the period of ion gyro-rotation [4]. However, ion cyclotron damping in a turbulent cascade predicts $\sim M^{0.8}$ dependence [5], which fits the data in figure 3 nearly equally well. CHERS data also show large impurity ion heating during reconnection event. The impurity ions attain temperatures greater than projected from the $\sqrt{M}$ scaling, but since their minority fraction is difficult to quantify their power balance is difficult to perform. The CHERS diagnostic installed on MST measures both the parallel and the perpendicular impurity ion temperature. These data reveal an apparent ion heating anisotropy in the parallel and perpendicular to the magnetic field. The

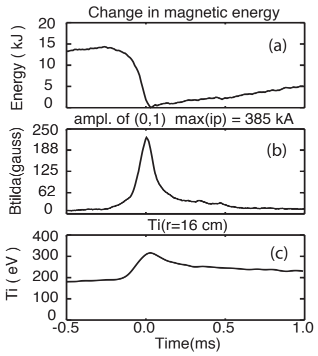

FIG. 1. (a) *Magnetic energy release during reconnection event, (b)(0,1) mode amplitude* (c) I*on temperature*

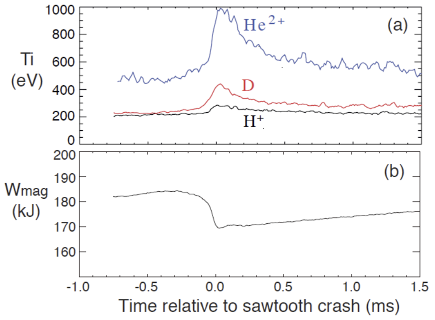

FIG 2. (a) Majority ion temperature for H, D, and He plasmas, (b) Magnetic energy release during reconnection event

perpendicular Carbon temperature always increases at a reconnection even where as the parallel carbon temperature increases only at low density. At plasma density higher than 10^{19} m^{-3} the parallel Carbon temperature shows no heating associated with reconnection events.

Under high current and low density conditions, reconnection events can be very intense, such that ions are heated to as high as 3 keV. In a unique mode of MST operation we inductively modify the parallel current profile shortly after such events, where the high ion temperature is sustained for longer than 10 ms as is shoeing in figure 4.. In a standard MST discharges the ion heating gained from a reconnection event is quickly lost within 1 ms. This mode of MST operation helps to establish MST's record energy confinement time of 12 ms.

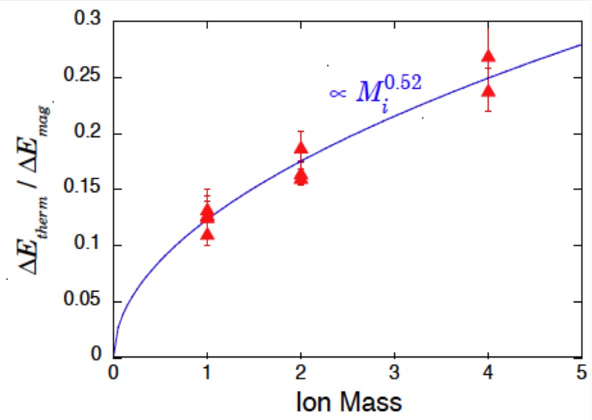

FIG. 3. Ion thermal energy increase normalized to changes in the magnetic energy for H, D, He

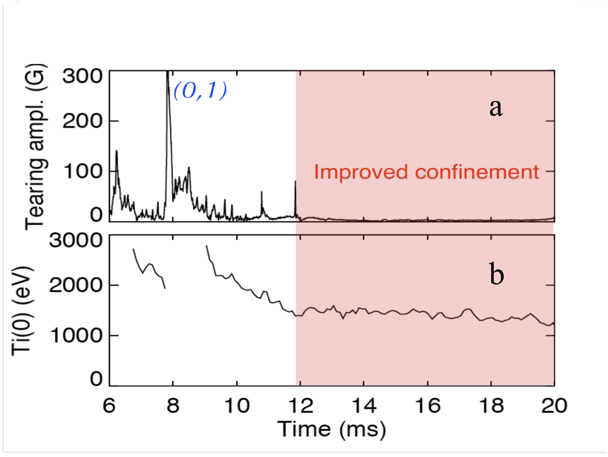

FIG. 4. (a) Shows the (0,1) mode amplitude, (b) shows the ion temperature before and during improved confinement

3. Magnetic turbulence

Magnetic turbulence cascade and dissipation is a candidate for the mechanism with which a fraction of the mean magnetic energy is converted into ion thermal energy. Magnetic fluctuation spectrum in MST is very broad. We measure fluctuations at spatial scales from the global tearing mode of 10's of cm down to the ion gyroradius level of fraction of cm. The long wavelengths of tearing modes are measured with a toroidal array of magnetic coils at the edge of MST plasma. The short wavelengths of the order of 0.5 cm are measured with magnetic probe that can be inserted into the plasma boundary. A typical magnetic fluctuation spectrum is shown in figure 5. The spectrum is divided into three characteristic frequency ranges showing the flow of energy from the tearing mode range down to the ion cyclotron range through the Alfven range. The magnetic energy cascade depends on the presence of the (0,1) mode. Without the (0,1) mode the energy in the Alfven and cyclotron range does not change at the sawtooth crash. When the (0,1) mode is present the spectrum shows an increase of energy at all high frequencies. The

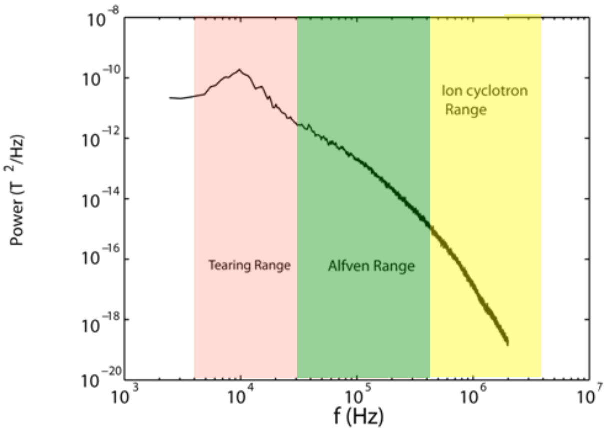

FIG. 5. The power spectrum of the magnetic fluctuations with three relevant ranges.

measured small-scale magnetic turbulence in MST is strongly anisotropic with respect to the background magnetic field. In the $(k_{//},k_{\perp})$ plane the magnetic energy is elongated in the direction perpendicular to the mean magnetic field. Figure 6 shows the spectral density function at the edge of MST plasma as a function of $k_{\perp}$ and $k_{//}$ during reconnection events. The ion diamagnetic direction is in the positive k direction and the electron diamagnetic direction is in the negative k direction. This plot shows that magnetic turbulence has power law and exponential law features. We observe a power law of $k_{//}^{-5.5}$ and $k_{\perp}^{-4}$ in the range $0.1 < k_{//,\perp}(cm^{-1}) < 1.0$. However, the dominant fluctuations exhibit an exponential law $e^{-4.6k_{\perp}}$ in the range $-1.5 < k_{\perp}(cm^{-1}) < -0.5$ with $k_{dis} = 0.22cm^{-1}$. This may be indicative of a dissipative mechanism that is responsible for the observed ion heating. Theoretical analysis shows that the observed dissipation in MST is stronger than can be accounted for by classical resistivity or viscosity [6].

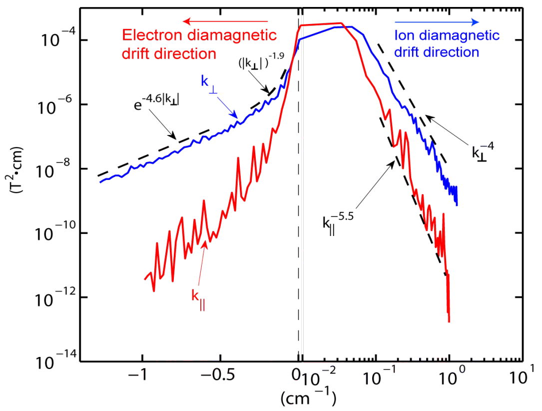

FIG. 6. The spectral density function

3. Summary

Non-collisional ion heating occurs in MST plasma during magnetic reconnection events. The heating practically large when the (0,1) mode is large. Energy of the magnetic turbulence cascades from the tearing mode range to the ion cyclotron range when the (0,1) mode is large. The cascade exhibits both power-law and exponential character. Most of the magnetic fluctuation power is in the perpendicular wave number. The dissipation implied by the exponential character of the cascade suggests connection to the observed non-collisional ion heating in MST plasma.

Work supported by the U.S. Department of Energy and National Science Foundation.

[1] B. E. Chapman *et al.*, Nucl. Fusion **49**, 104020 (2009).
[2] S. Cranmer, Astrophys. J. 532, 1179 (2000).
[3] J. W. Belcher and L. Davis Jr., J. Geophys. Res. 76, 3534 (1971).
[4] G. Fiksel *et al.*, Phys. Rev. Lett. **103**, 145002 (2009).
[5] V. Tangri, et. al. Phys. Plasmas **15**, 11250 (2008)
[6] P.W. Terry, and V. Tangri, Phys. Plasmas **16**, 82305 (2009)