Ion Heating During Reconnection in the Madison Symmetric Torus

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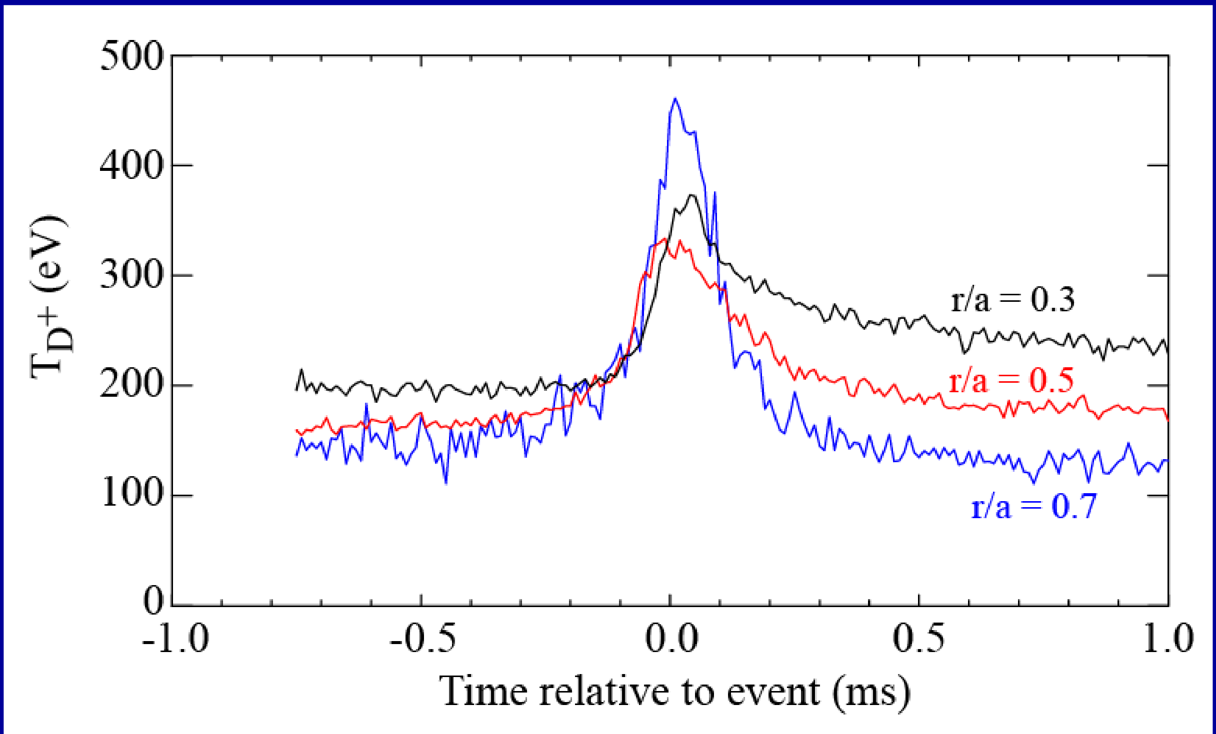
APS-DPP Meeting
November 14, 2007
Orlando, FL

Magnetic energy released during reconnection events can lead to strong ion heating in MST.

$\Delta T_i = 200$ eV
$n_i = 10^{19}$ m^{-3}
$\Delta t = 100$ μs

$\Delta U_{th} \sim 4$ kJ
$P_i > 40$ MW



Note:

$\Delta U_{mag} \sim 20$ kJ

$\Delta U_{th}/\Delta U_{mag} \sim 20$ %

What is the mechanism for this heating?

Overview and Outline

- New beam-based diagnostics provide a new window on the longstanding ion heating problem

- In the Madison Symmetric Torus (MST) we find that ion heating during reconnection events is
    - Concentrated in regions where reconnection is occurring
    - Roughly proportional to the drop in magnetic energy
    - Different for different ion species
    - Largely isotropic

- These observations have rekindled theoretical work on heating mechanisms although none is a clear winner

- Ion heating, coupled to good confinement has been used to generate plasmas with T_e and $T_i > 1$ keV

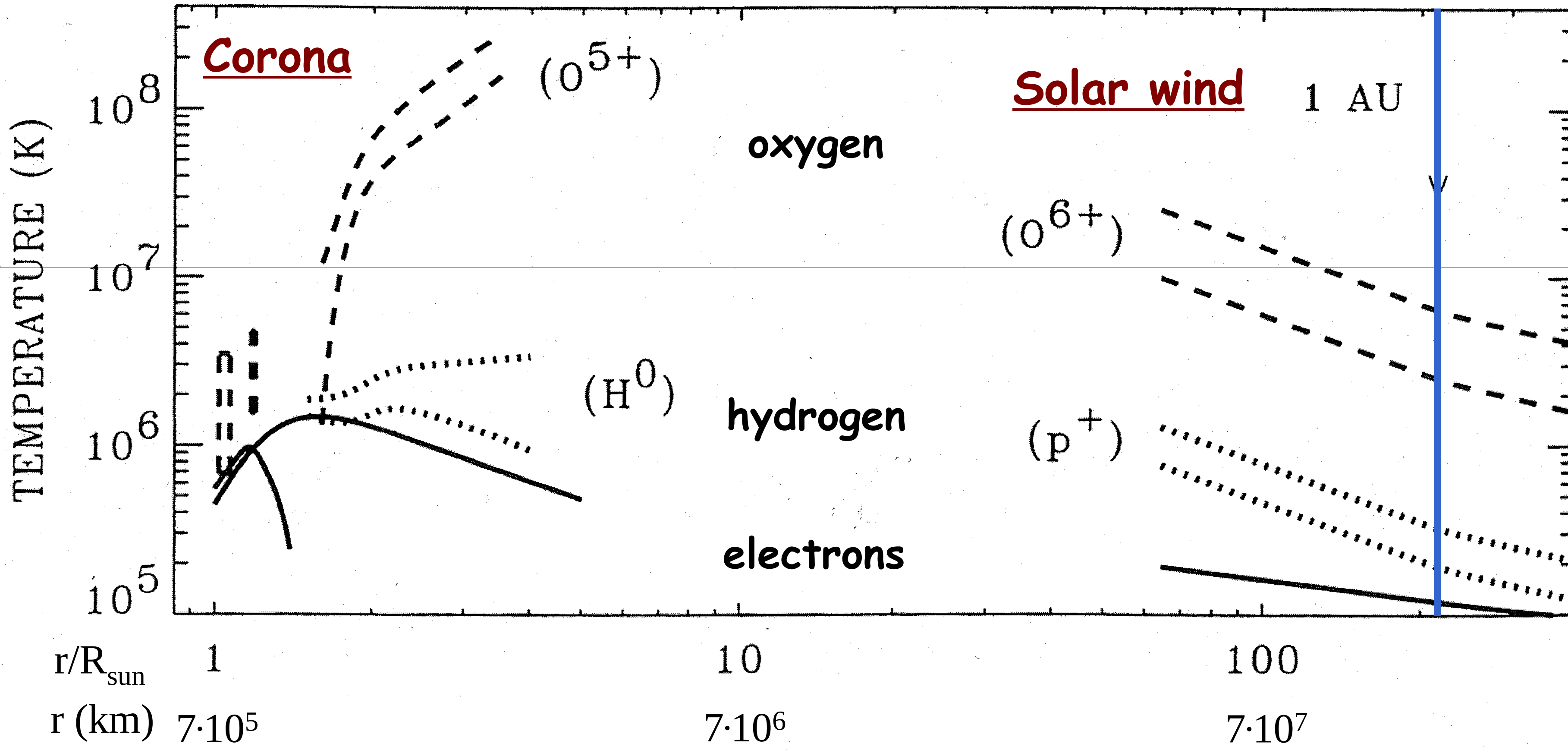
‘Anomalous’ ion heating is common in laboratory plasmas with reconnection.

- Reversed Field Pinch Experiments
  (ZT-40, HBTX, Extrap-T1, Repute, MST)
- Spheromaks (CTX, SPHEX, SSPX)
- Spherical Tokamaks (TST-2, HIT-II)
- Merging experiments (TS-3, SSX, MRX)

- Typical results:
  - $\rightarrow$ T_i greater than expected from collisional coupling to e^-’s
  - $\rightarrow$ $T_i > T_e$ in many cases
  - $\rightarrow$ Efficient conversion of magnetic energy to ion thermal energy (some estimates close to 100%)
  - $\rightarrow$ Heating coincident with MHD activity and reconnection

Ion heating also apparent in the solar corona …

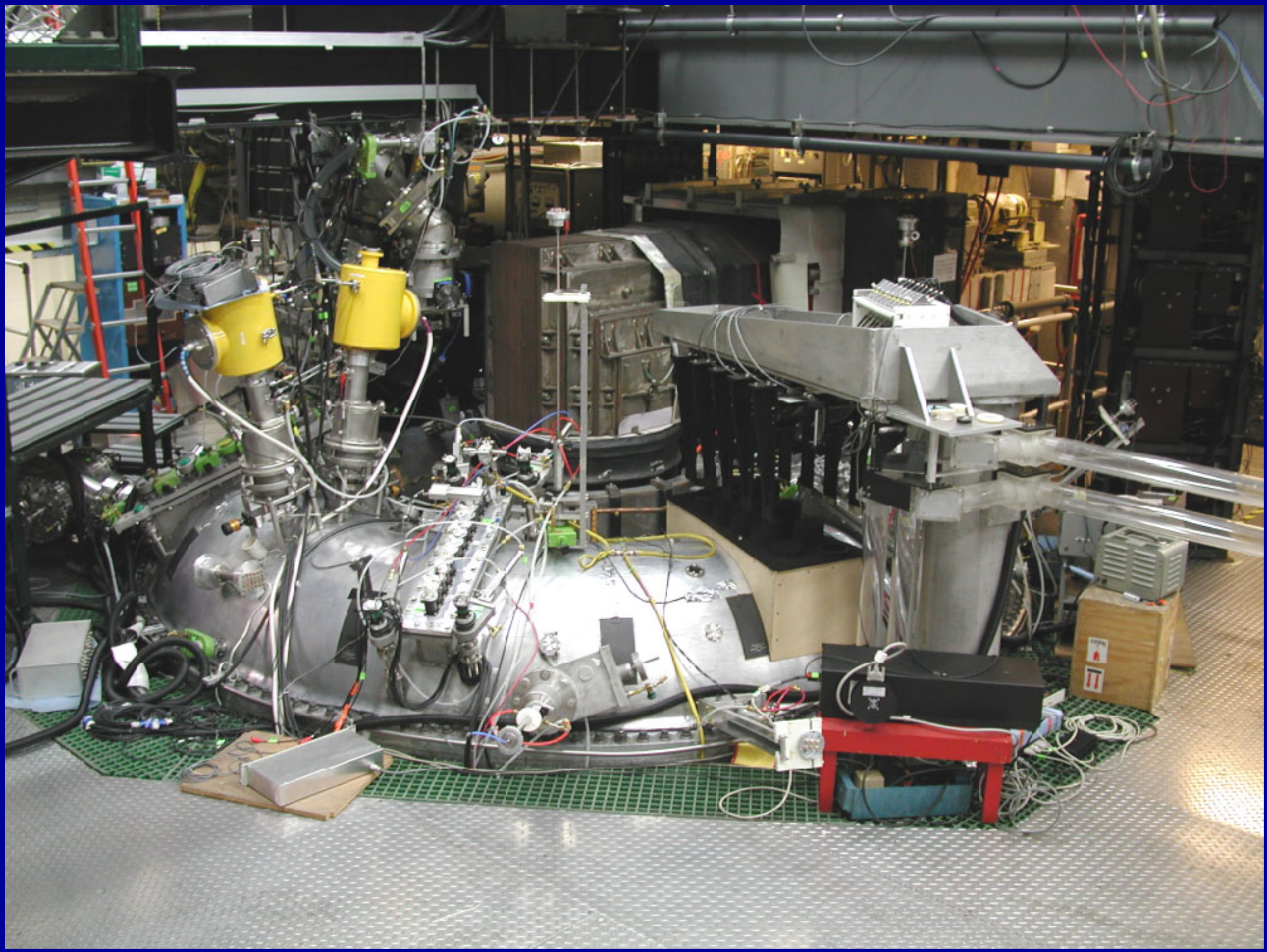
From: Cranmer et al., ApJ (2000); Marsch (1991)



… and in the Earth's magnetosphere

Madison Symmetric Torus (MST)

$R = 1.5$ m	$I_p \leq 600$ kA	$n_e \sim 10^{19}$ m^{-3}	$\beta \leq 26\%$
$a = 0.52$ m	$B \sim 0.5$ T	$T_e = 0.2$ - 2keV	$S \leq 10^7$



Development of two beam-based diagnostics provides new window on ion heating in MST.

1. Charge Exchange Recombination Spectroscopy (CHERS)
   - Impurity ion temperature profiles

2. Rutherford Scattering (RS)
   - Bulk ion temperature profiles

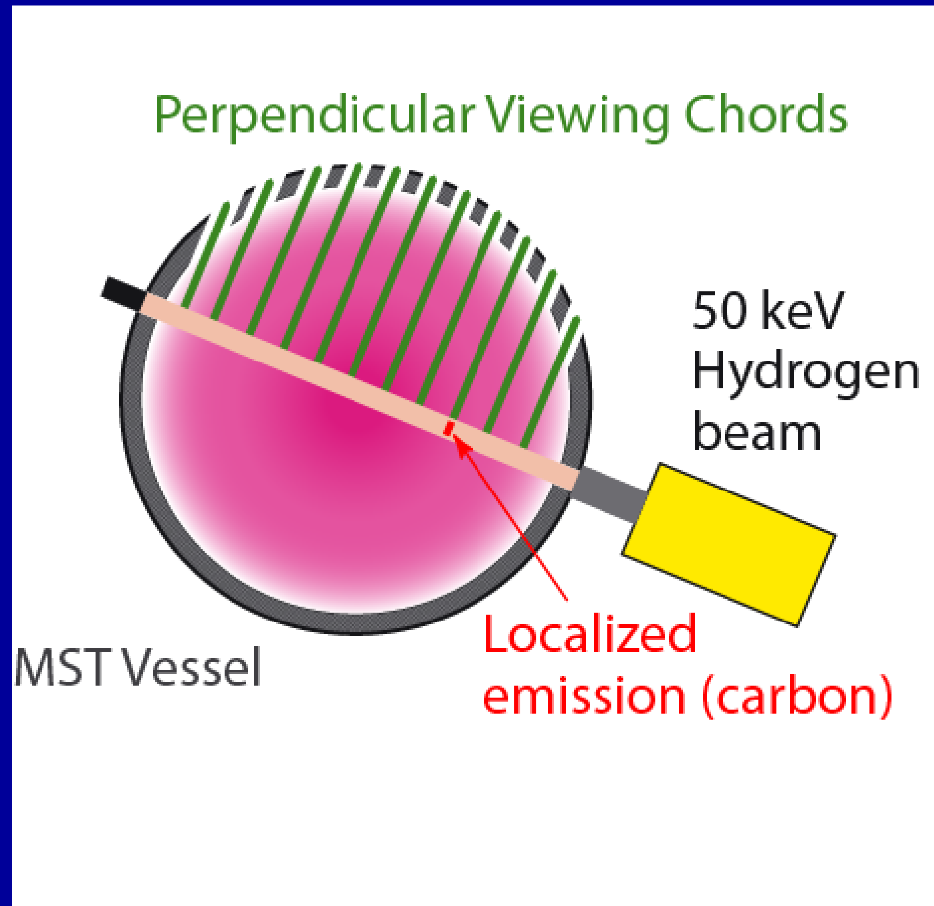
Both diagnostics have excellent time resolution permitting time resolved measurements during reconnection events.

CHERS provides fast localized measurements of impurity ion dynamics.

• Neutral beam atoms undergo CX with impurity ions in plasma

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

• Custom-built spectrometer provides high spectral and temporal resolution



$\Delta r \sim 1$ cm $\quad \Delta t \sim 10\text{-}100\ \mu s$

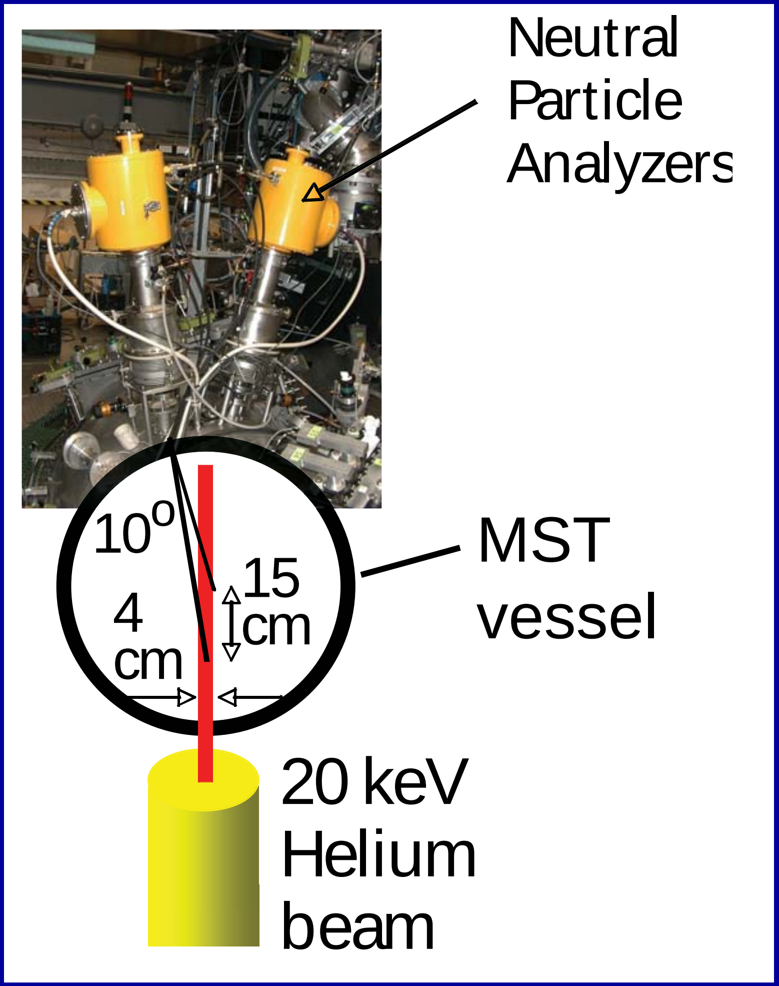
Rutherford Scattering (RS) provides fast localized measurements of bulk ion dynamics.

• Neutral beam atoms scatter elastically from plasma ions

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

• High intensity beam provides high time resolution

$\Delta r \sim 15$ cm $\Delta t \sim 30$ μs



Diagnostics address key questions related to potential mechanisms for ion heating:

- Is there a spatial correspondence between where reconnection occurs and where ion heating occurs in MST?

- How does the ion heating scale with the amount of magnetic energy released during reconnection?

- Are different ion species heated at different rates?

- Is the heating isotropic?

Where does reconnection happen in MST?

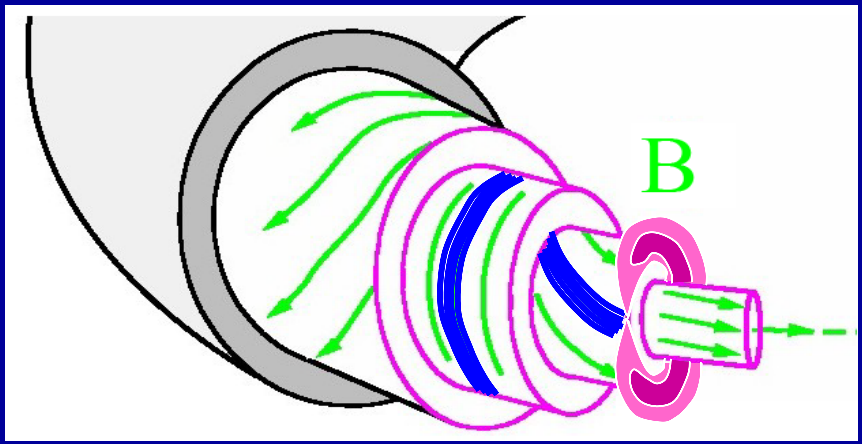
Reconnection occurs on helical strips aligned with B

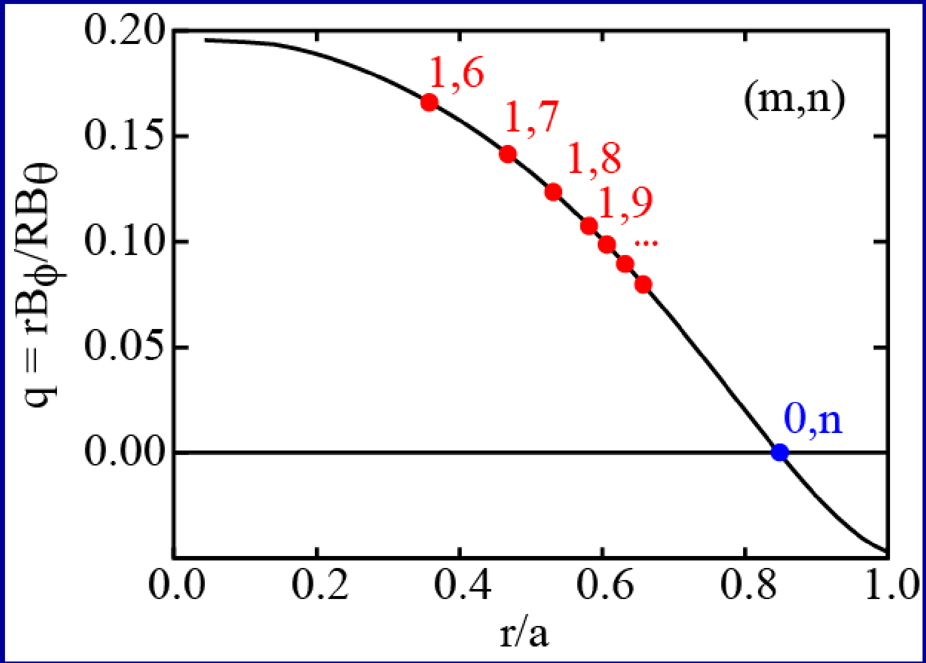
→ x-points of tearing modes

→ most significant for long wavelength modes

→ concentrated at radii where $\mathbf{k} \cdot \mathbf{B} = 0$ (or q = m/n)

→ time changing magnetic fluctuation indicates reconnection at that particular resonant surface





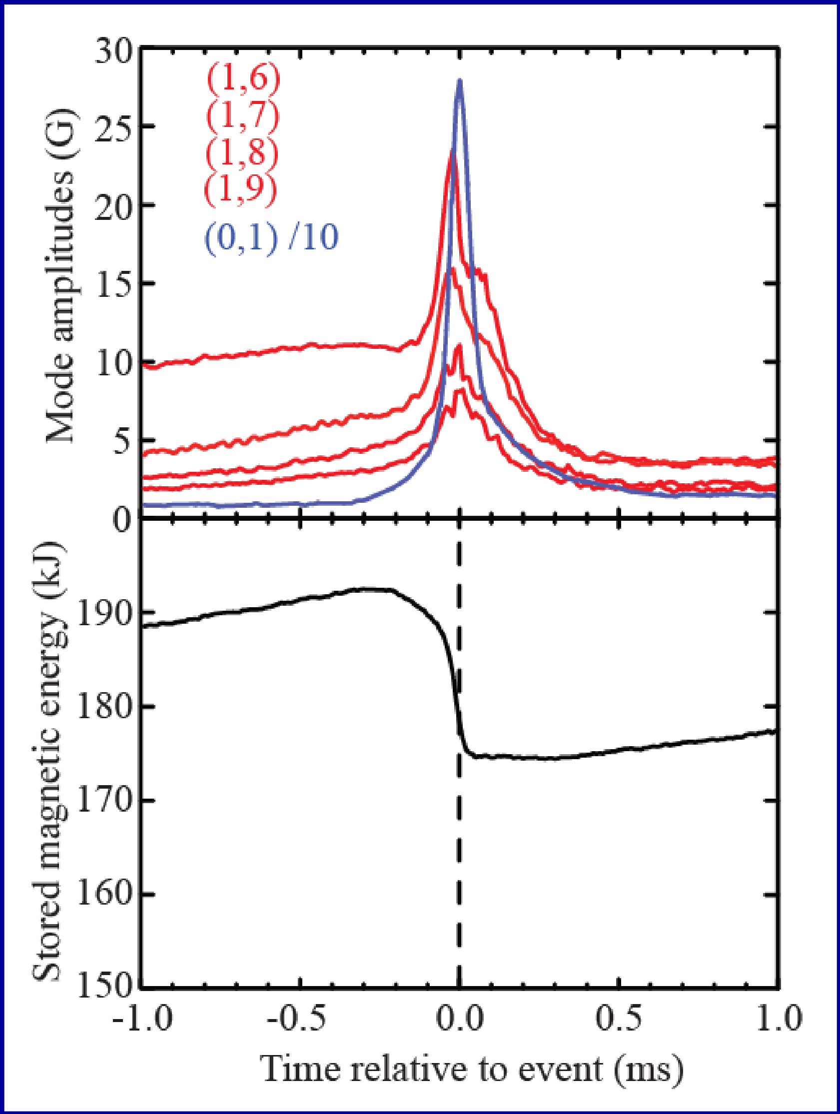
Examine ion heating profile in three different types of reconnection events.

1. Global reconnection event – large drop in U_{mag}

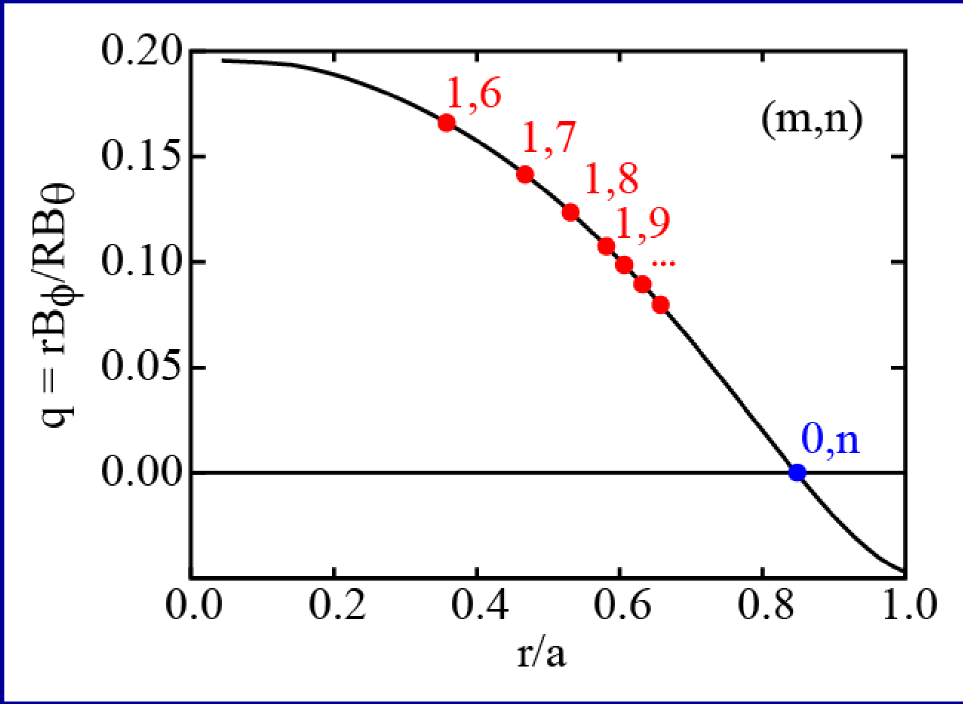
2. Edge reconnection event – small drop in U_{mag}

3. Core reconnection event – no drop in U_{mag}

Global reconnection events involve all tearing modes resonant throughout the plasma.

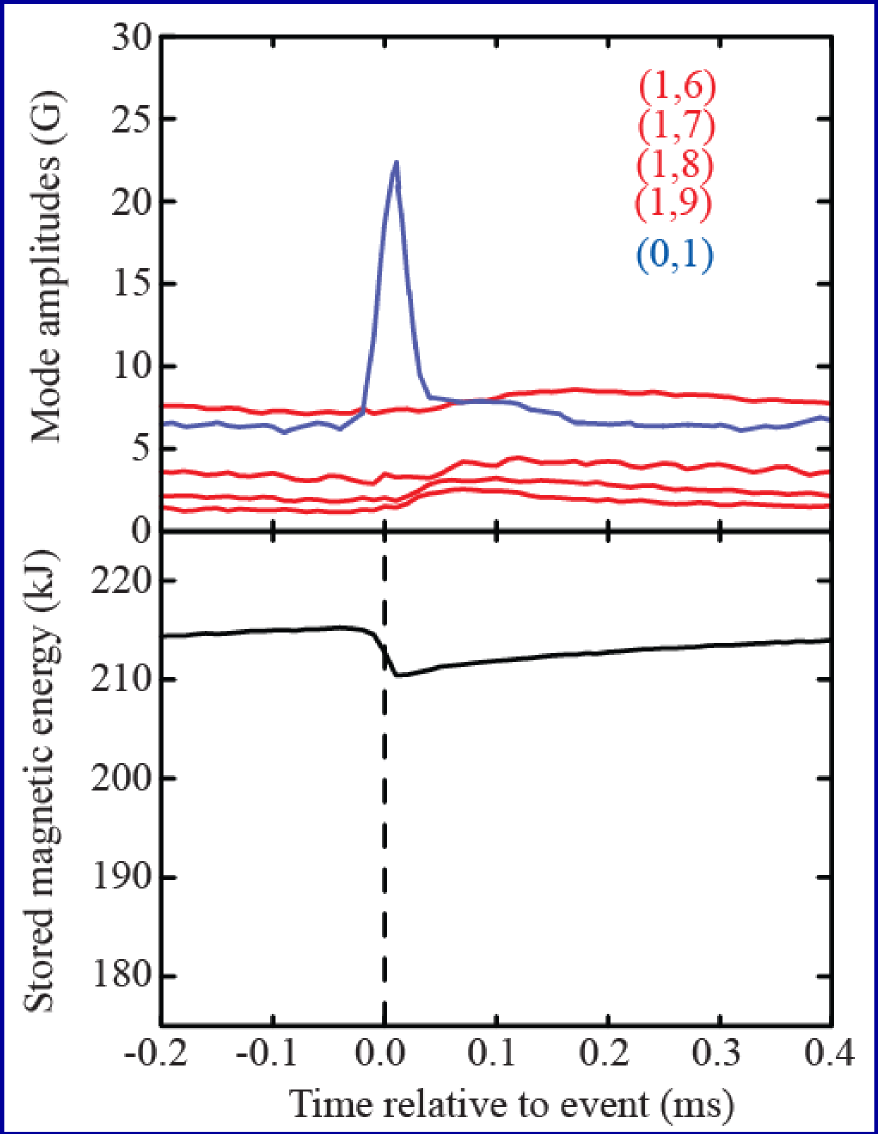


• Reconnection everywhere

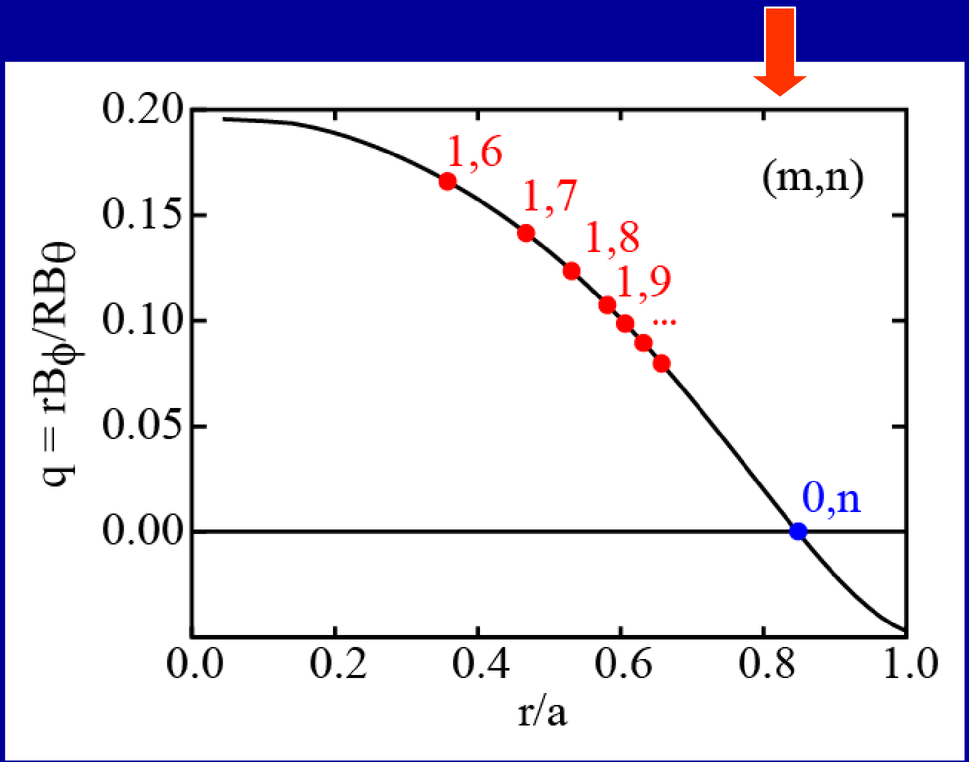


• Large drop in U_{mag}

Edge reconnection events involve only edge resonant tearing modes.

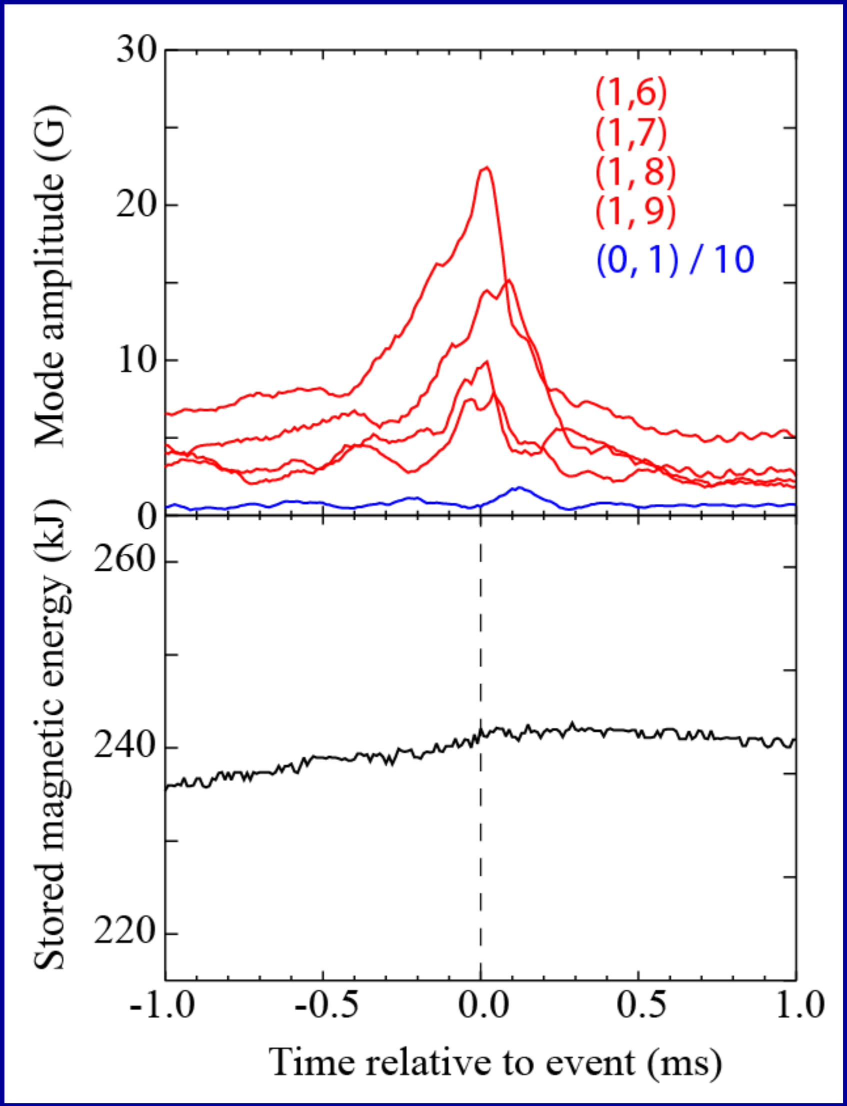


- Reconnection limited to edge

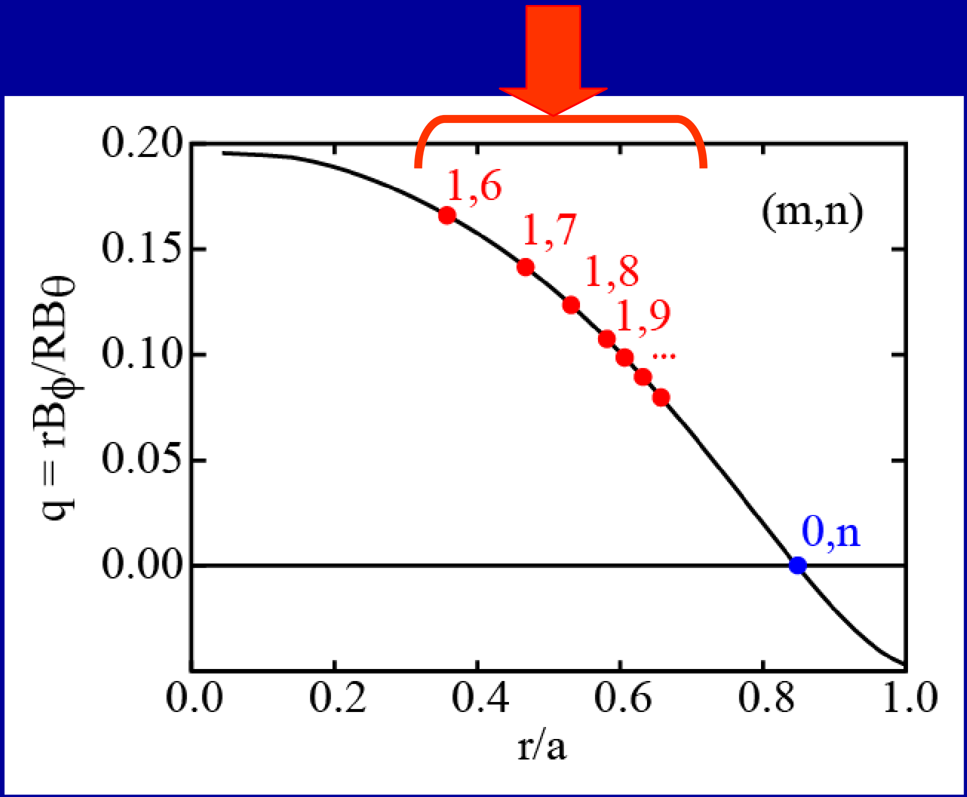


- Small drop in U_{mag}

Core reconnection events involve only core resonant tearing modes.



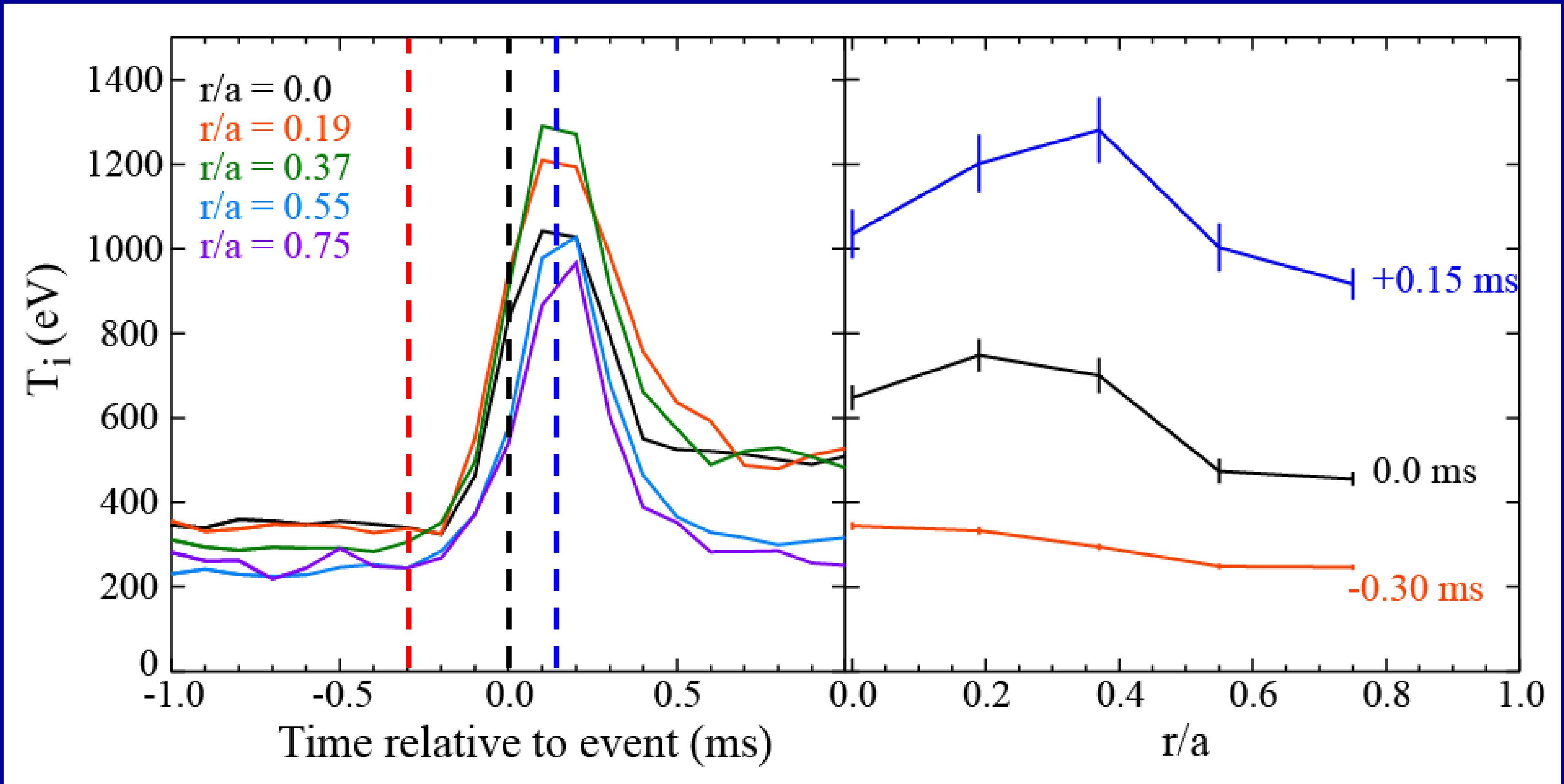
- Reconnection limited to core



- No drop in U_{mag}

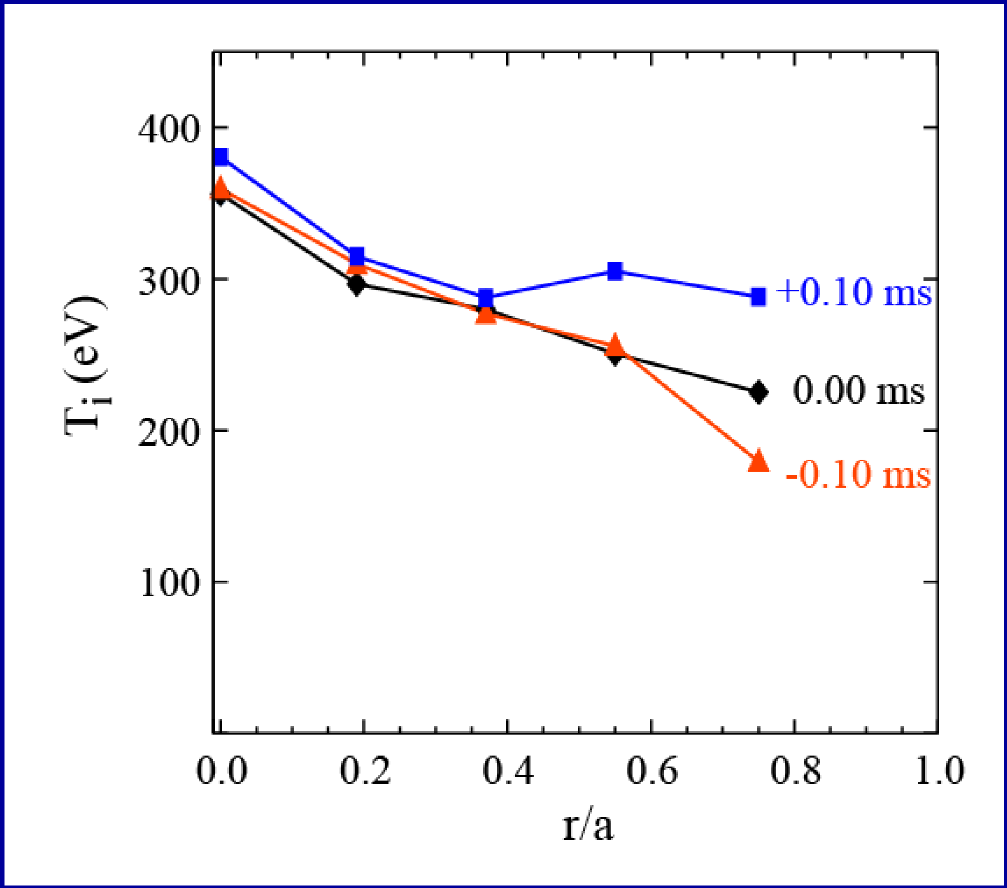
Ion heating is strong and global during global reconnection events.

- Reconnection is occurring at all radii, and drop in U_{mag} is large

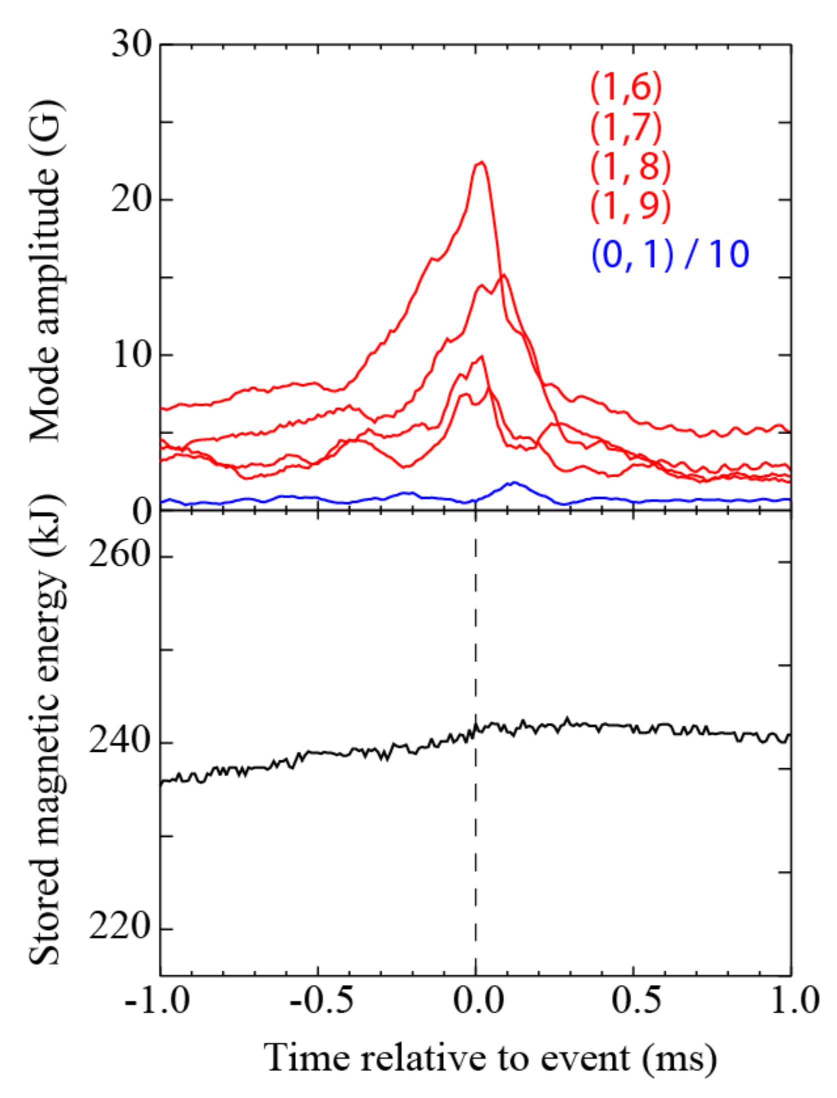


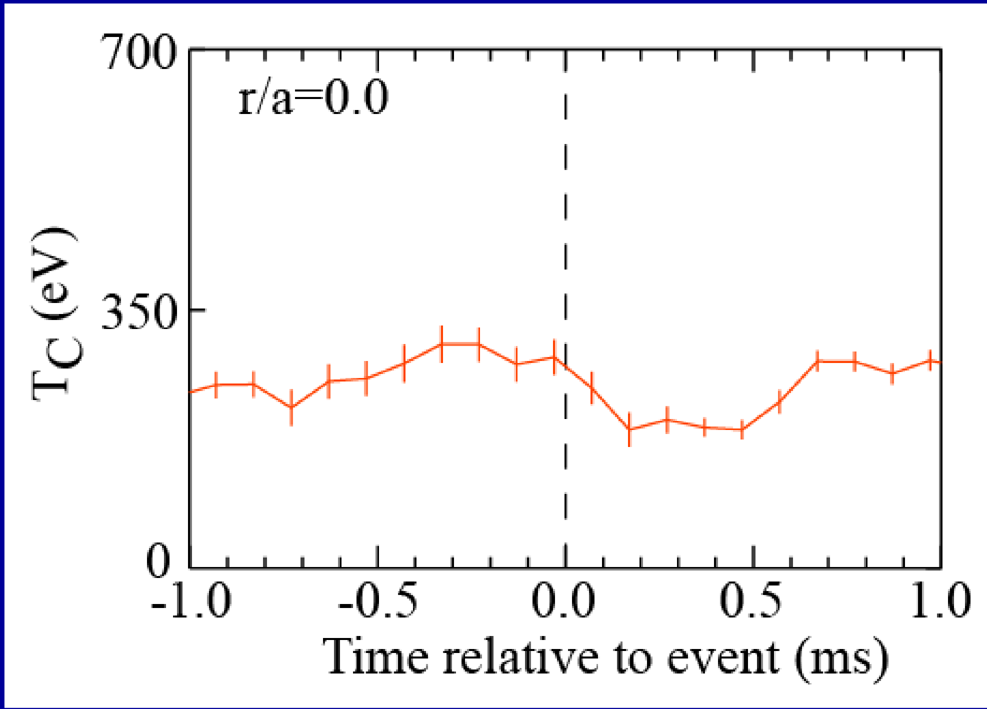
Ion heating is weaker and limited to the edge during edge reconnection events.

- Reconnection only in edge, drop in U_{mag} is small



Ion heating is absent during core-only reconnection events in which ΔU_{mag}=0



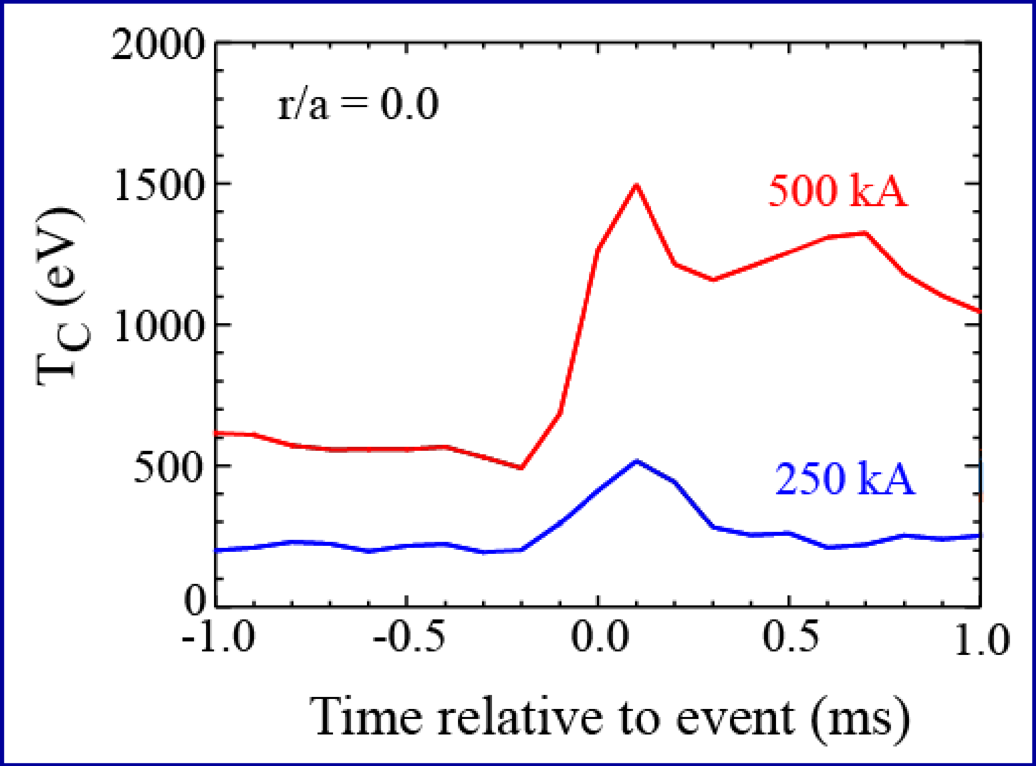


ΔU_{th} is closely tied to ΔU_{mag}

- ΔU_{mag} varies for different types of reconnection events

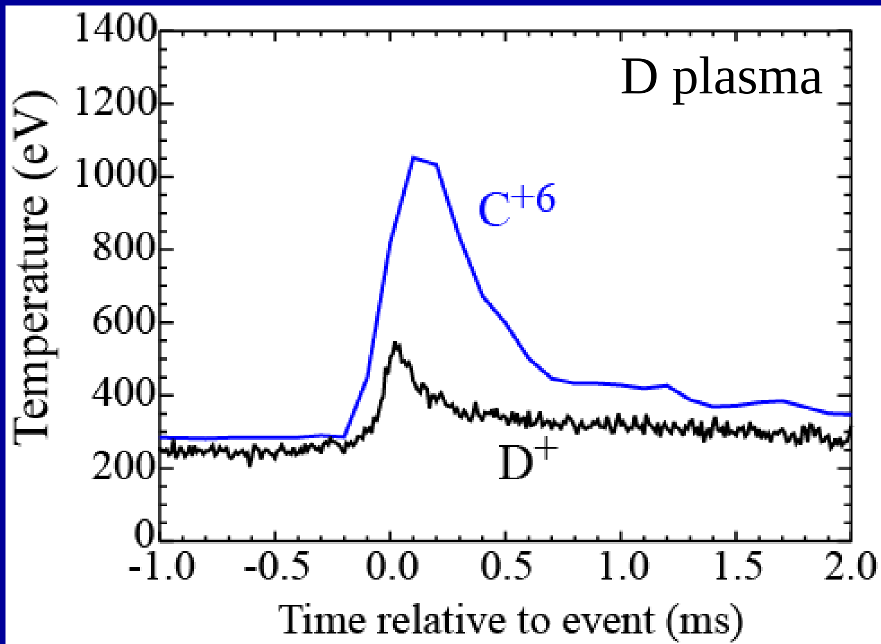
  Global > Edge > Core

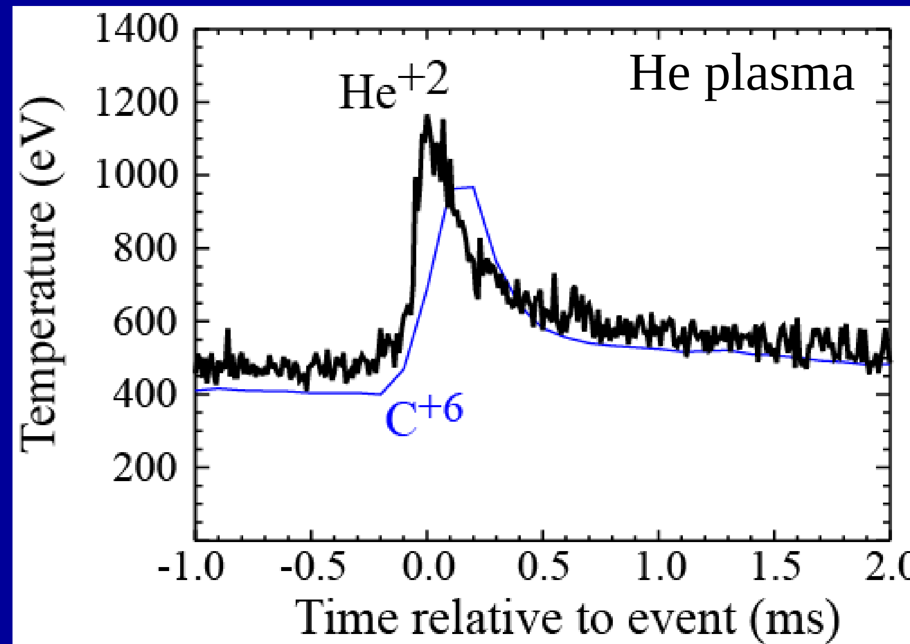
- ΔU_{th} follows this ordering
- ΔU_{mag} and ΔU_{th} also strongly dependent on plasma current



- $\Delta U_{th}/\Delta U_{mag}$ = 10-20% over a wide range of plasma current and density

Carbon and Helium temperature rise is much higher than that of Deuterium ions.

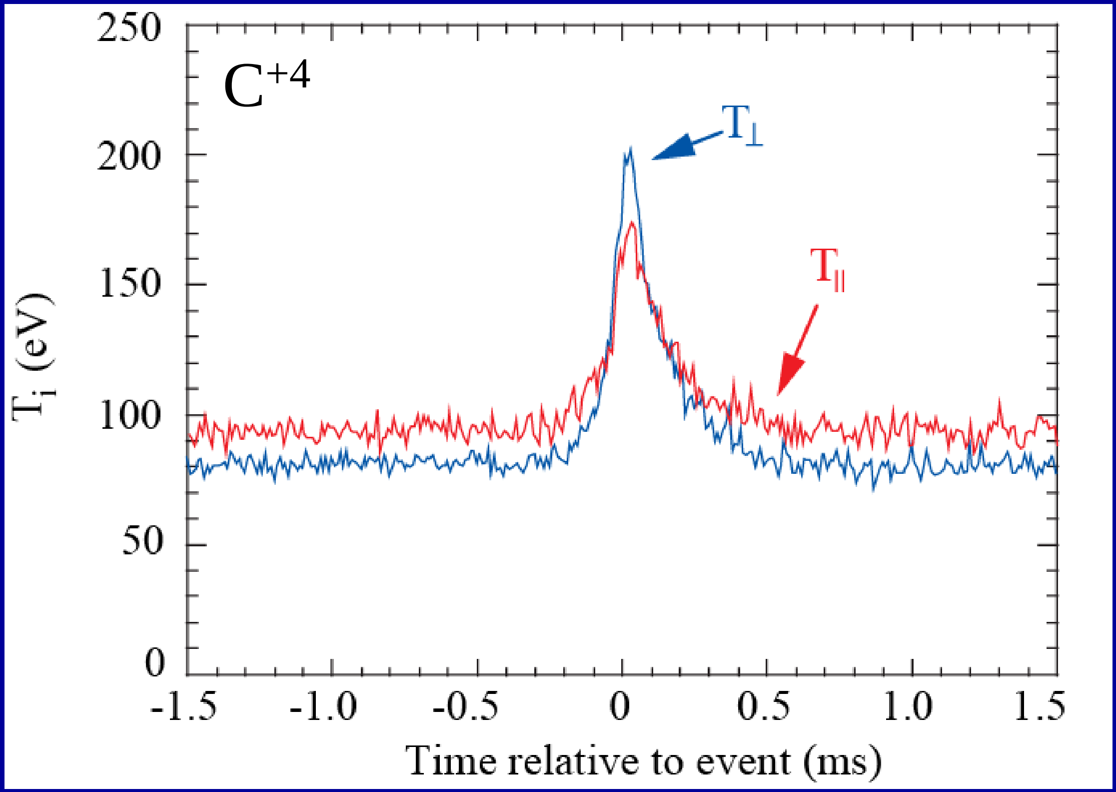




- Heating may be charge and/or mass dependent
- Note: q/m = 2 for all three species
- Energy loss for D^{+} is larger than for He^{+2} and C^{+6} (CX loss) but too small to explain this difference

Ion heating is largely isotropic in MST.

- Passive Doppler measures global increase in $T_\perp$ and $T_\|$



- Efforts underway to obtain localized $T_\perp$ vs $T_\|$ comparison
  - CHERS and RS currently measure $T_\perp$ in core and $T_\|$ in edge

Viscous damping of tearing mode flows is a potential mechanism for ion heating in MST.

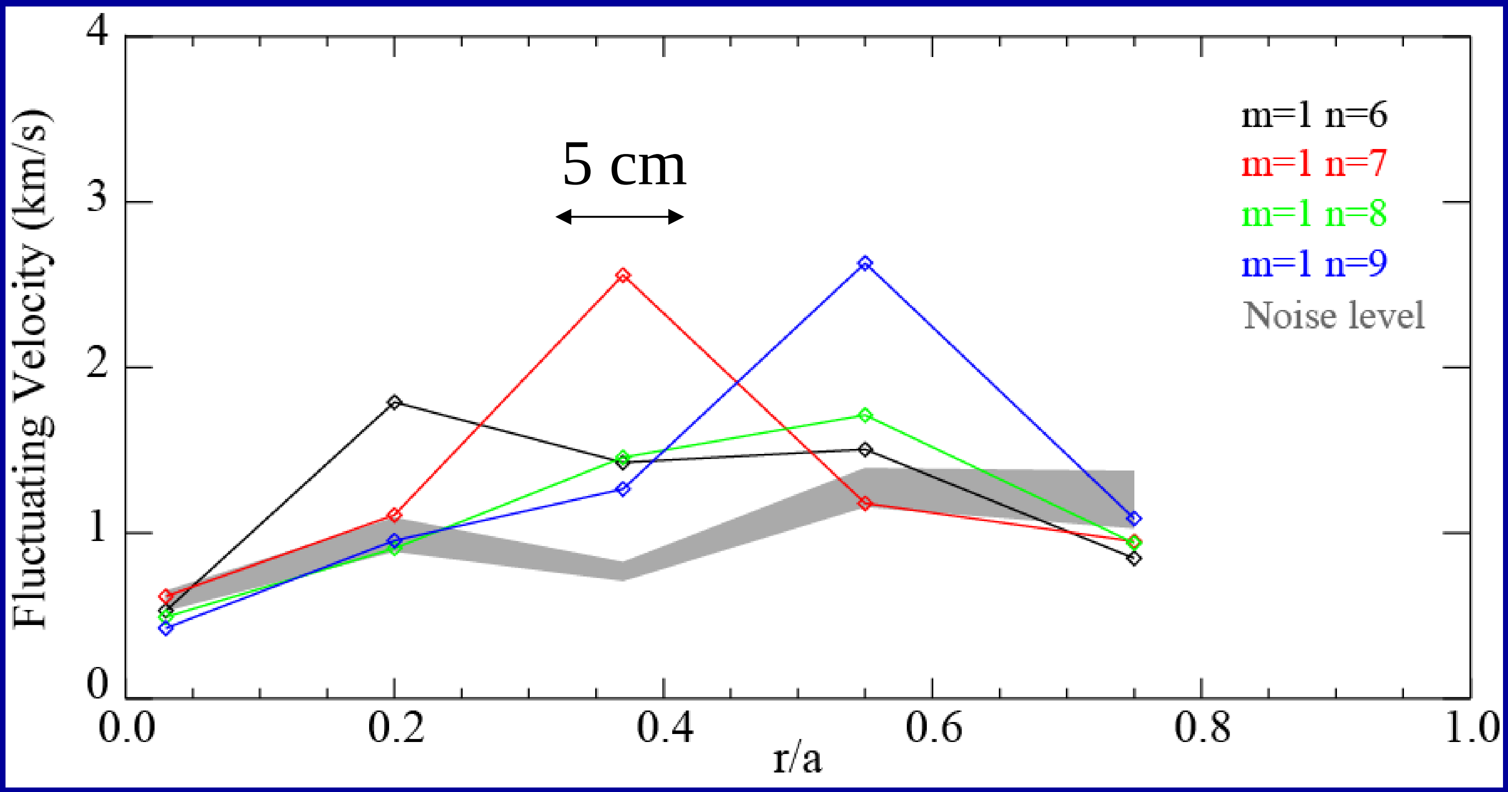
• Suggested early on for RFP ion heating *(Gimblett)*

• Damping by perpendicular viscosity requires $v \sim v_{th}$ with structure on the scale of the ion gyroradius *(Svidzinski & Mirnov)*

• Damping by parallel viscosity could be large if have significant flow variation along field lines

CHERS is also able to resolve tearing mode flow fluctuation profiles.

- Flows have radial structure with Δr ~ 5-10 cm ($> \rho_i$ ~ 1 cm)
- Flow is well below thermal speed (v_{th} ~ 50-100 km/s)
- Measured modes appear too small for significant heating
  - May be other small scale flows not yet measured



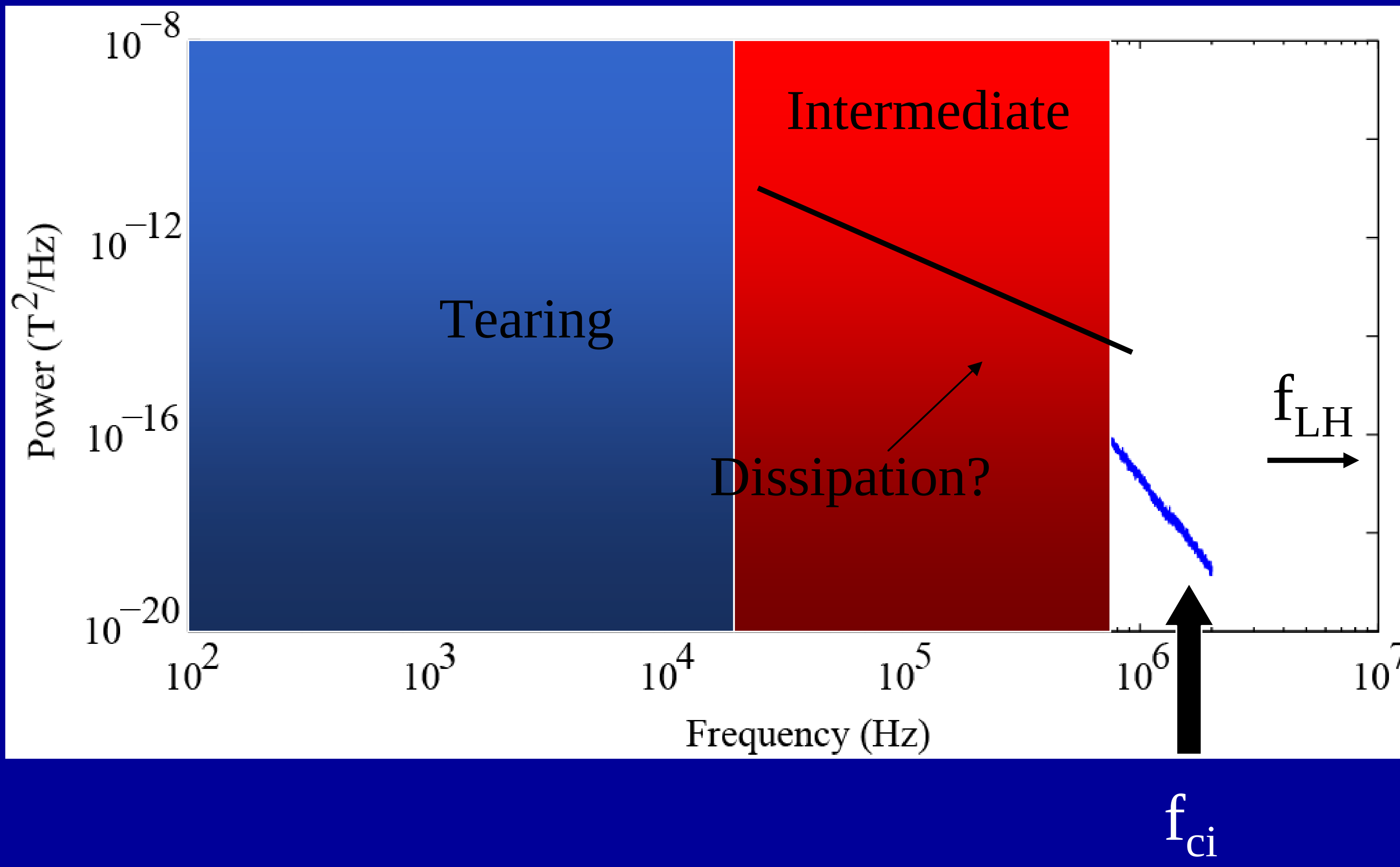
Several wave mechanisms have also been proposed for ion heating.

- Nonlinear cascade of tearing mode fluctuations to ion cyclotron frequency *(Mattor and Terry; Tangri and Terry)*
  - Favors $T_\perp$ but see isotropic heating
  - Impurities make heating stronger, and enhance collisionality

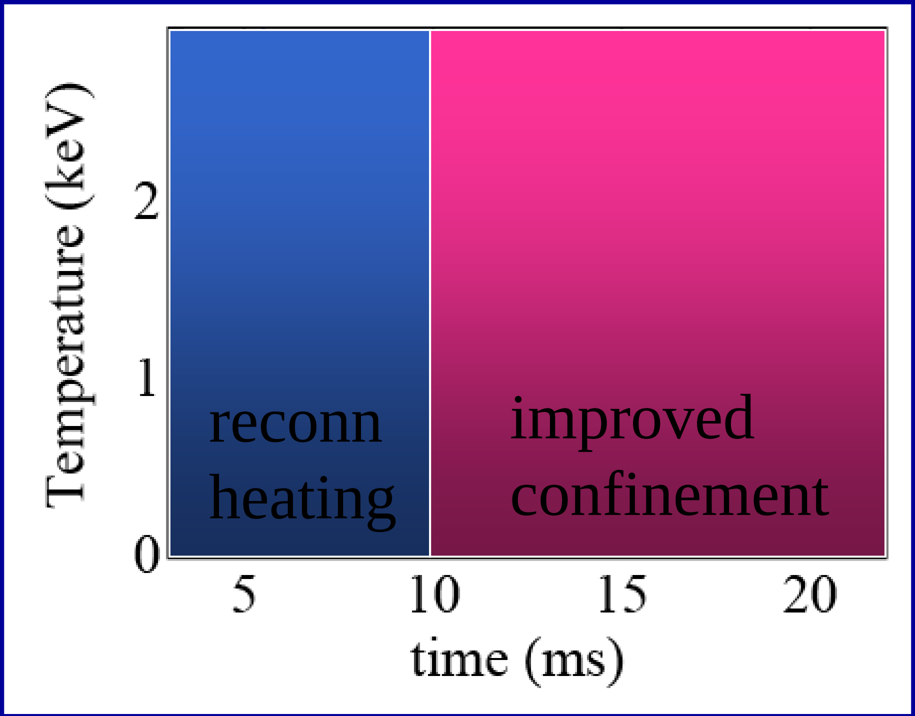
- Nonlinear cascade to intermediate scales where $k\rho_i \sim 1$
  - Favors impurities

- Waves may preferentially appear near reconnection sites

Broad spectrum of magnetic flucutations is observed in MST.



Ion heating can be coupled to plasmas with improved electron confinement to produce T_e and T_i > 1 keV



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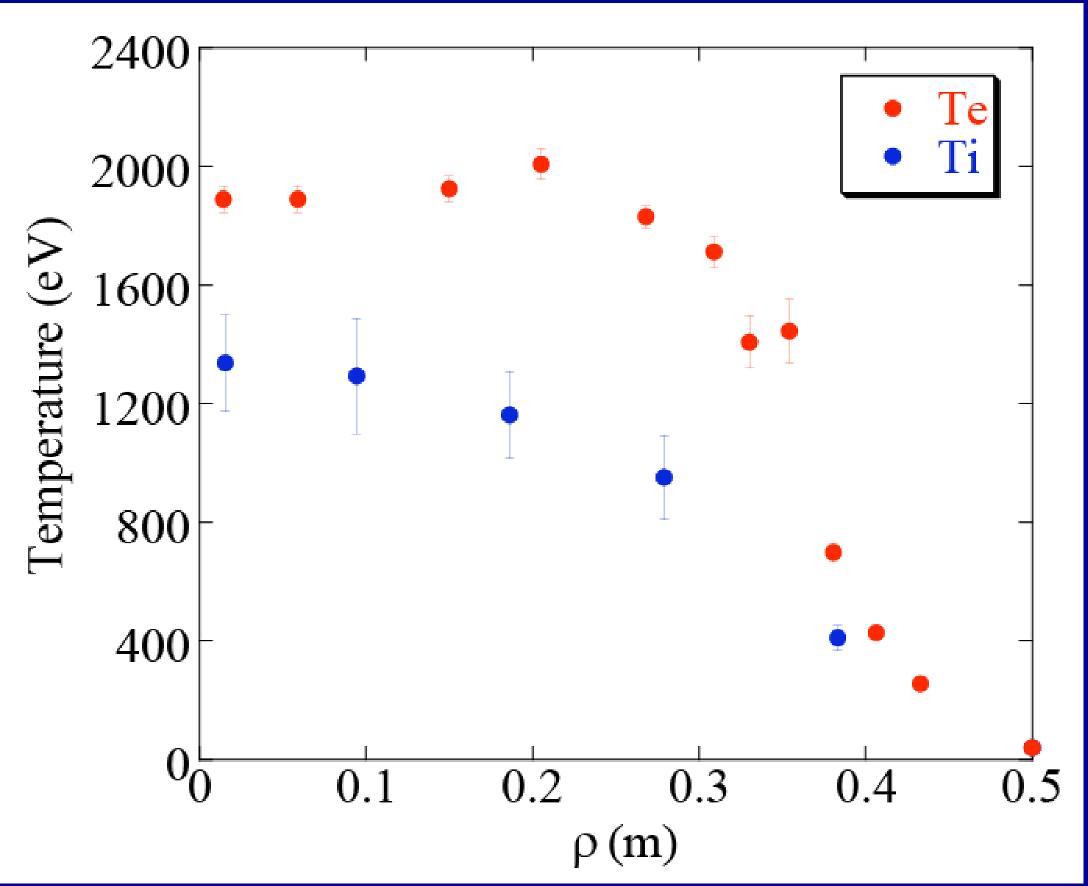

Summary

- Ion heating problem in RFP is longstanding and bears remarkable similarities to ion heating in other venues where reconnection is taking place

- Ion heating in MST during reconnection events is
  - Concentrated in regions where reconnection is occurring
  - Proportional to drop in magnetic energy
  - Different for different ion species
  - Largely isotropic

- Ion heating by reconnection can be captured to produce plasmas with T_i and T_e both > 1 keV

- No single mechanism for the heating is a clear winner – multiple mechanisms active at the same time?