Ion Heating on the Madison Symmetric Torus

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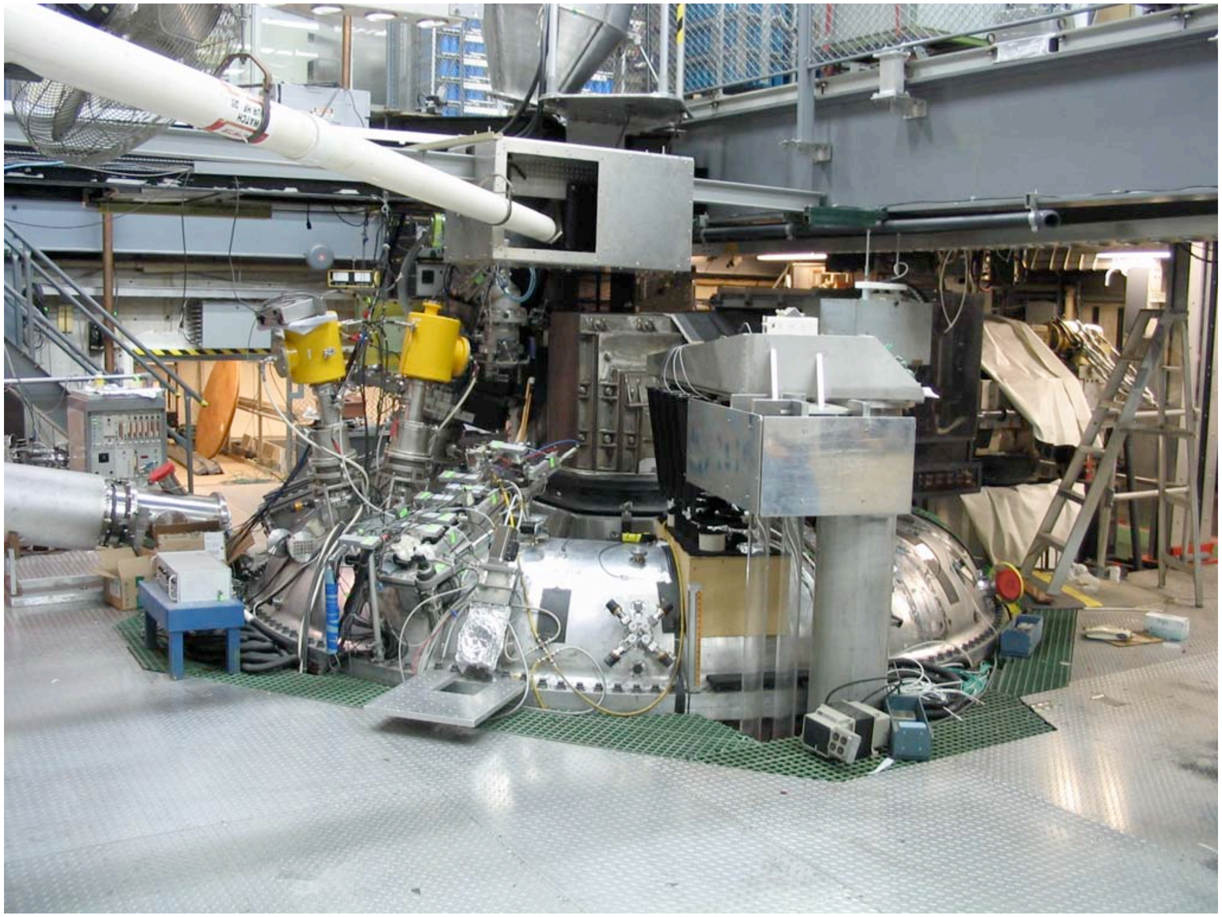
Outline

1. MST Overview
2. MST Diagnostics
3. Observations of Ion Heating on MST
4. Observations of Ion Heating in Astrophysics
5. Associated Observations
6. Proposed Explanations
7. Summary and Conclusions

The MST Experiment

(University of Wisconsin--Madison)



Major Radius:
R=1.5 m

Minor radius:
r=0.52 m

Plasma density:
$n_e < 4 \times 10^{13}$/cc

Electron Temperature:
$T_e < 1$ KeV

Pulse Length < 80ms

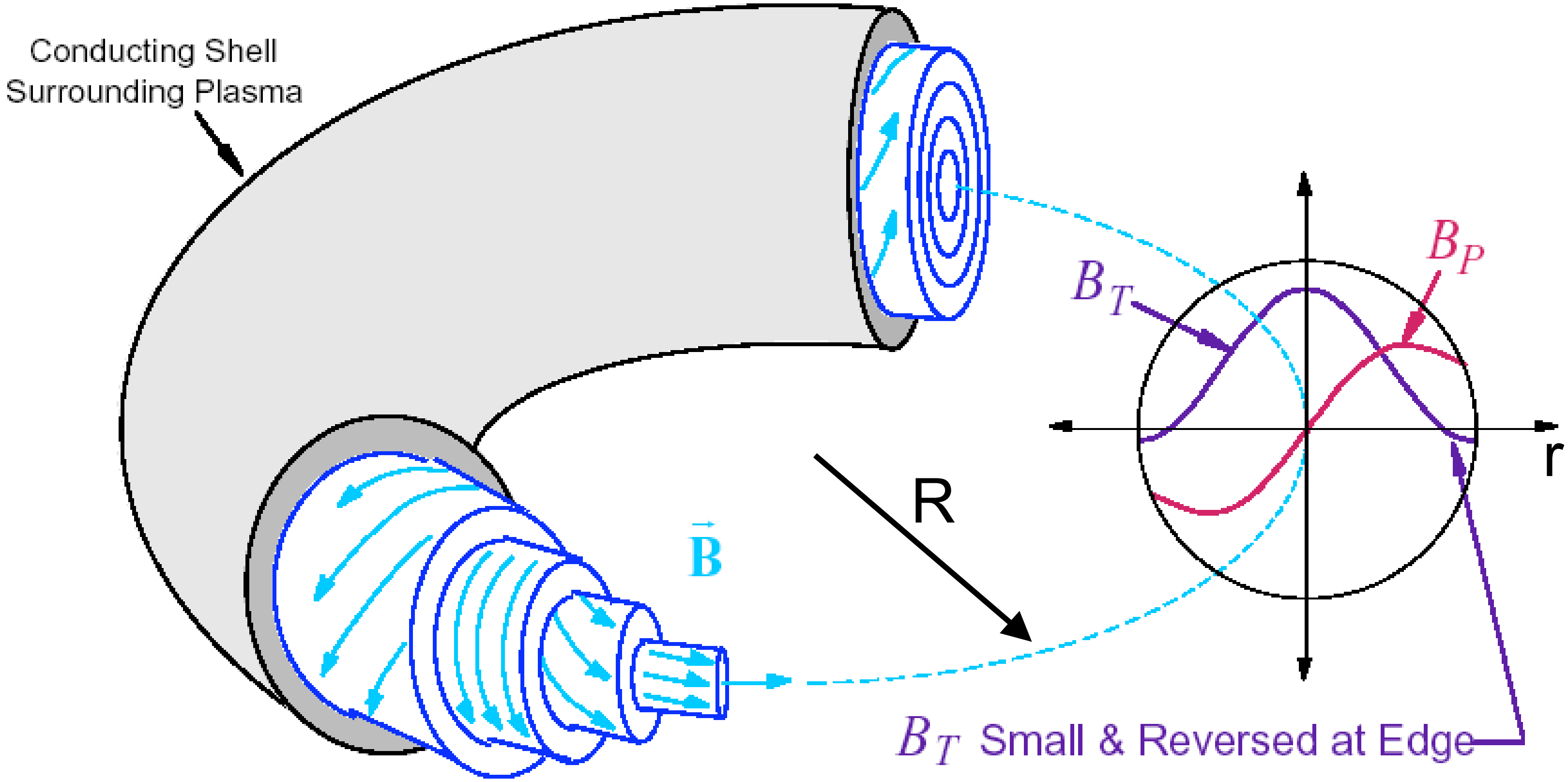
Heating: Ohmic

Dexter et al., Fusion Tech., **19**, 131 (1991)

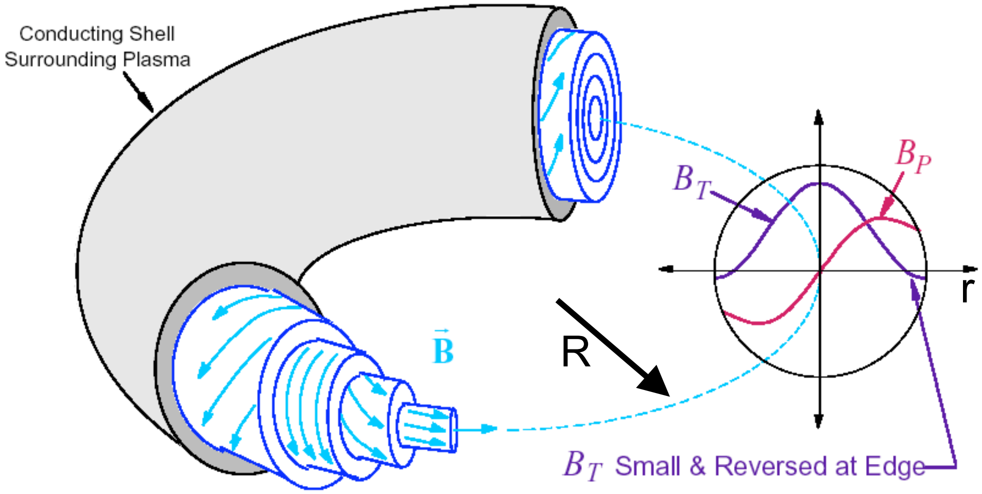
MST Magnetic Geometry

In Equilibrium

Reversed field pinch

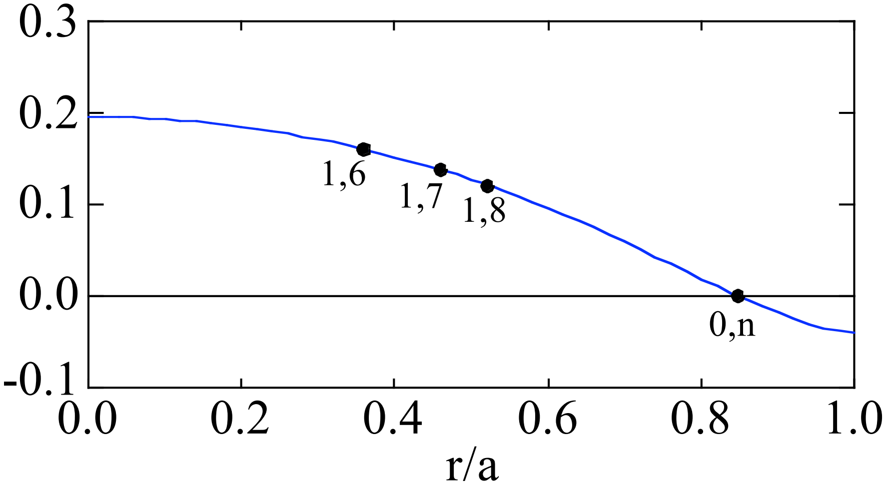


MST Magnetic Geometry



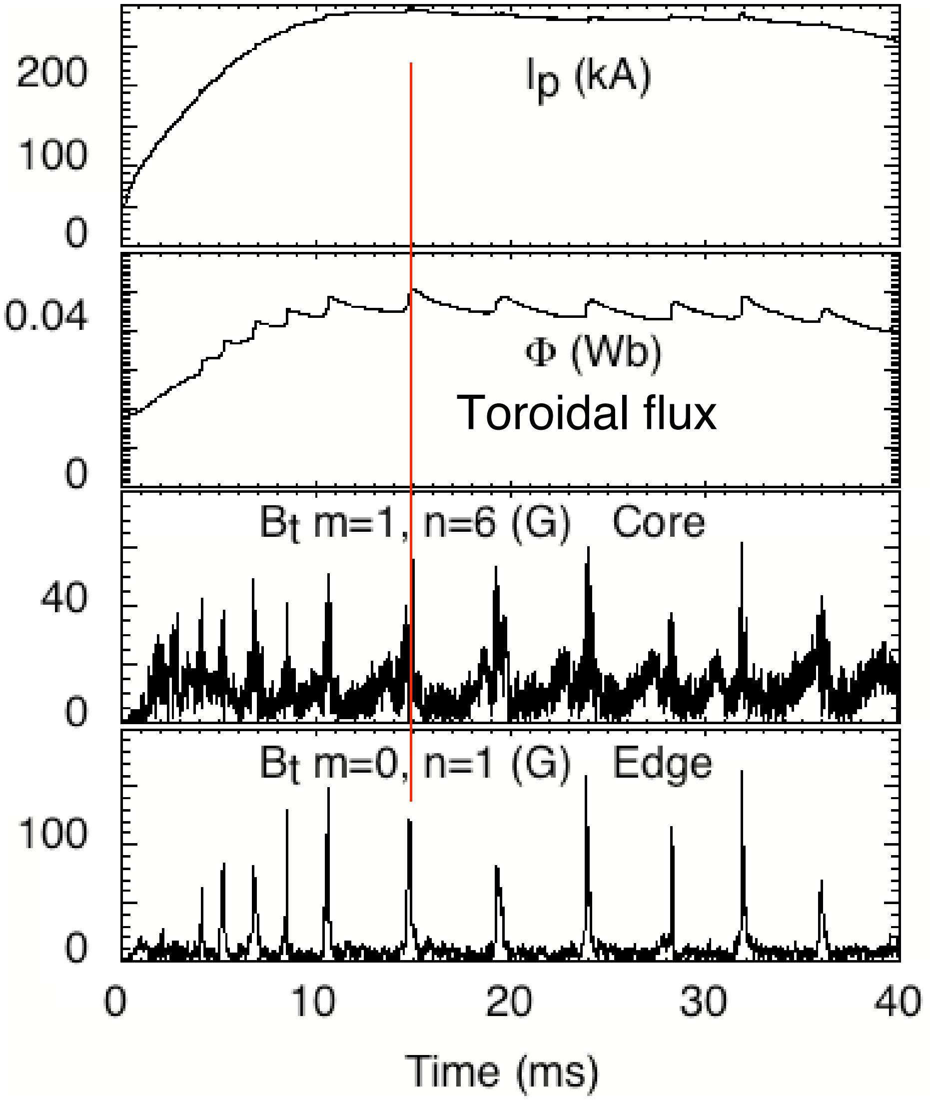
At certain values of r, magnetic field lines have finite length: “rational surfaces”

$$q = \frac{rB_t}{RB_p}$$



Tearing mode perturbations are unstable on rational surfaces

Typical MST Plasma



Inductively-driven toroidal plasma current

Discrete dynamo events turn poloidal flux into toroidal flux

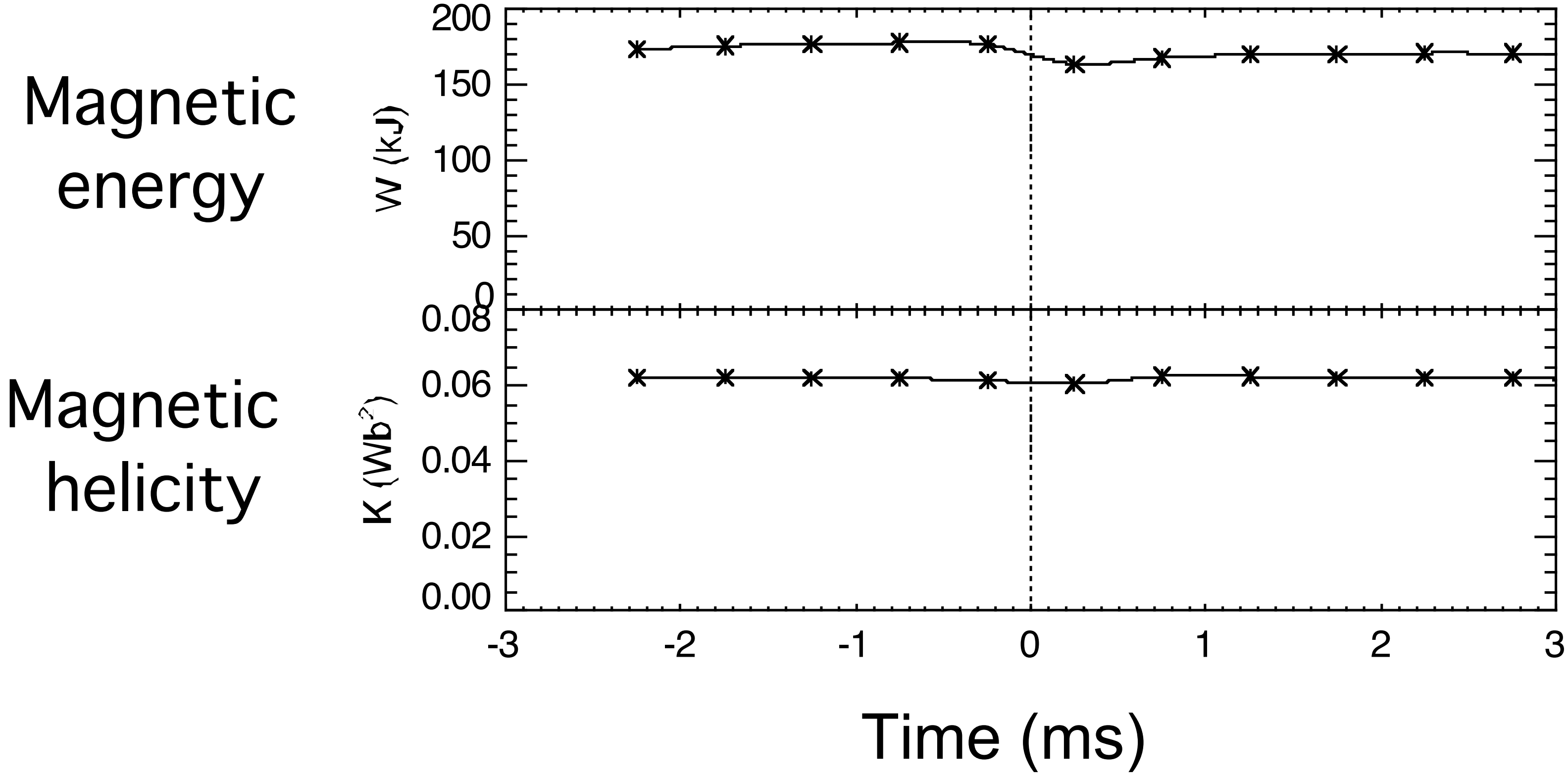
Large tearing mode fluctuations are observed to be indispensable to sustainment of plasma

Single Fluid / Taylor Relaxation

(J.B. Taylor, *PRL* **33** ,1139 (1974))

Global magnetic helicity ($K_m = \int A \cdot B \, dV$) “conserved”

- Plasma relaxes to minimum magnetic energy holding K_m fixed
  (happens via $\tilde{v} \times \tilde{b}$ in MHD)
- Relaxation only occurs when fluctuations are strong



MST Temperature Diagnostics

TS: Thomson Scattering (electron)

- Time resolution 100 ns, limited by counting statistics
- Spatial resolution +/- 4 cm (centered at r/a =0.0)
- Signal increases with density and decreases with temperature

RS: Rutherford Scattering (Deuterium)

- Time resolution ~30 μs, limited by plasma electrical noise
- Spatial resolution +/- 7 cm
- Signal increases with density and decreases with temperature

IDS: Impurity Dynamics Spectrometer (C^V Line Emission)

- Time resolution ~10 μs, limited by digitization
- emitting region can be far from the core and move during the shot
- T_{IMP} calculated from average of anti-parallel tangential views

MST Temperature Diagnostics
(continued)

Charge Exchange Recombination Scattering (Deuterium)

- Time resolution 100 μs
- Spatial resolution +/- 4 cm

Neutron Detection (Deuterium)

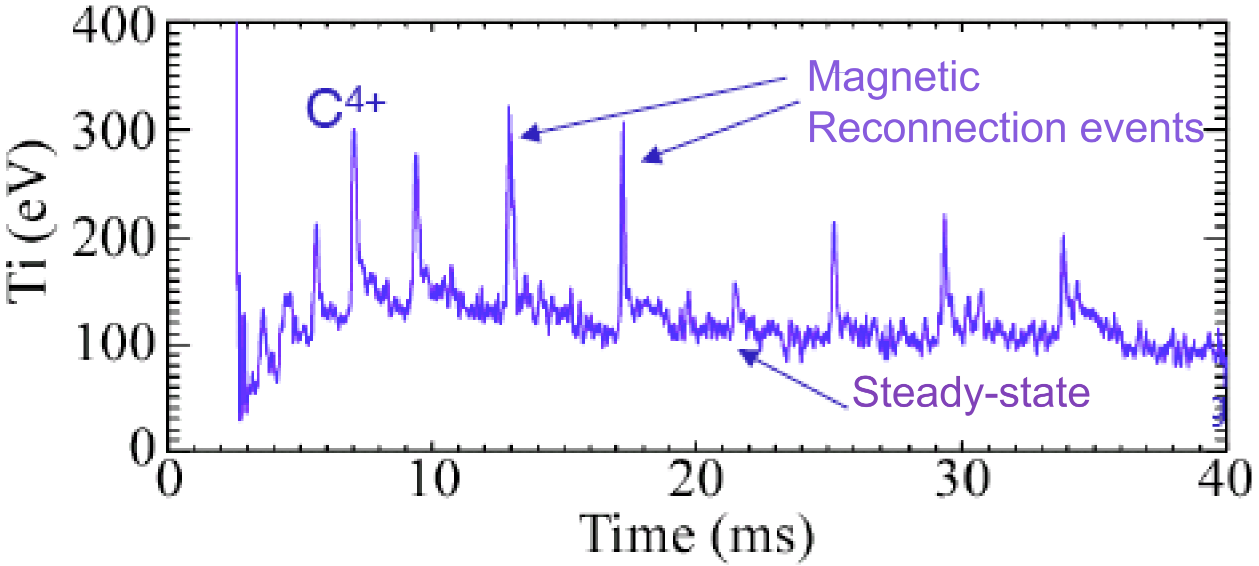
- Time resolution 10 μs
- global measurement of fusion rate
- absolute calibration rate 5 x 10^9 n/s/V, to within a factor of two

No longer operational:
Passive Charge Exchange (Hydrogen or deuterium)

See Scime et al., Phys. Fluids B **4**, 4062 (1992) for observations of Ion heating using the passive charge exchange diagnostic.

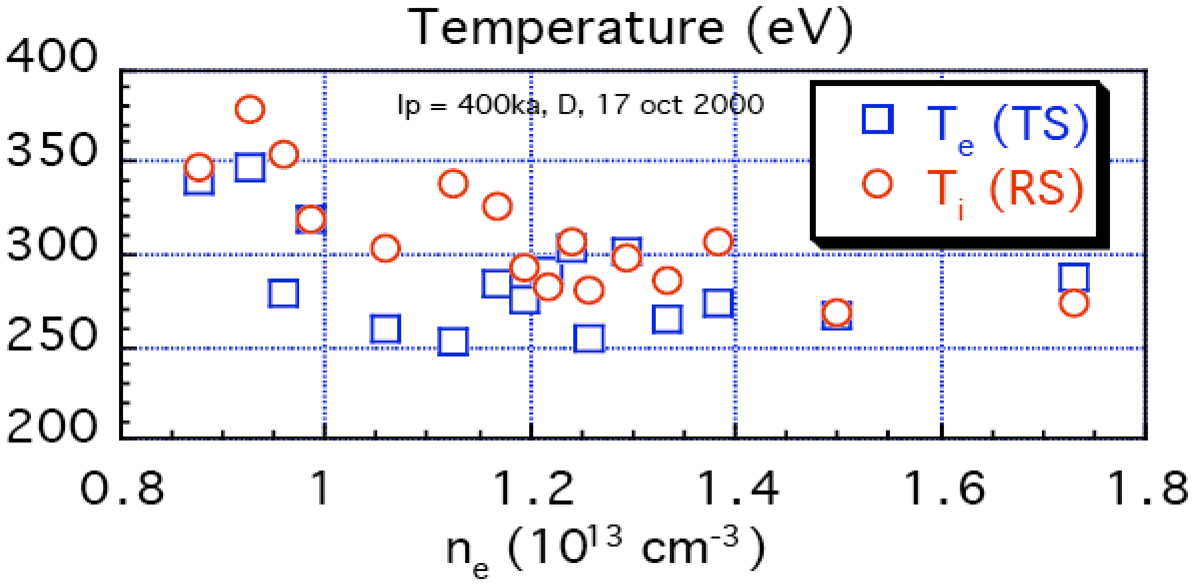
Typical MST Ion Temperature Data

IDS Measurement:



Ion temperature suddenly doubles (without the experimenter doing anything!) at Magnetic Reconnection Events (MREs).

Steady-state $T_i \sim T_e$ in MST



Cannot be explained by electron-ion collisions:

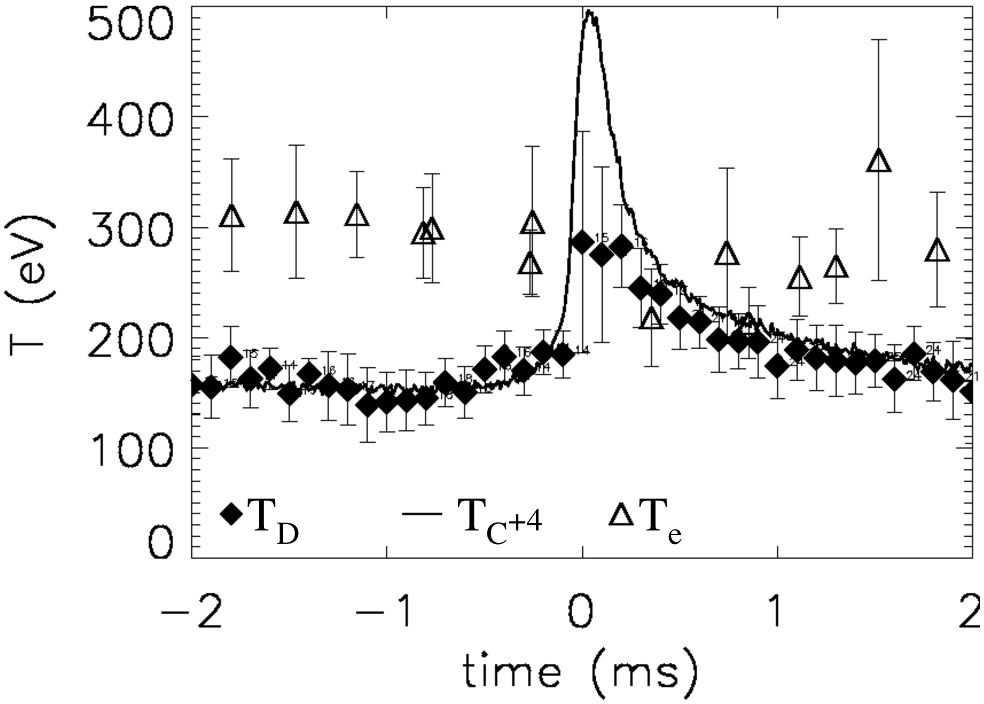
$$Q_\alpha = \frac{3m_e}{m_i}\frac{nk}{\tau_e}(T_e - T_i)$$

$$\tau_e = \frac{3\sqrt{m_e}(kT_e)^{3/2}}{4\sqrt{2\pi}n\lambda e^4} = 3.44\times10^5\frac{T_e^{3/2}}{n\lambda}\sec$$

} Imply $T_i < T_e$

Ion Heating at Magnetic Reconnection Event

T_D from Rutherford scattering (RS) at $0.4 < r/a < 0.5$ (35 crashes, on 2 June 2001)
$T_{C^{+4}}$ from Doppler emission (IDS) (from C^{+4}) $0.3 < r/a < 0.6$ (352 crashes, on 4 July 2001)
T_e from Thomson scattering (TS) at $0.4 < r/a < 0.5$ (~60 crashes, Nov 2000)

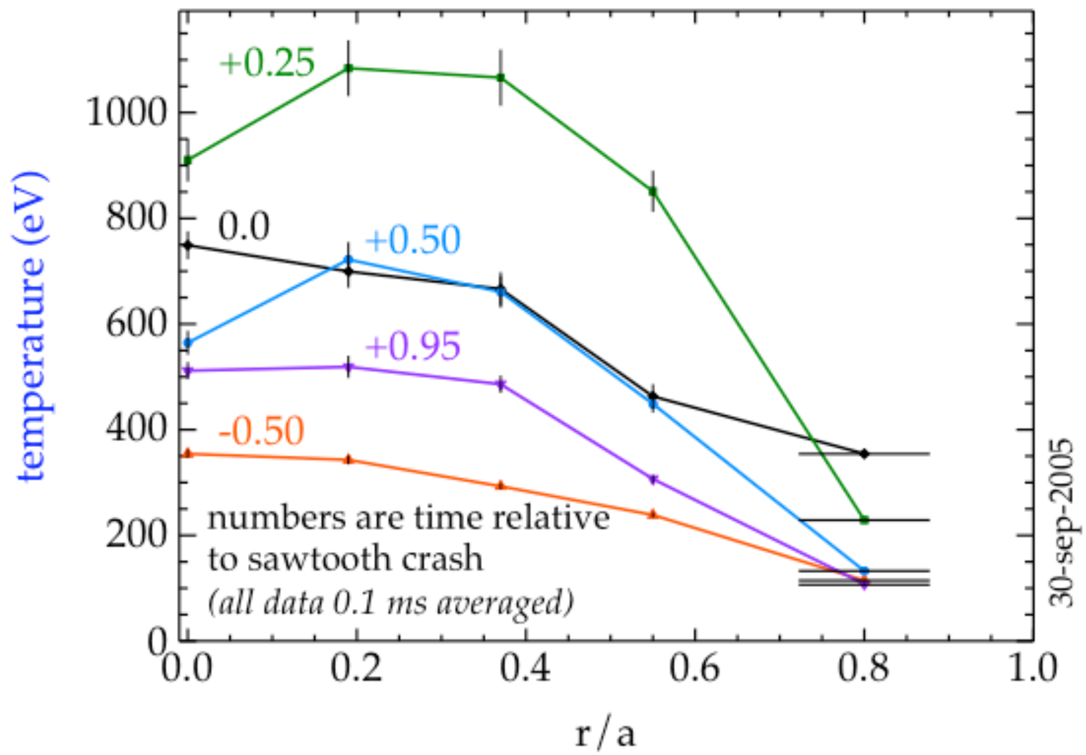


Ensemble parameters:

- medium density ($8\ 10^{12}\ \mathrm{cm}^{-3} < n_e < 1.1\ 10^{13}\ \mathrm{cm}^{-3}$)
- $f \sim -0.22$
- $I_p = 380$ kA

At the time of a magnetic reconnection event, $T_{C^{+4}}$ increases by a factor of ~3, T_D increases by ~50%, while T_e remains nearly unchanged.

Ion heating profiles (CHERS)

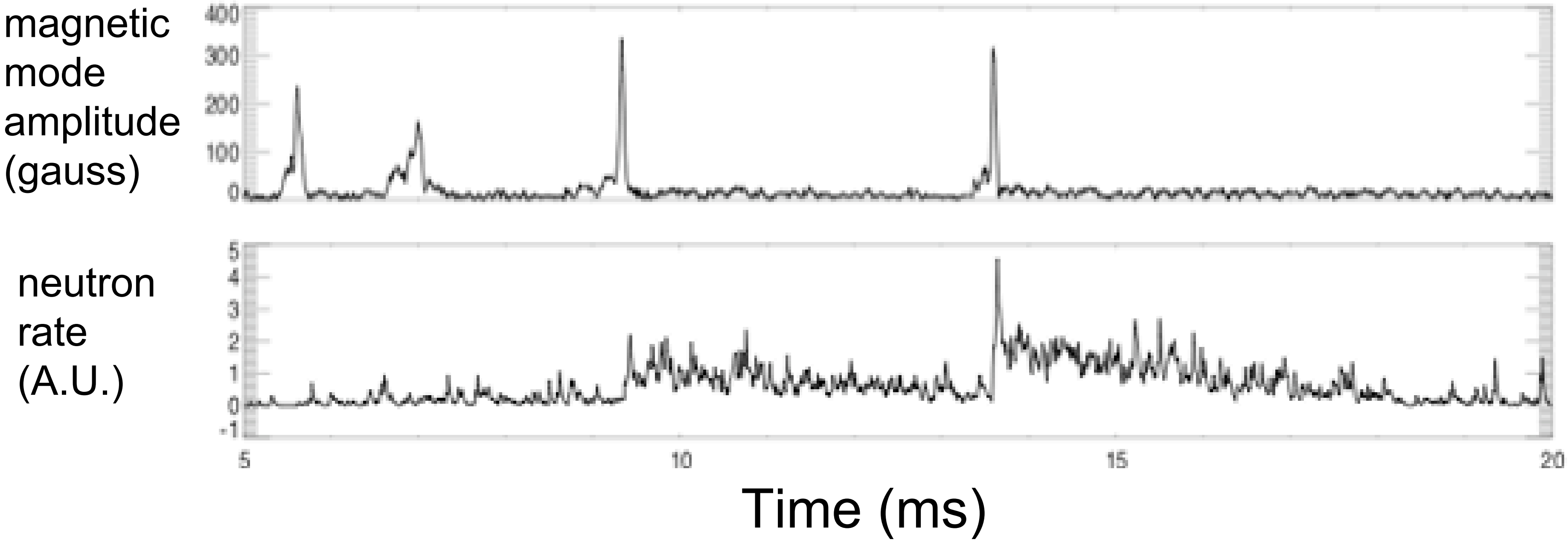


- ➢ Ion heating is active throughout the entire plasma volume
- ➢ Different heating of different radial positions
- ➢ Cooling fastest in the edge

Courtesy S. Gangadhara, UW

Observation of Fusion Neutrons (2005)

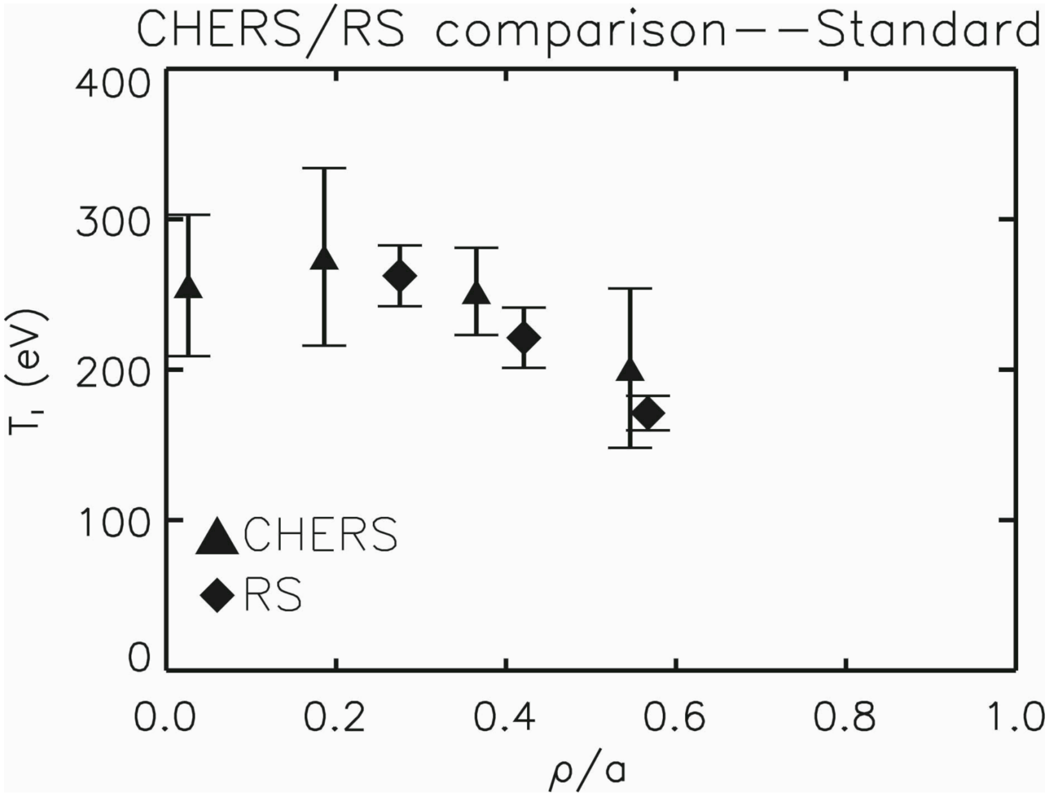
Neutron rate increases dramatically at a magnetic reconnection event:



Data courtesy Rich Magee, UW

Consistency checks

Do simultaneous measurements with different diagnostics give the same results?



(simultaneous measurements using CHERS and Rutherford Scattering, away from Magnetic Reconnection Events)

(Reardon et al., Rev. Sci. Inst., **74** (3) 1892 (2003))

Alternative Explanations

- Ground loops?

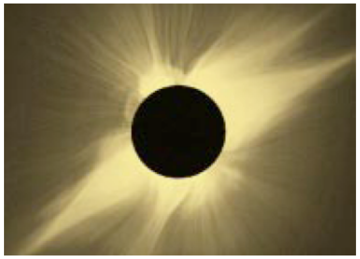
  (No, we check for these every day)
- Enhanced particle/UV flux?

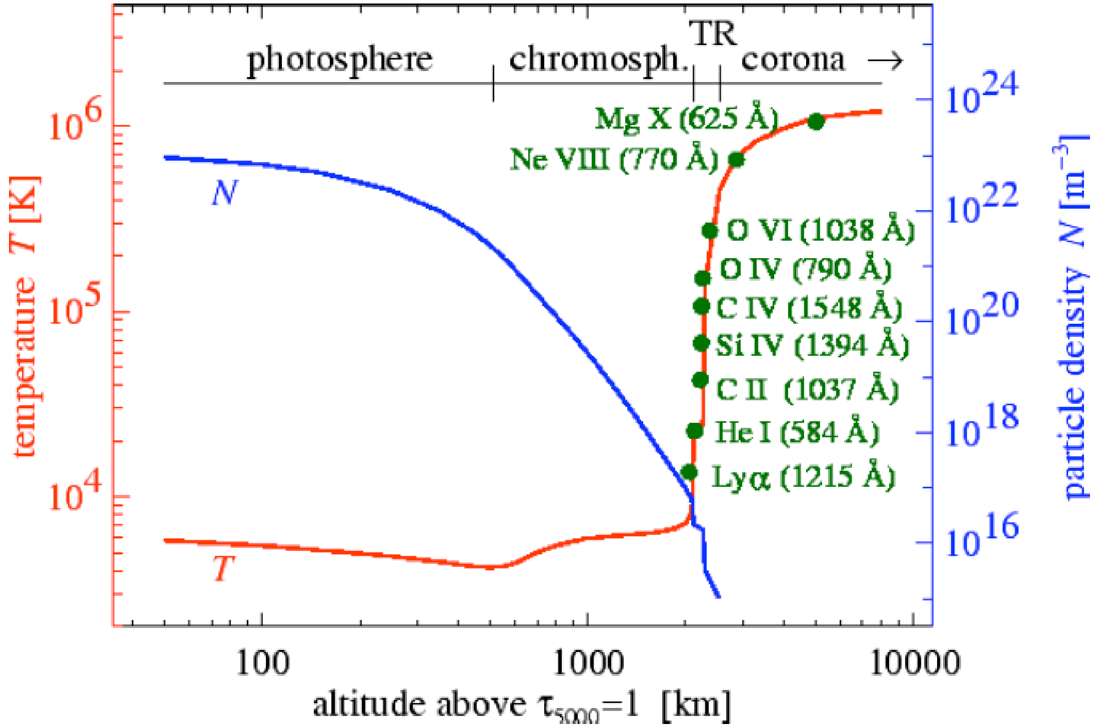
  (not all diagnostics are sensitive to this)
- Electrical noise pickup?

  (not all diagnostics are sensitive to this)
- Non-Maxwellian features?

  (can't prove ions are Maxwellian--but whatever the distribution function, energy is going into the ions)

Observations of Ion Heating in Astrophysics #1: Solar Corona



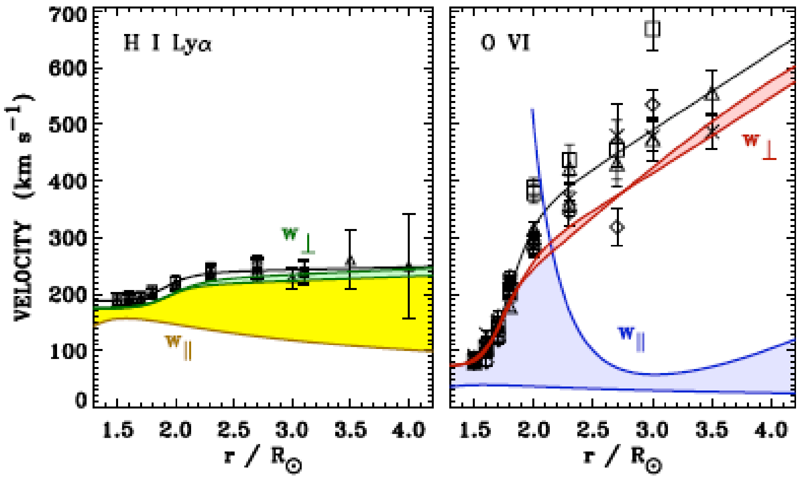


Photosphere:
T~5800 K (blackbody)

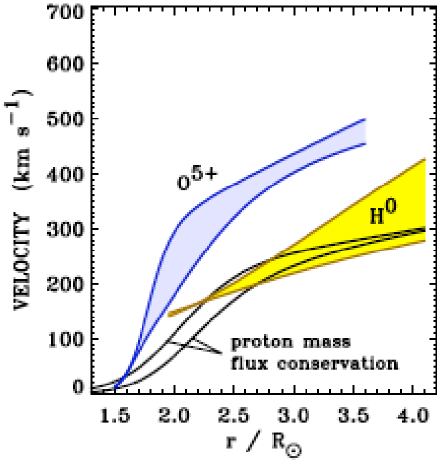
Corona:
T>10^6 K (Ca^{12+}, Fe^{9+}, etc.)

Observations of Ion Heating in Astrophysics #2: Solar Wind

Most-probable speeds:



Outflow velocities:



$$u_{\mathrm{ion}} > u_p$$

$$\left(\frac{T_{\mathrm{ion}}}{T_p}\right) > \left(\frac{m_{\mathrm{ion}}}{m_p}\right)$$

$$T_\perp > T_\parallel$$

(... similar to *in situ*)

At about 2 $R_\odot$ outflowing particles are accelerated to escape velocity and beyond.

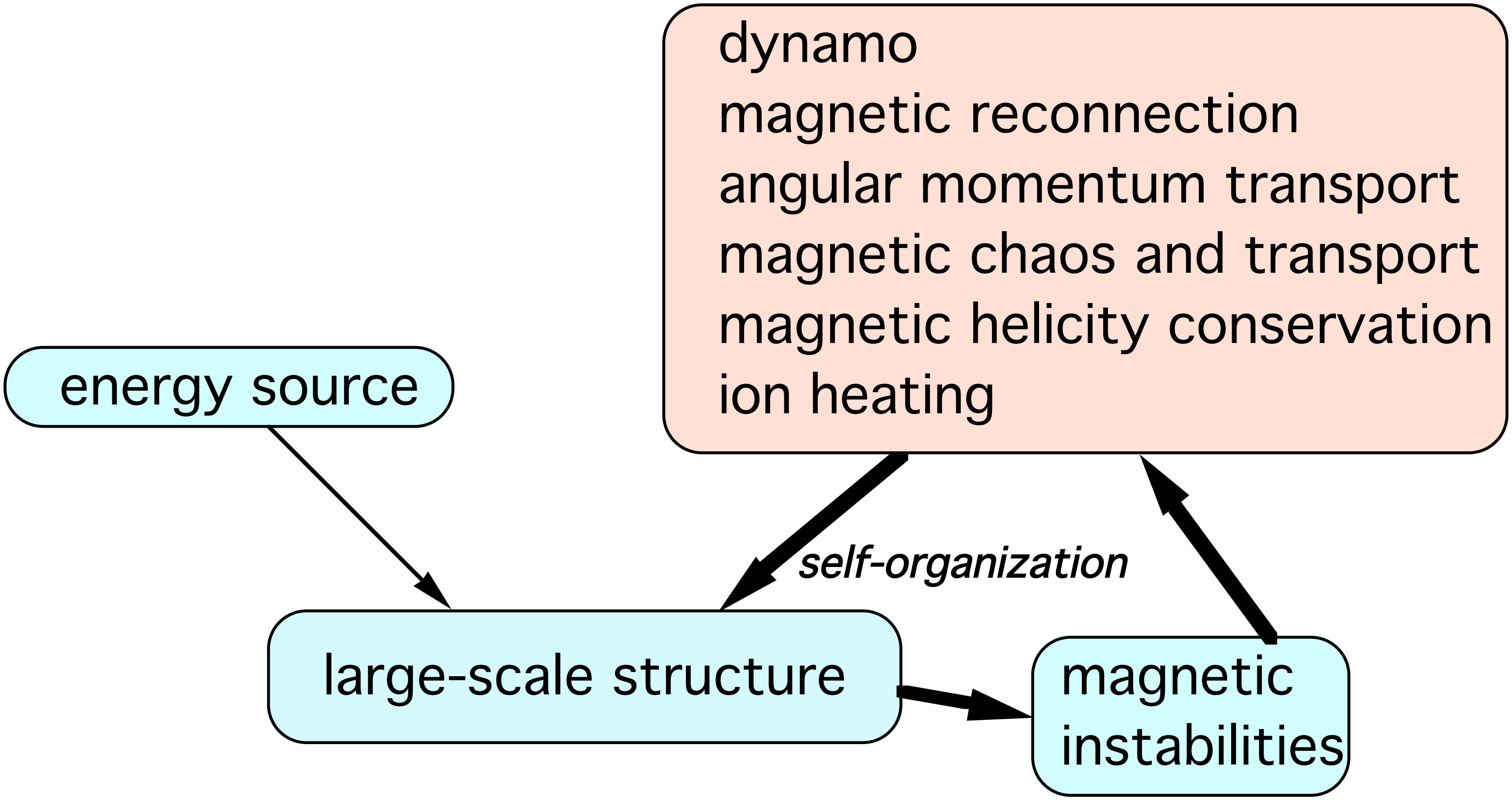
Measurements by the Ultraviolet Coronagraph Spectrometer (UVCS), One of 12 instruments on The Solar and Heliospheric Observatory (SOHO).

Data after Cranmer et al., Ap. J., 511, 481 (1999)

Similarities between Laboratory and Astrophysical observations

- Ion heating
- Magnetic reconnection
- Momentum transport
- Magnetic turbulence
- Dynamo
- Helicity conservation

Magnetic Self-Organization



dynamo
magnetic reconnection
angular momentum transport
magnetic chaos and transport
magnetic helicity conservation
ion heating

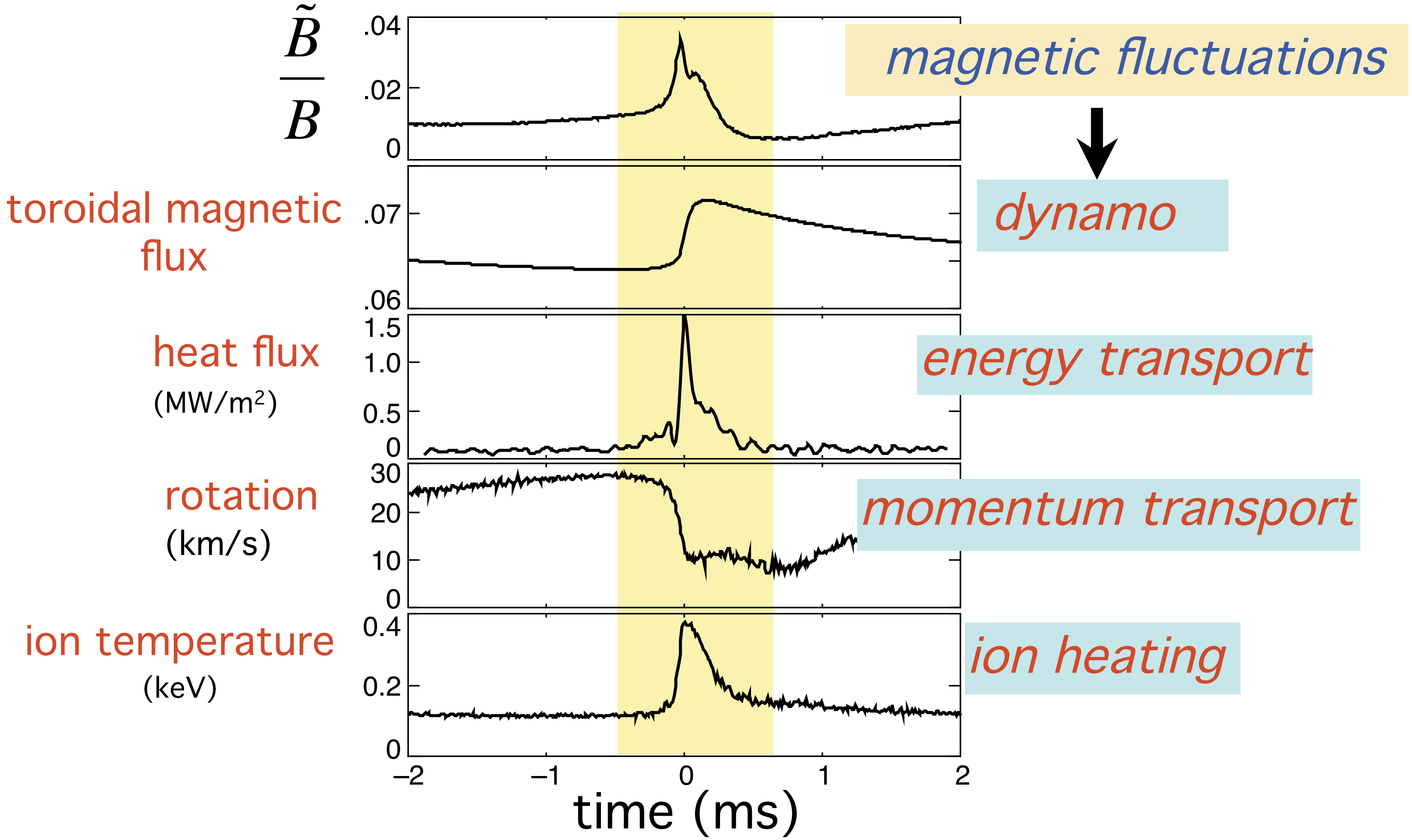
energy source

self-organization

large-scale structure

magnetic instabilities

Magnetic Self-Organization in the Lab



magnetic fluctuations

↓

dynamo

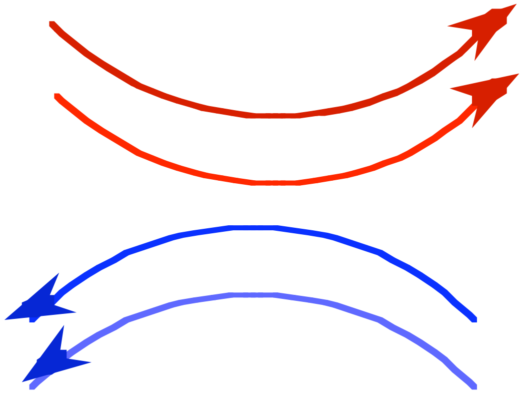
energy transport

momentum transport

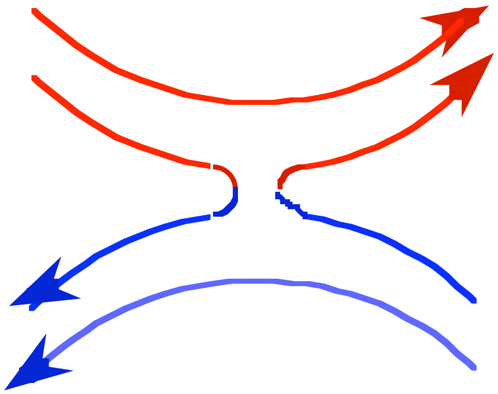
ion heating

Magnetic Reconnection

- Topological rearrangement of magnetic field lines



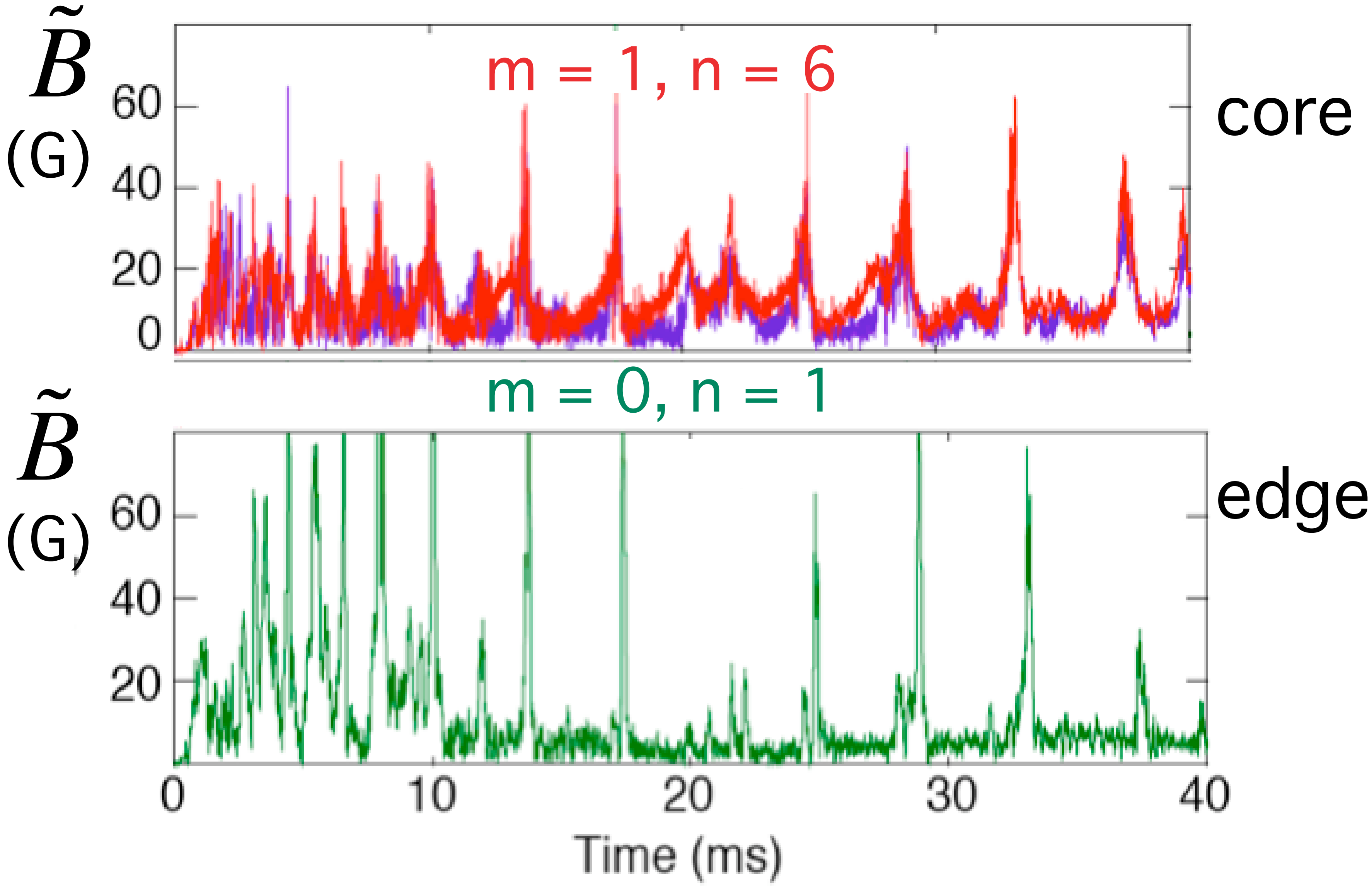
Before reconnection



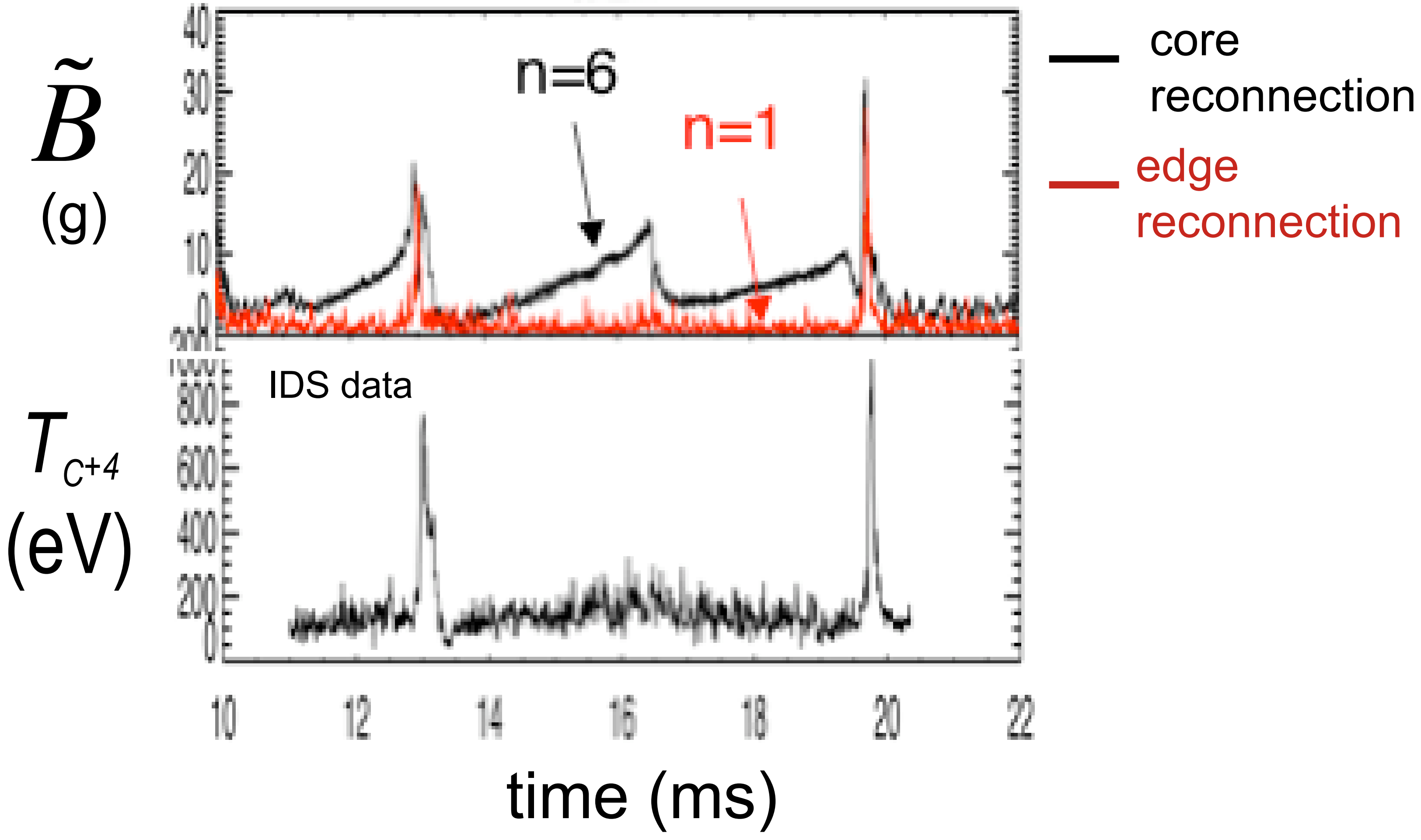
After reconnection

- Key to ion heating in lab plasmas (as well as stellar flares, coronal heating, star formation, and astrophysical jets)

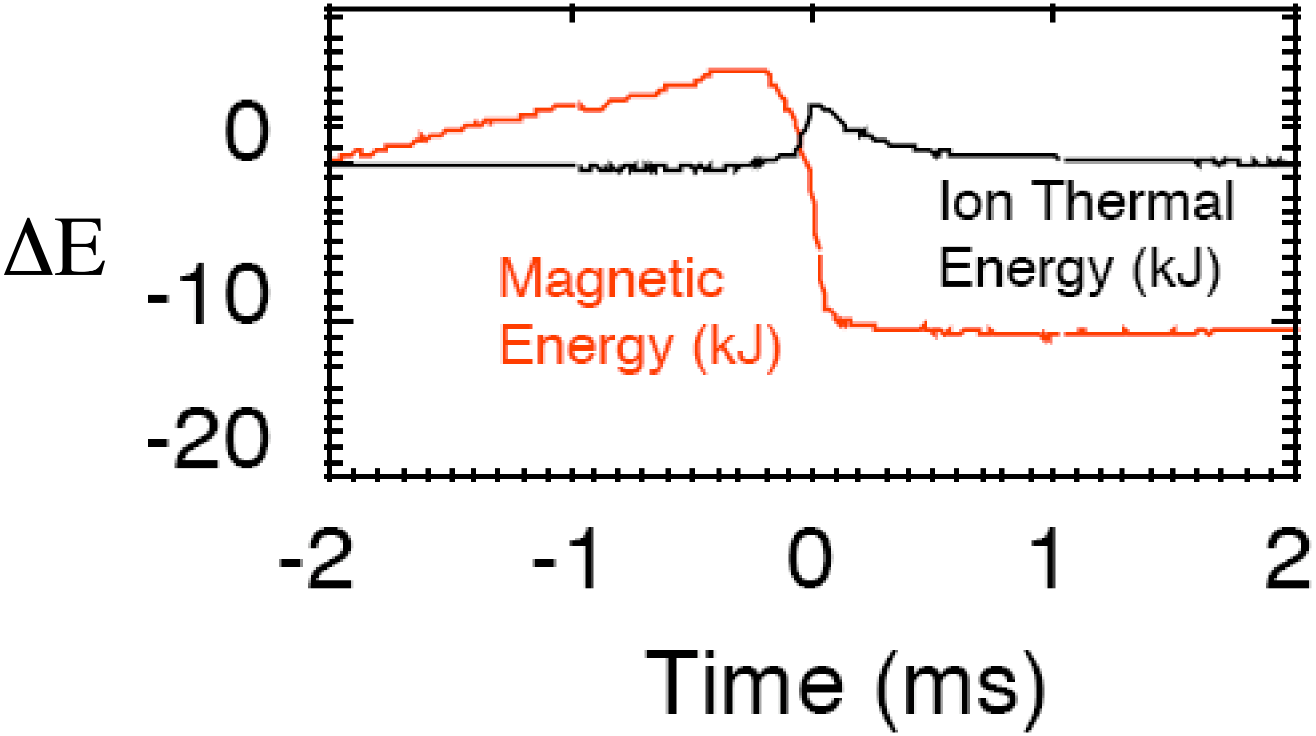
Reconnection on MST Occurs in Bursts



Ions heated only with core AND edge reconnection



Changes in Stored Energy at Magnetic Reconnection Event



Possible Microscopic Explanations for Ion Heating #1: Wave-particle Resonance

- Circularly polarized Alfven waves (eg) with $\omega - \mathbf{v}_{||}\mathbf{k}_{||} \approx \boldsymbol{\Omega}_{\mathbf{ion}}$ are resonant with ion orbits : ions see DC electric field!
- Pluses: efficient heating of ions
- Minuses: neither theory nor simulation have been able to account for creation of such waves, nor are they observed

Possible Microscopic Explanations for Ion Heating #2

- Frictional heating due to sheared flow (two-fluid model) caused by tearing modes
- Plusses: theory is well-understood, heating scales with Larmor radius
- Minuses: not fast enough to explain observed ion heating

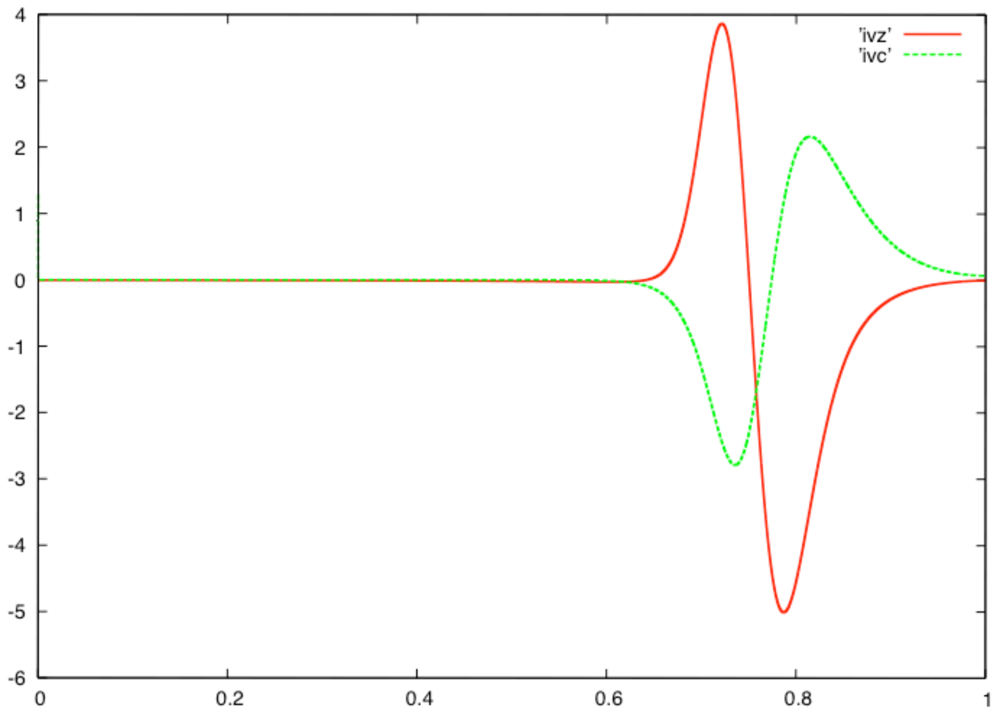
Possible Microscopic Explanations for Ion Heating #2

M=0,n=1 Tearing mode

Flow

Velocity

(V/V_{A})



Normalized minor radius

Courtesy V. Mirnov, UW

Possible Microscopic Explanations for Ion Heating #3

- Wake-field heating (Kinetic Theory): stochastic field lines cause electron clumps, which move through the ambient plasma; wake field of clumps heats ions
- Plusses:
- Minuses:

Too soon to know!

Gatto and Terry, Phys. Plas., **8**(3) 825 (2001)

Planned experiments on MST

- More accurate measurements of spatial profiles of ion heating and mode structure

- Maximize ion heating

Conclusions

- Ion heating on MST is real!
- Several competing theoretical explanations
- Understanding ion heating on MST would be a big step forward in understanding ion heating in the solar atmosphere