

Ion Heating in Laboratory and Space plasma

(Part I)

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PAC 2005 Recommendations

“....At this point, the coupling of the laboratory results to theory and to astrophysics is not yet well developed. This seems particularly promising in the area of impurity or minority ion heating. It might be interesting to see how heating compares to the turbulent flux of energy to small scales (this may be deduced from the fluctuation spectrum with some theoretical assumptions). We recommend that CMSO develop further connections to scientific work on theory and observations regarding such phenomena in solar-heliospheric physics. Specific questions include whether the dynamics on MST might also be present in the solar wind, and if so how one might detect it? The theoretical work needs to proceed to quantitative predictions, doubtless subject to assumptions, that can be compared with trends in the data.”

Major directions and achievements

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- Spatially and temporally resolved measurements of both minority and majority ions.
- Influence of reconnection topology on ion heating.
- Preferential heating of impurity ions.
- Study of different mechanisms of tearing modes viscous dissipation.
- Revised theory of ion heating via Alfvénic cascade.
- Reported at 2005 PAC meeting
 - Spatially localized bi-directional flows - SSX
 - Ion heating during spheromak merging - MRX

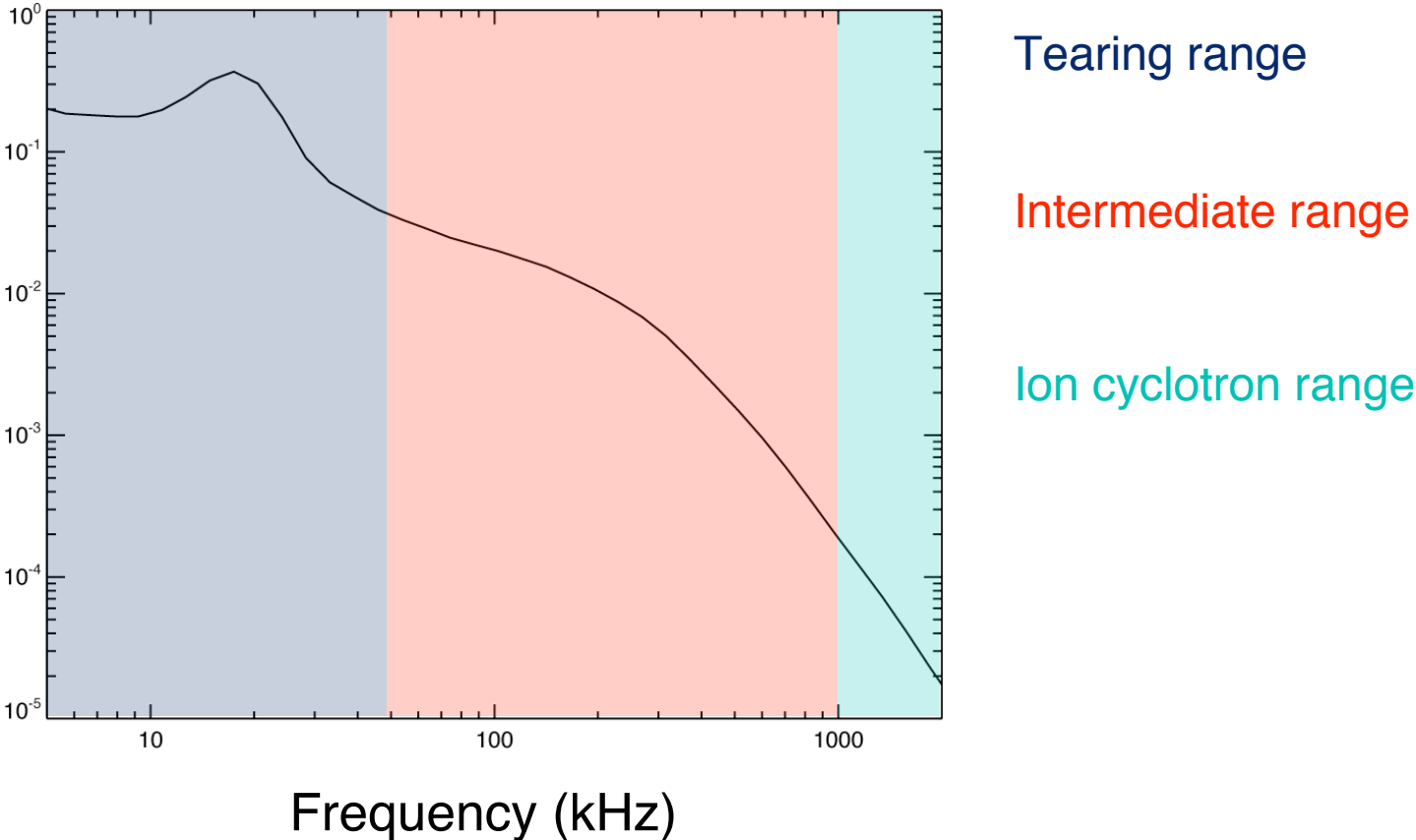
Outline

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- Magnetic fluctuation spectra and ion heating in MST
- Tearing range
 - localization of reconnection events and ion heating
 - ion heating via viscous dissipation
- Intermediate range - initial observations
- Ion cyclotron range
 - ion cyclotron heating via Alfvén cascade and collisions with minority ions
- Future work

Turbulent energy cascade and ion heating

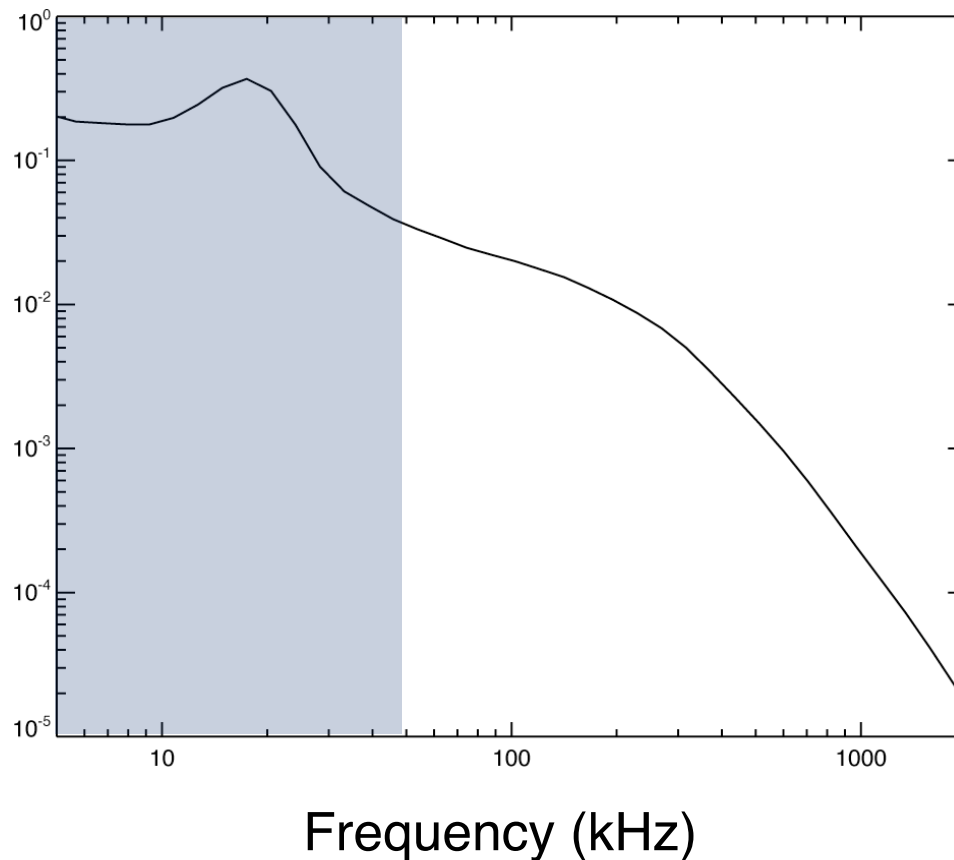
Typical power spectra of magnetic fluctuations in MST



Tearing range - global modes

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Typical power spectra of magnetic fluctuations in MST



Global tearing modes excited at different spatial locations.

Localization of tearing activity affects the ion heating.

The ion heating rate depends on the amount of released magnetic energy.

Proposed heating mechanism - viscous dissipation of tearing modes.

Localization of ion heating correlates with localization of reconnection

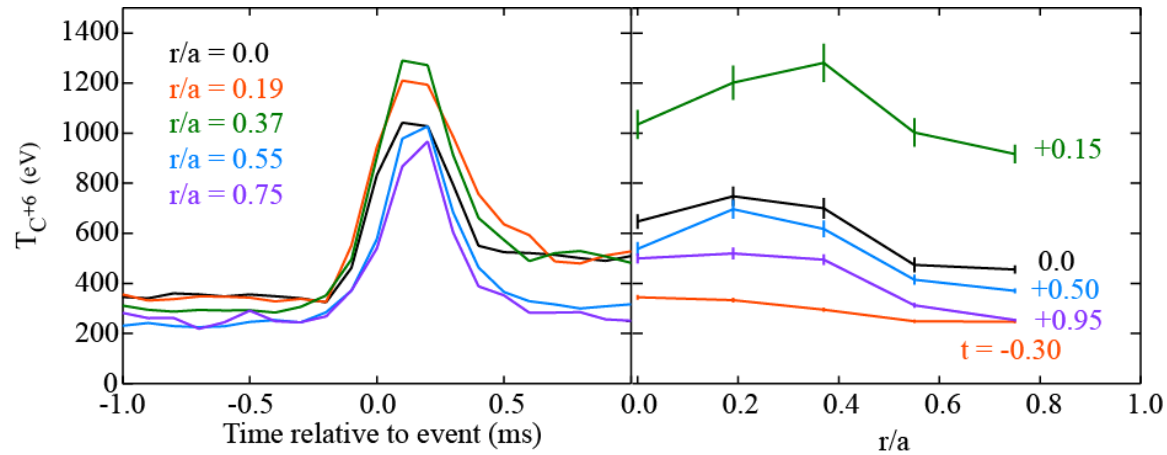
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- **Global reconnections.** Both core resonant tearing modes ($m=1, n=6,7,8,\dots$) and edge modes ($m=0, n=1,2,3,\dots$) are excited.
 - Large change in the equilibrium B-field energy.
 - Strong ion heating over entire plasma volume.
- **Edge reconnections.** Only edge resonant modes ($m=0, n=1,2,3,\dots$) are excited.
 - Moderate change in the equilibrium B-field energy.
 - Ion heating is observed only at the edge.
- **Core reconnections.** Only core resonant modes are excited.
 - No change in the equilibrium B-field energy.
 - No ion heating is observed.
- Results suggest that non-linear mode coupling is essential

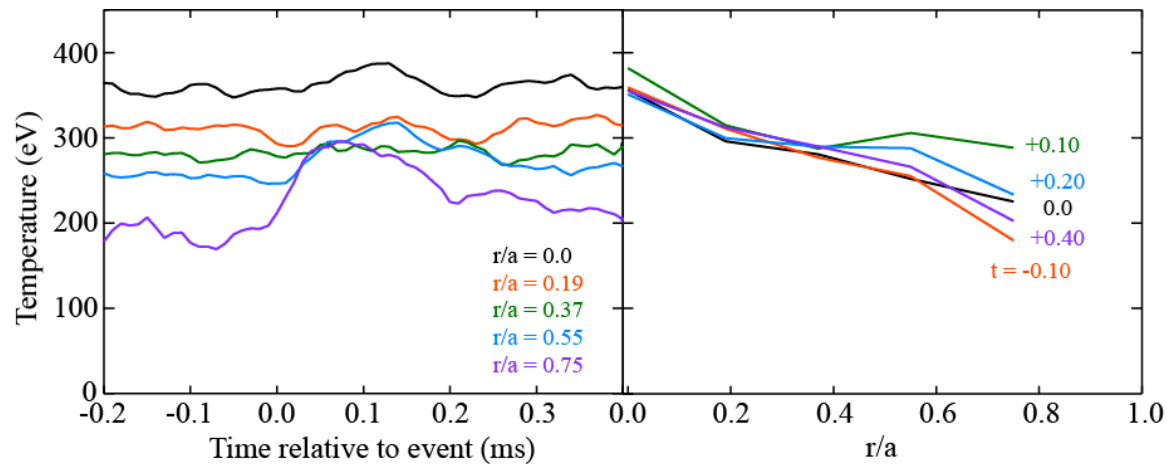
Published: S. Gangadhara *et. al.* Phys. Rev. Lett. **98**, 075001

Comparison of core and edge events

Global events. T_i increases at all radii



Edge events. T_i increases only at the edge.



Ion heating via viscous dissipation of tearing modes.

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Cross-field flow

Generalization of Braginskii viscous dissipation:

- short time scales $\ll \nu_{ii}^{-1}$ (dielectric tensor formalism)
- short spatial scales $\ll \rho_{Li}$ (kinetic equation modeling)

Publications: being prepared - V. Mirnov, V. Svidzinski.

Parallel flow

Dissipation based on η_{\perp} viscosity

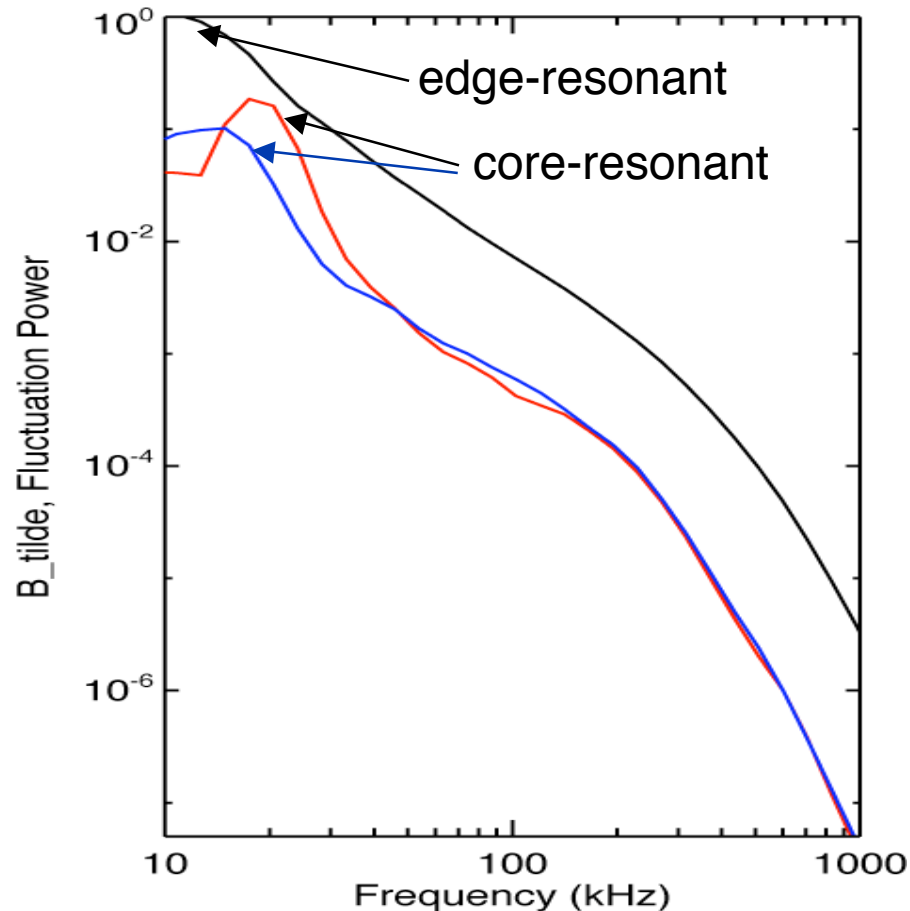
- Flow variation in parallel direction (kinetic approach)
- Flow shear in the perpendicular direction.

Ongoing and future work - dissipation based on large η_0 viscosity

- time dependant cross-field flows (gyro-relaxation heating)
- neoclassical damping of parallel flows due to spatial variation of magnetic field (large fraction of trapped particles).

Global ($m=0$) and Core (no $m=0$) reconnections affect the turbulent cascade

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Away from reconnection event

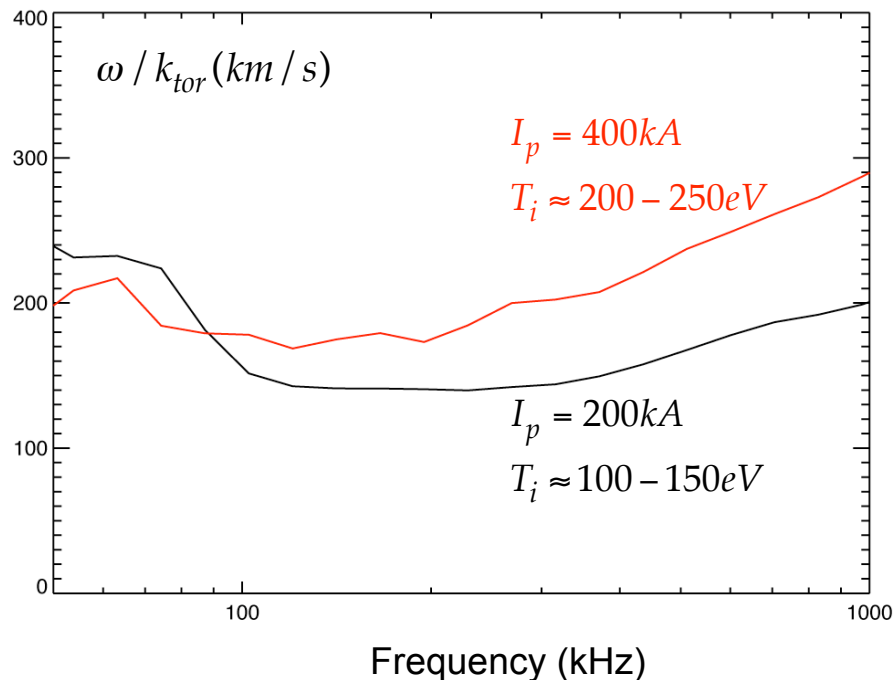
Core reconnection - no ion heating

Global reconnection - ion heating

- Cascade is inhibited during core reconnection.
- In particular, intermediate frequency fluctuations are not excited.
- What is their nature?
- Can they be responsible for ion heating?

Intermediate range fluctuations propagate with (approximately) ion thermal speed

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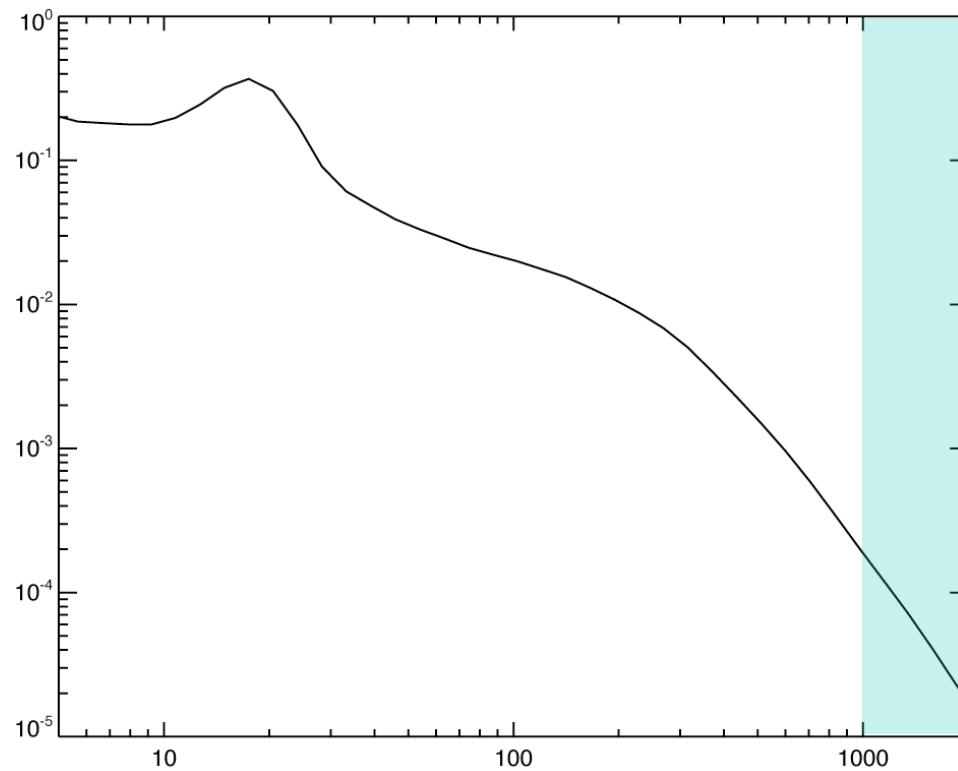


- Some candidates to consider:
 - magnetosonic waves
 - kinetic Alfvén waves
- Widely considered in space and solar plasma literature. Have not been looked at in MST.
- Energy dissipation via:
 - Landau damping
 - transit-time damping

- Ongoing work - experimental study with high frequency insertable magnetic probes - measurements of wave polarization and k- spectra.
- Future - investigate relevance of magnetosonic and kinetic Alfvén modes for MST plasma heating.
- Possible connection to solar plasma?

Ion cyclotron range

Typical power spectra of magnetic fluctuations in MST



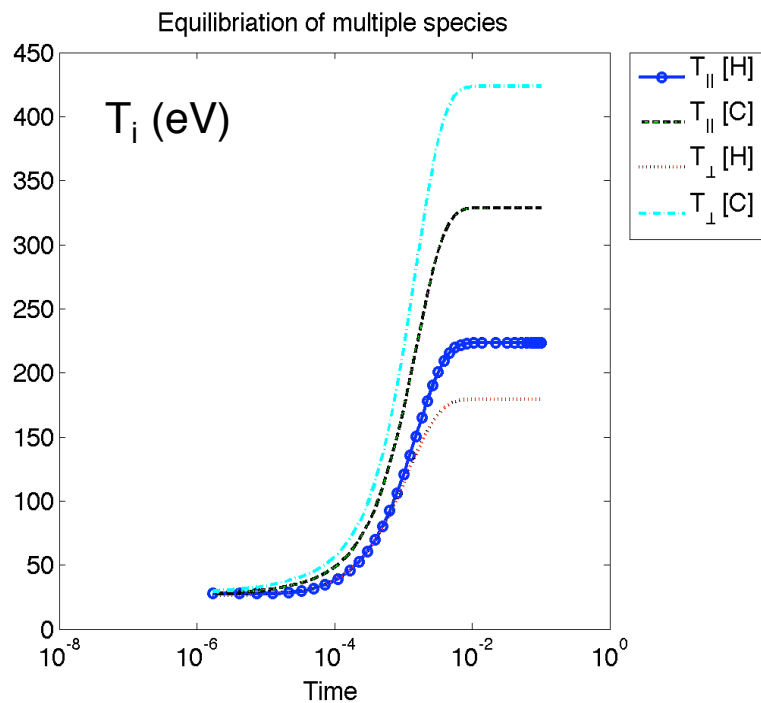
Ion cyclotron dissipation augmented by collisional heating with impurities.

Frequency (kHz)

Collisional heating is included in a model of ion cyclotron heating via Alfvén cascade

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$$n_H = 0.2 \times 10^{13} \quad n_C = 0.05 \times 10^{13}$$

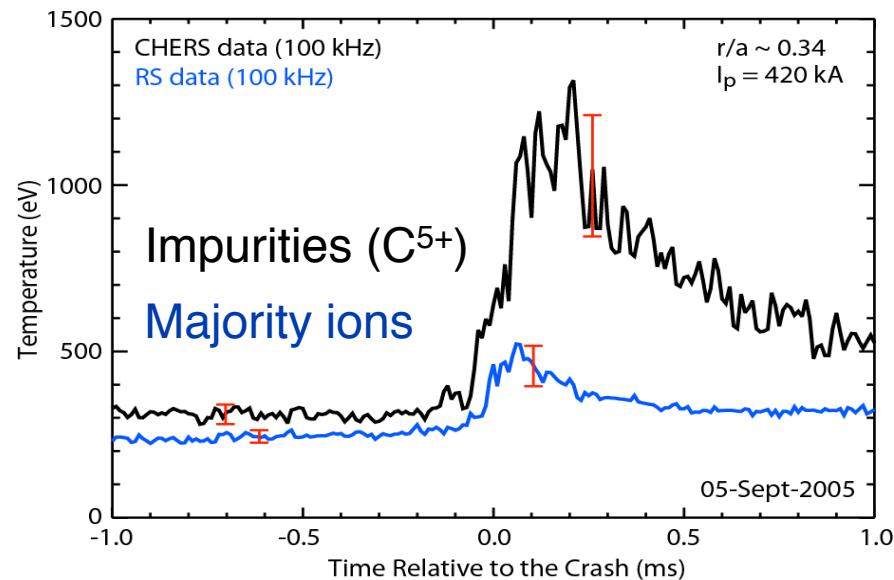


- Previous work (Mattor et. al) is extended to include impurity species and collisional energy exchange in reverse field pinch plasmas.
- The heavier mass of some species allows them to be gyro-resonant at lower frequencies, where more energy is present in the fluctuations.
- The heating rate depends on the plasma density and the charge state.
- Future: compare with experiments and solar plasma.
- Publication - being prepared - Varun Tangri, Paul Terry.

Experiment: impurities are hotter in MST plasma ...

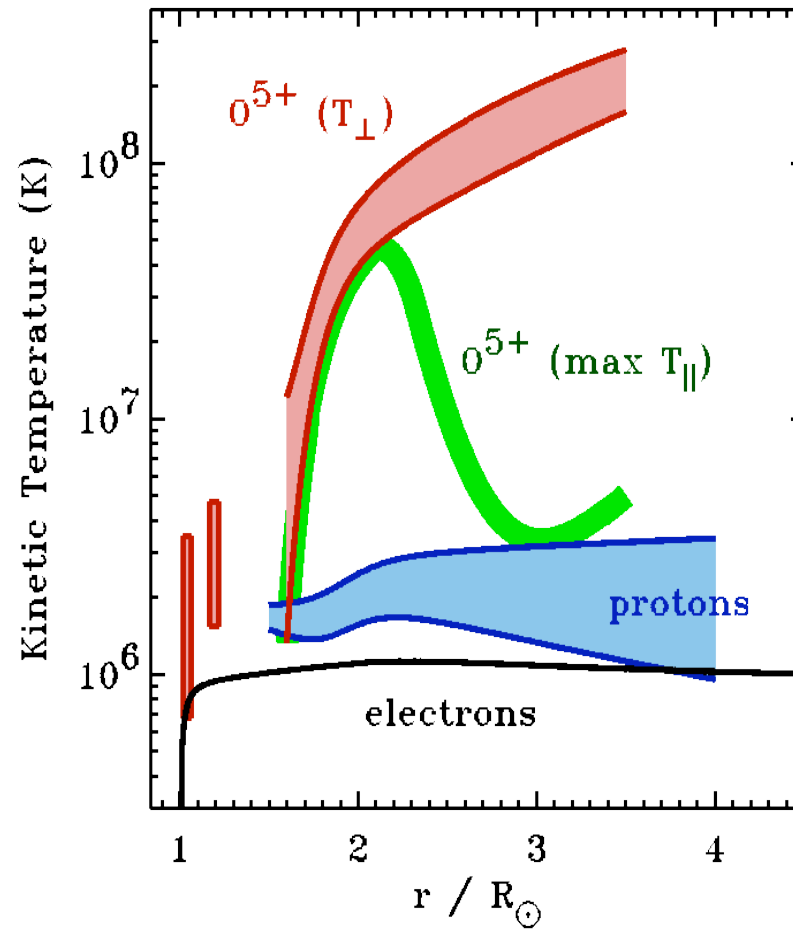
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- Ion diagnostic with good spatial and time resolution
- Carbon ions C^{5+} - CHERS; Deuterium ions - Rutherford scattering.
- C^{5+} ions are hotter than bulk ions. The difference is especially drastic at the impulse reconnection event.
- Implications:
 - Heating mechanism is charge/mass dependant.
 - Collisional energy transport from high-Z minority ions to bulk ions can be large (~ 1 MW for MST) and should be included in modeling.



...and solar plasma

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More about connections with solar plasma heating in Part 2
(Bhattacharjee)

Ion heating studies - future work

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- Diagnostic upgrade - higher sensitivity, better localization. Will allow a better diagnostic of impurities with weaker spectral lines.
- Comparison of bulk ion and minority ion heating. Relate to preferential impurity heating in solar plasma.
- Comparison of T_{parallel} and T_{perp} and relation to anisotropic heating in solar plasma.
- Further study of turbulent cascade and its relation to ion heating.
- Conclude studies of viscous dissipation of tearing modes.