Ions Heating
During Magnetic Reconnection
in the Reversed Field Pinch

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In many lab and astro-plasmas ions are anomalously hot

- Hot ions in Solar plasma - much hotter than electrons
- In RFP ions are much hotter than expected from e/i collisional heating
- In MST RFP, the ion heating is especially prominent during magnetic reconnection and bursts of magnetic fluctuations
- We are trying to understand this connection
Outline

• Spontaneous magnetic reconnections in MST
• Ion heating - strong and robust; mechanism still not understood
• Mass scaling of ion heating
• Well confined plasma with hot ions
• Conclusions
Madison Symmetric Torus Reversed Field Pinch

$R = 1.5 \text{ m, } a = 0.5 \text{ m}$

$I_p = 600 \text{ kA, } B=0.5 \text{ T}$

$n_e=1-3 \times 10^{19} \text{ m}^{-3}$

$T_e, T_i = 1-2 \text{ keV}$
Neutral beam atoms scatter elastically from plasma ions.

Measure energy spectrum of scattered atoms arriving from one location along beam.

Spectrum shift and broadening => ion flow and temperature.

Measures bulk ions.

High intensity beam provides high time resolution.

\[ \Delta r \sim 15 \text{ cm} \quad \Delta t \sim 30 \mu \text{s} \]
Neutral beam atoms undergo CX with impurity ions in plasma

Radiation from impurity ions localized to intersection of beam and viewing chord

Doppler shift and broadening => ion flow and temperature

Custom-built spectrometer provides high spectral and temporal resolution

\[ \Delta r \sim 1 \text{ cm} \quad \Delta t \sim 10-100 \text{ µs} \]
Insertable Doppler spectroscopy probe - edge impurity ion dynamics

- Samples radiation from a small plasma volume
- Doppler shift of a radiation line (e.g. HeII) gives local measurement of ion flow
- Doppler width gives temperature
Resistive tearing modes in RFP

- Resistive tearing modes are unstable - current driven
- Multiple resonant surfaces exist across the plasma

![Graph showing q = m/n relation with poloidal and toroidal numbers](image)

\[ q = \frac{rB_t}{RB_p} \]
Magnetic activity has a relaxation character

Current gradient - free energy source

Free energy reduced
Current peaking

Current relaxation

Instability

\( \tilde{j}, \tilde{b}, \tilde{v} \)

Current transport
Bursts of magnetic fluctuation - magnetic reconnection

Global reconnection - both core- and edge modes are excited

\[ q = \frac{rB_t}{RB_p} \]

Core Mode \((m,n) = (1,6)\)

Edge Mode \((m,n) = (0,1)\)
Global reconnection results in a large change of stored magnetic energy

- Reconnection modifies the equilibrium magnetic field profile
- Stored magnetic energy drops

![Graph showing the change in stored magnetic energy over time](image-url)
Strong and global ion heating is observed

- Bulk ion (D\textsuperscript{+}) temperature measured with Rutherford scattering.
- T\textsubscript{i} quickly rises at all plasma radii
- T\textsubscript{i} rise time \(\sim 100\mu s\), \(\tau\text{coll} \sim 1ms\)

![Graph showing D\textsuperscript{+} temperature over time for different plasma radii]
Impurities are heated stronger than bulk ions

- Similar to Solar plasma
- Possibly a clue to the heating mechanism, which is still unknown

![Graph showing the heating of impurities and bulk ions over time](image)

**D+**

- $T_{D+}$ vs. Time reconnection (ms)
- Curves for $r/a = 0.3$, $r/a = 0.5$, and $r/a = 0.7$

**C^6+**

- $T_{C^6+}$ vs. Time relative to event (ms)
- Curves for $r/a = 0.0$, $r/a = 0.19$, $r/a = 0.37$, $r/a = 0.55$, and $r/a = 0.75$
Recent measurements - heavier bulk ions are heated stronger as well
Calculate thermal and magnetic energy

Since the density and temperature of the bulk ions is known, we can calculate the total thermal energy and compare it with the released magnetic energy.

\[ E_{\text{thermal}} = \int \frac{3}{2} kT_i \frac{n_e}{Z_i} \, dV \]

\[ E_{\text{mag}} = \int B^2 / 2 \mu_0 \, dV \]
Heating efficiency $\approx (M_i)^{0.5}$ dependance on ion mass
Weak dependence on $I_p$ and $n_e$

$\alpha = \frac{\Delta E_{\text{thermal}}}{\Delta E_{\text{mag}}}$
Include losses

\[ T_i = T_0 + T_1 \]
\[
\frac{3}{2} n_i \frac{dT_1}{dt} = \alpha \dot{E}_{mag} - \frac{3}{2} n_i \frac{T_1}{\tau}
\]

\[ E_{thermal} = \int \frac{3}{2} kT_i \frac{n_e}{Z_i} dV \]
\[ E_{mag} = \int B^2 / 2\mu_0 dV \]

\[ \alpha = \frac{\Delta E_{thermal} + \frac{3}{2} n_i \int T_1 dt}{\Delta E_{mag}} \]

\[ e^{-t/\tau} \]
With losses

\[
\alpha = \frac{\Delta E_{\text{thermal}} + \frac{3}{2} \frac{n_i}{\tau} \int T_1 dt}{\Delta E_{\text{mag}}}
\]

\[0.15 (M_i)^{0.54}\]

- H⁺
- D⁺
- He²⁺
Global reconnection needed for ion heating - just a large amplitude mode is not enough

- Sometimes, very large core-resonant mode $m=1, n=6$ is excited
- Other modes, in particular the edge-resonant $m=0, n=6$ mode, are small.
- Similar to the RFX-machine QSH (quasi-single helicity) mode.
- No change in the equilibrium magnetic field profile. No change in the equilibrium magnetic energy
- No ion heating observed
New regime of hot ion plasma - synergetic use of reconnection heating and improved confinement

- Reconnections “preheat” ions
- Following by auxiliary inductive current profile control reduces the tearing activity. Reduction of magnetic fluctuations and confinement improved, up to ten-fold
- Hot ions (and electron) plasma with good confinement
Simultaneous hot electrons and ions

![Graph showing $T_e$ and $T_i$ vs. $r/a$ for standard RFP](image-url)
Simultaneous hot electrons and ions

![Graph showing the profiles of $T_e$ and $T_i$ for improved confinement and standard RFP conditions.](image)
Summary

- Strong ion heating occur during reconnection events
- Magnetic energy release is a likely source for ion heating. However, the mechanism is still unknown.
- Mass-scaling can be a constraint for choosing the heating mechanism.
- Combination of reconnection heating and confinement improvement results in hot ion, well confined plasma
- Future measurements will evaluate the heating anisotropy - another constraint.
Soon - add toroidal view to evaluate heating anisotropy
The End
Fermi-like acceleration - possible mechanism?

- Bouncing ball and a moving wall model

\[ v_i' = v_i + 2v_0 \]
\[ v_i'^2 = v_i^2 + 4v_i v_0 + 4v_0^2 \]

Energy increases in the head-on collision and decreases in tail-on.

Suppose the wall oscillates \( v_0 = v_0 \cos(\omega t) \)

\[ \langle v_i'^2 \rangle = \langle v_i^2 \rangle + \langle 4v_i v_0 \rangle + \langle 4v_0^2 \rangle \]
\[ \langle \Delta \epsilon \rangle = m_i v_0^2 \]

Rate of thermal energy change:
- proportional to \( (m_i)^{1/2} \)
- does not depend on \( Z_i \)