Ion Heating and Acceleration in the Reversed Field Pinch

John Sarff

A. Almagri, J. Anderson, B. Chapman, D. Den Hartog, S. Eilerman, G. Fiksel, S. Kumar, R.M. Magee, V. Mirnov, M. Nornberg, J. Reusch

MST Team and Collaborators

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Outline

- Reminder of tearing magnetic reconnection in the RFP
- Features of ion heating and acceleration during impulsive “sawtooth” events:
  - Majority ion heating increases with $\sqrt{m_i}$
  - Preliminary evidence for Z/m_z dependence, in minority ions
  - Anisotropic heating $T_\perp > T_{||}$, for minority ions
  - Energetic tail forms spontaneously
    - Extends to at least 35 keV
    - Power-law energy dependence
    - Acceleration of “test” ions created by neutral beam injection
- Confinement characteristics
  - Classical confinement of energetic ions
  - Comments on electron heating and stochastic transport

The MST reversed field pinch at UW-Madison

R/a = 1.5 m / 0.5 m

$I_p < 0.6$ MA

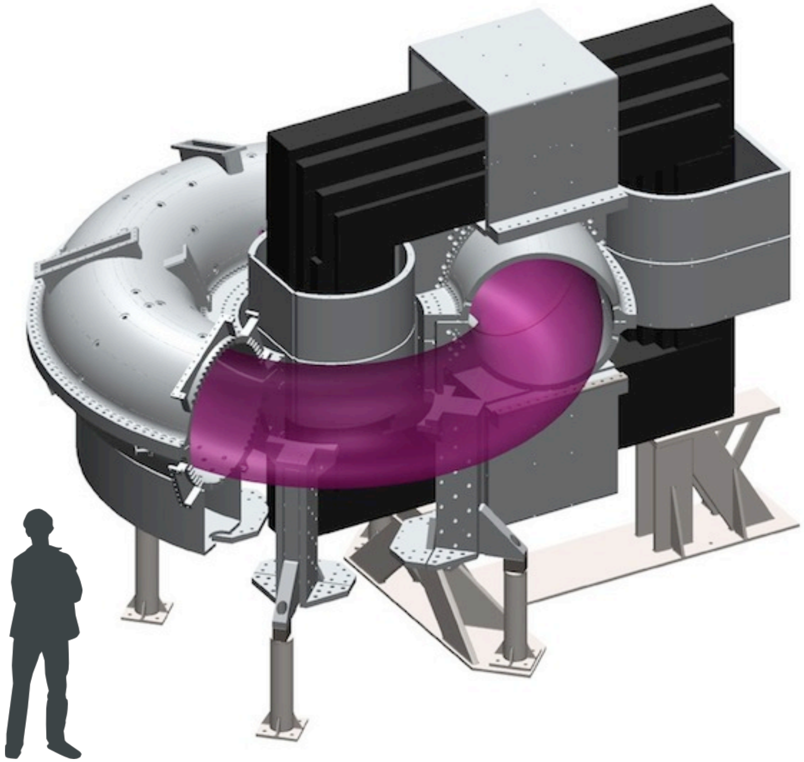
$B < 0.5$ T

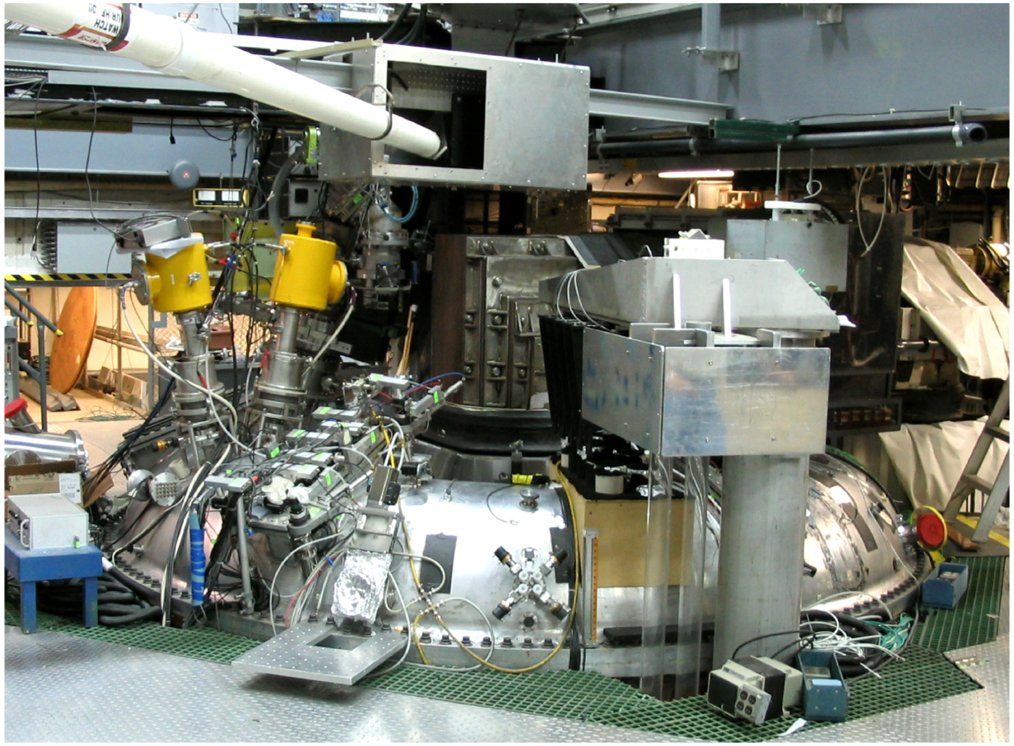
$n \sim 10^{19}$ m^{-3}

$T_e \sim T_{ion} < 2$ keV

$\beta < 25\%$

$S = 5 \times 10^{5-6}$





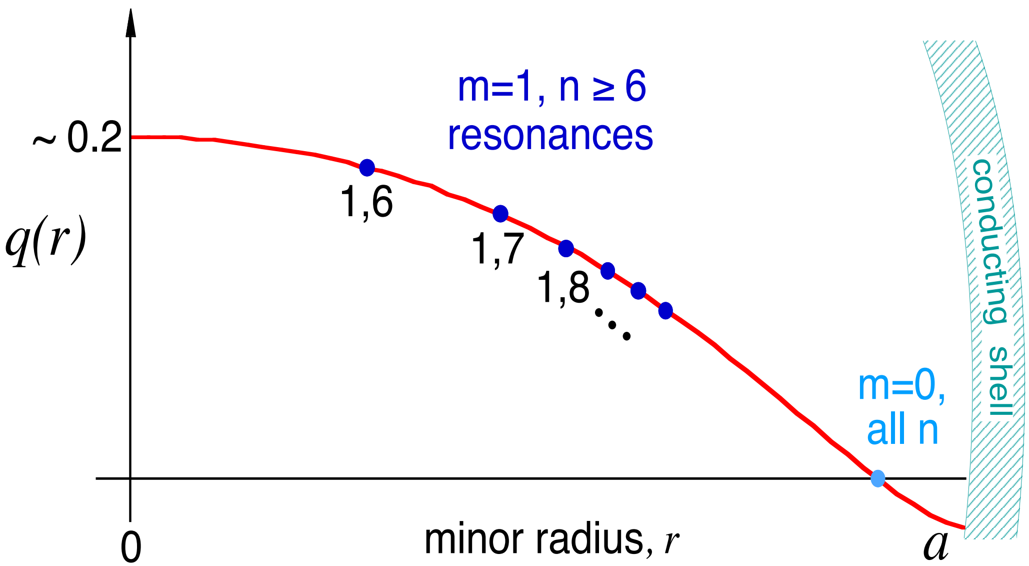
Tearing instability and nonlinear coupling results in multiple magnetic reconnection sites

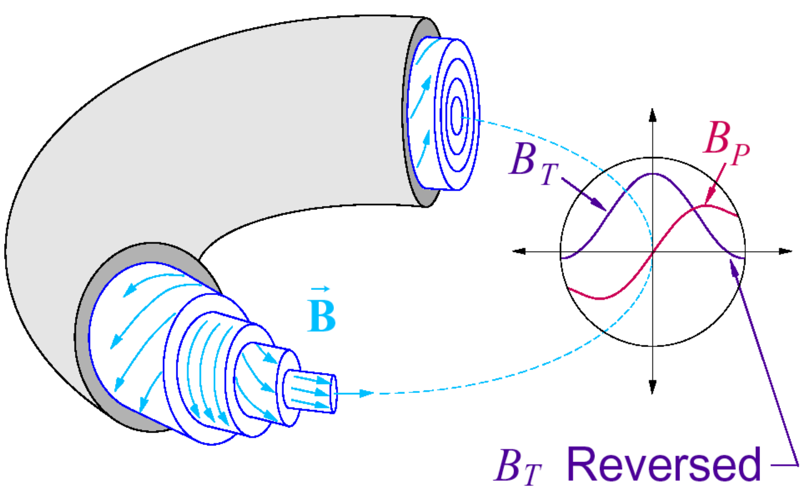
Tearing resonance:

$$0 = \mathbf{k} \cdot \mathbf{B} = \frac{m}{r} B_\theta + \frac{n}{R} B_\phi \quad \Rightarrow \quad q(r) = \frac{r B_\phi}{R B_\theta} = \frac{m}{n}$$

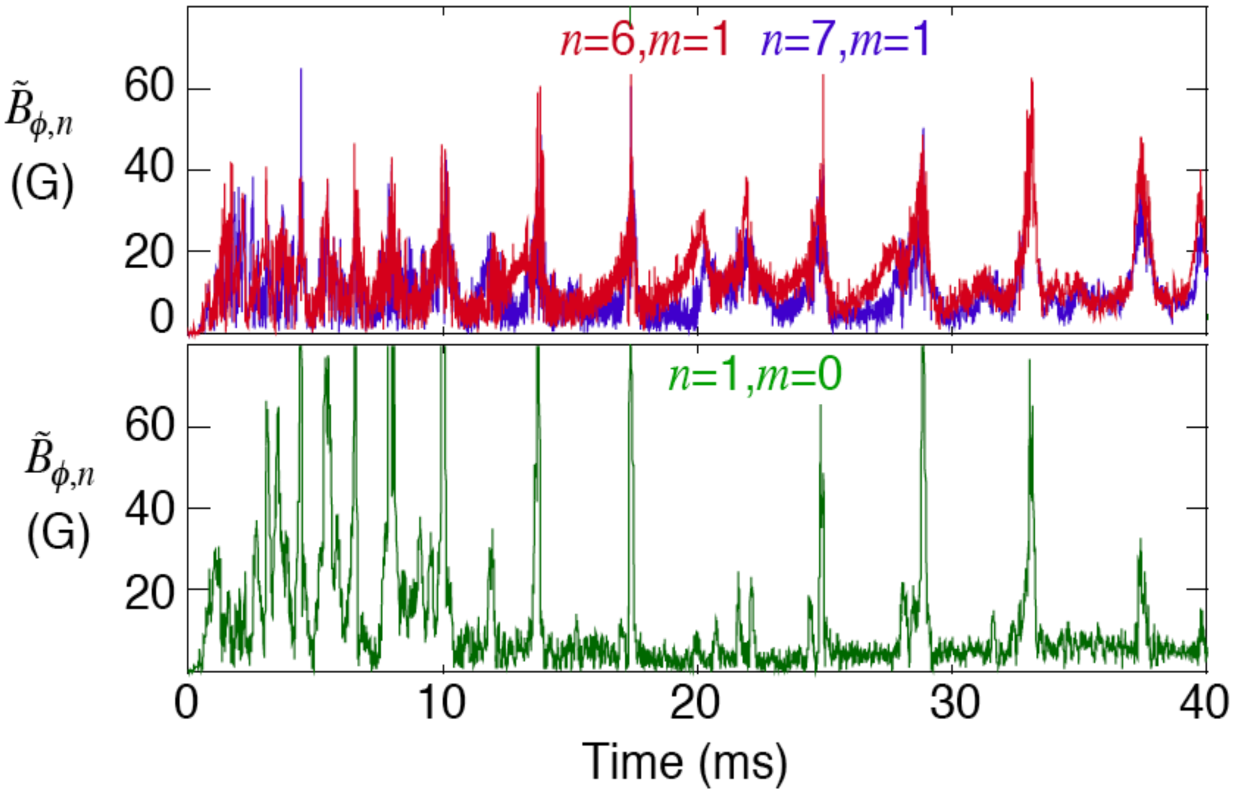
m = poloidal mode number

n = toroidal mode number





Quasi-periodic impulsive reconnection events (sawteeth) are associated with tearing modes

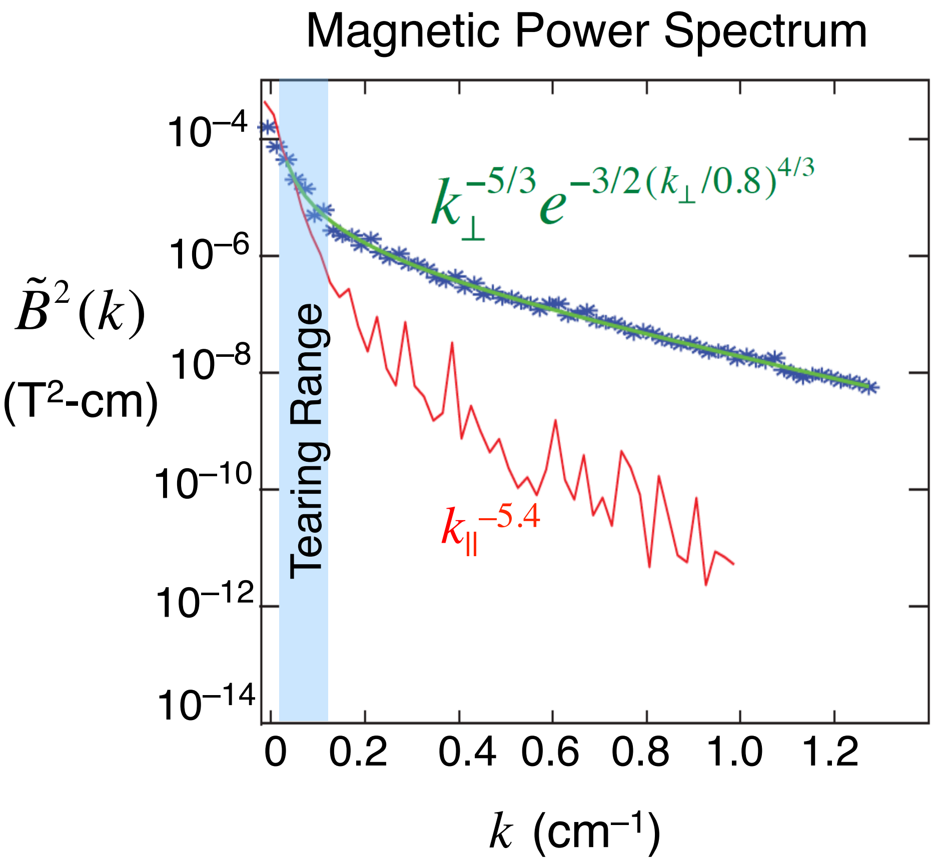


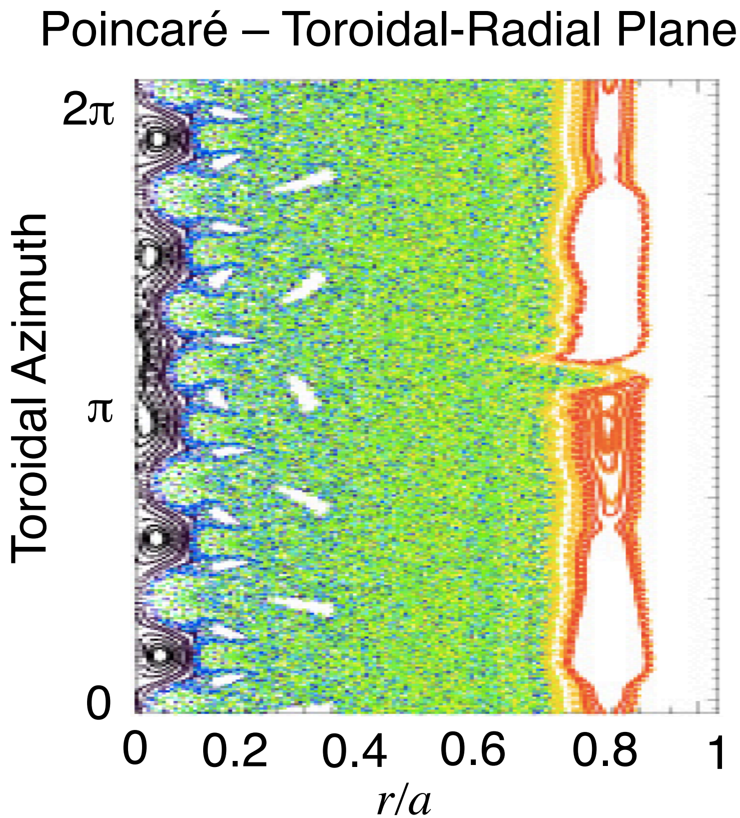
Core-resonant m=1 modes are largest, linearly unstable from the gradient $\nabla_r (J_{\|} / B)$

Linearly stable mode, energized by nonlinear 3-wave coupling

$k_3 = k_1 \pm k_2$

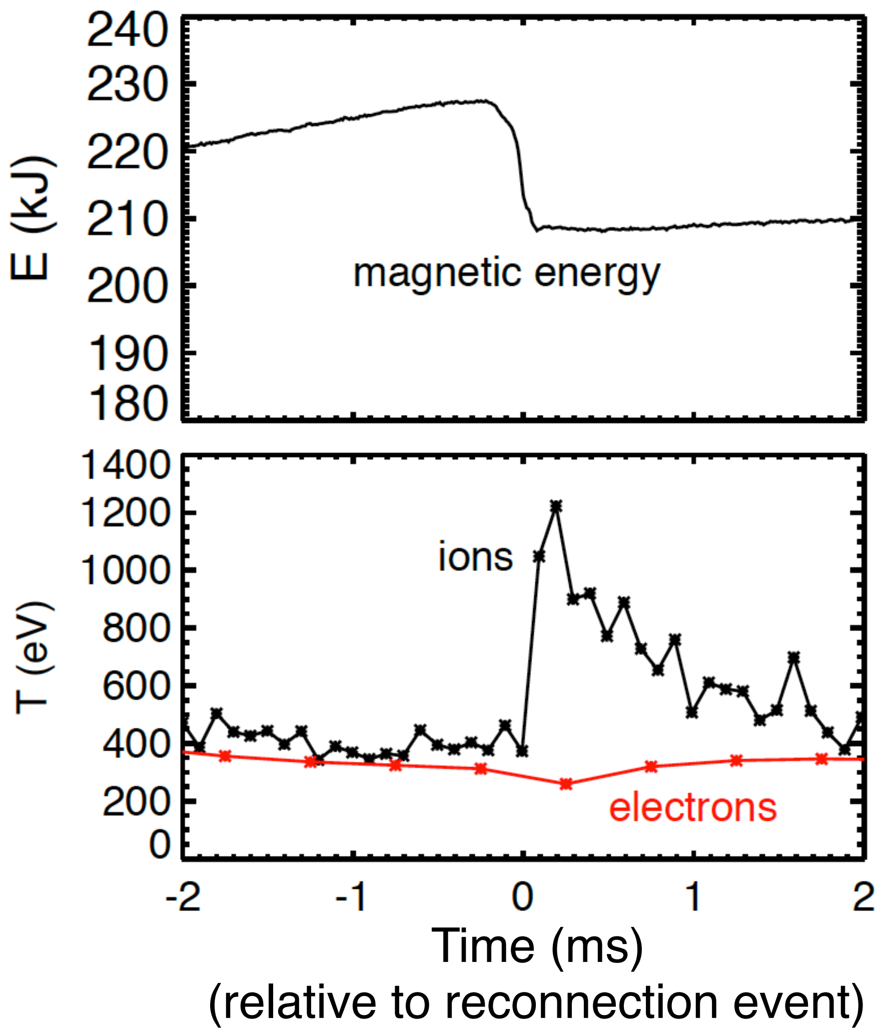
Multiple-mode interaction leads to anisotropic turbulent cascade and stochastic magnetic field





Y. Ren et al, PRL 2011
P.W. Terry, PoP 2009, 2012

Powerful ion heating occurs during the impulsive reconnection events



A large fraction of the magnetic energy released by reconnection is transferred to the ions

$T_i > T_e$

$\Delta t \sim 100\ \mu s << e\text{-}i$ equil. time

Clearly the ion heating mechanism is not collisional

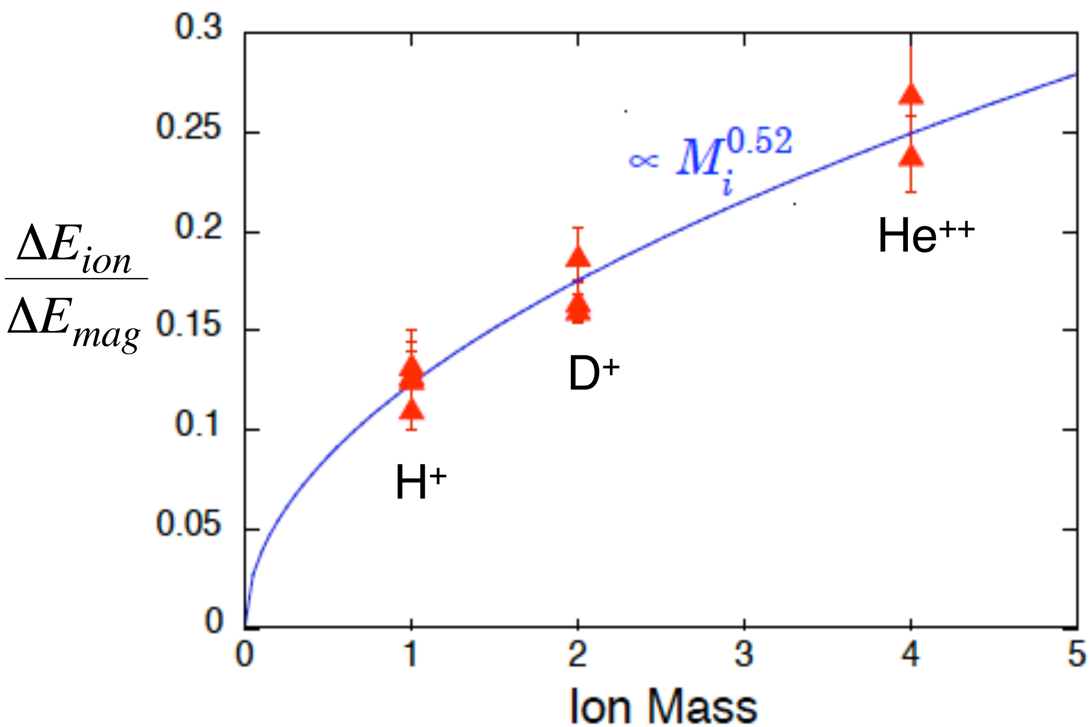
(Note that this is an ohmically heated plasma, through inductive current drive)

MST's diagnostic capability to characterize ion heating and acceleration steadily improved

- Rutherford scattering, using diagnostic neutral beam: majority ions (H, D, He)
- Charge-exchange recombination (CHERS) with DNB: minority ions (C, B, Al, …)
- Passive Doppler spectroscopy: minority ions (line-of-sight average)
- Neutron emission (scintillator): energetic D ions (> 20keV)
- Two neutral particle analyzers: resolves distribution function (via charge-exchange)
  - "Compact" NPA, measures D, for 0.3-5 keV
  - "Advanced" NPA, simultaneously measures H and D, for 0.5-35 keV
- 25 keV neutral beam injector (1 MW), creates energetic "test ions"

Majority ion heating depends on ion mass

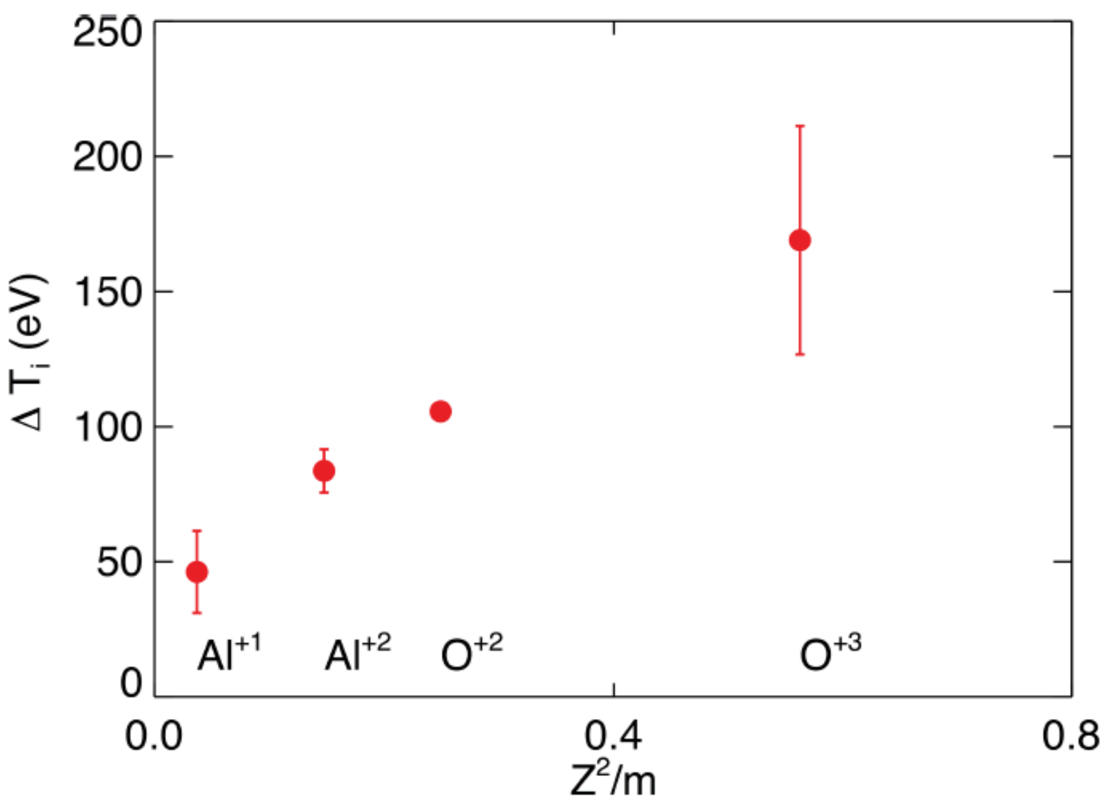
- Suggestive of stochastic heating process
- Note that D^+ and He^{++} have the same Z/m



G. Fiksel et al, PRL 2009

Preliminary evidence for Z/m dependence in minority ions

- Passive (line-of-sight) Doppler spectroscopy for edge chords, $r/a \sim 0.8$
- View is oblique to $\mathbf{B}$ (does not resolve possible anisotropy)
- $\Delta T_i \approx 400$ eV for fully-stripped carbon C^{+6} in the core (Z^2/m=3) – see next slides

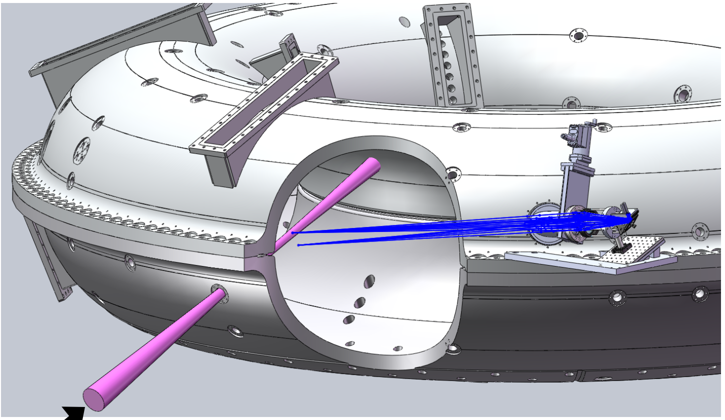


Kumar et al

Charge-exchange recombination spectroscopy (CHERS) is a local measurement, allowing measurement of heating isotropy

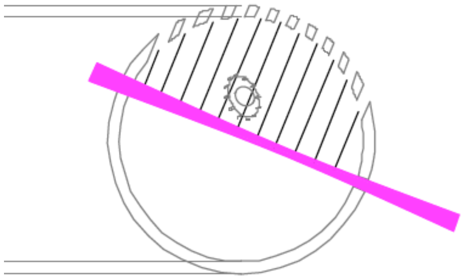
- Monitor the actively-excited carbon, boron, etc

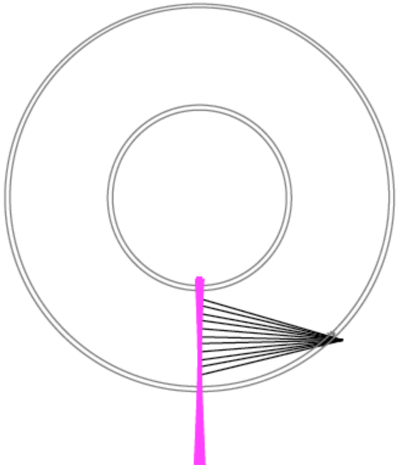
$$H^0 + C^{+6} \rightarrow H^+ + C^{+5*} \rightarrow C^{+5} + h\nu$$



H^0

Diagnostic neutral beam

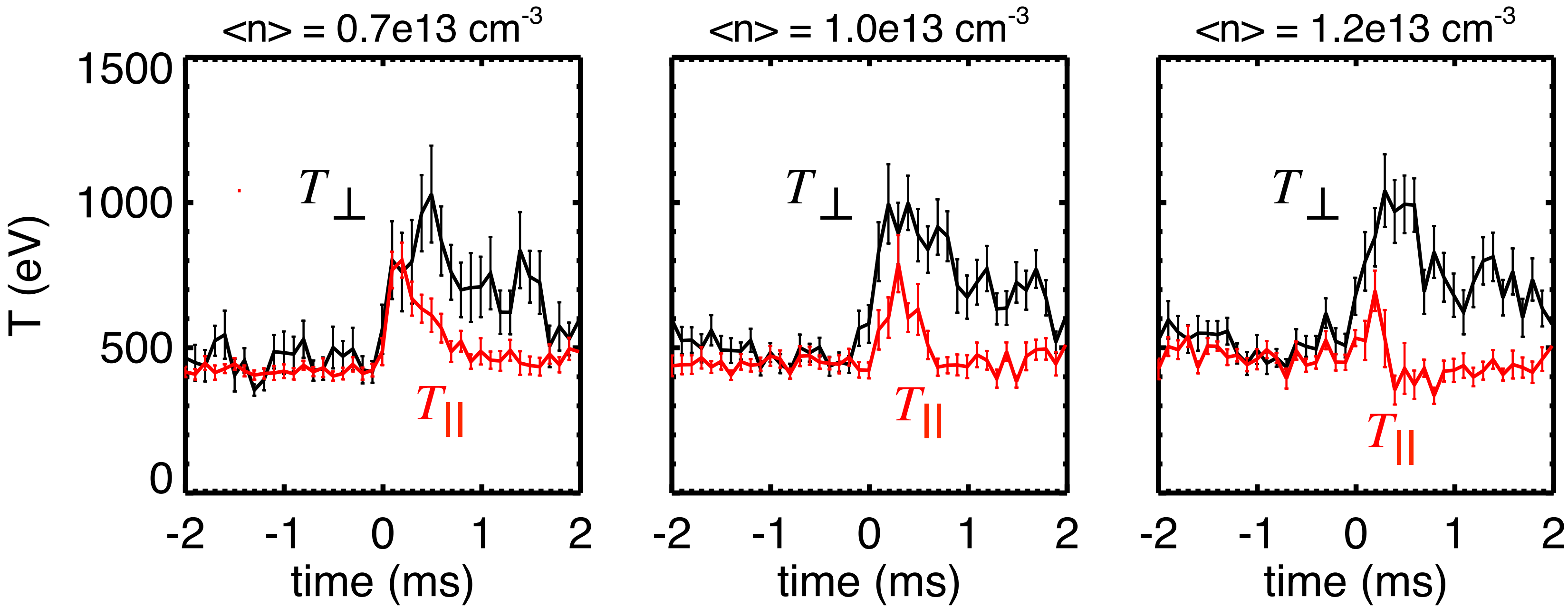




Poloidal and toroidal views allow measurement parallel and perpendicular to **B**

Minority ion heating is anisotropic relative to the equilibrium field direction

- $T_\perp > T_{||}$ during event (equilibrates later)
- Larger anisotropy at high density, likely reflects inherited Z_{eff} dependence



(relative to reconnection event)

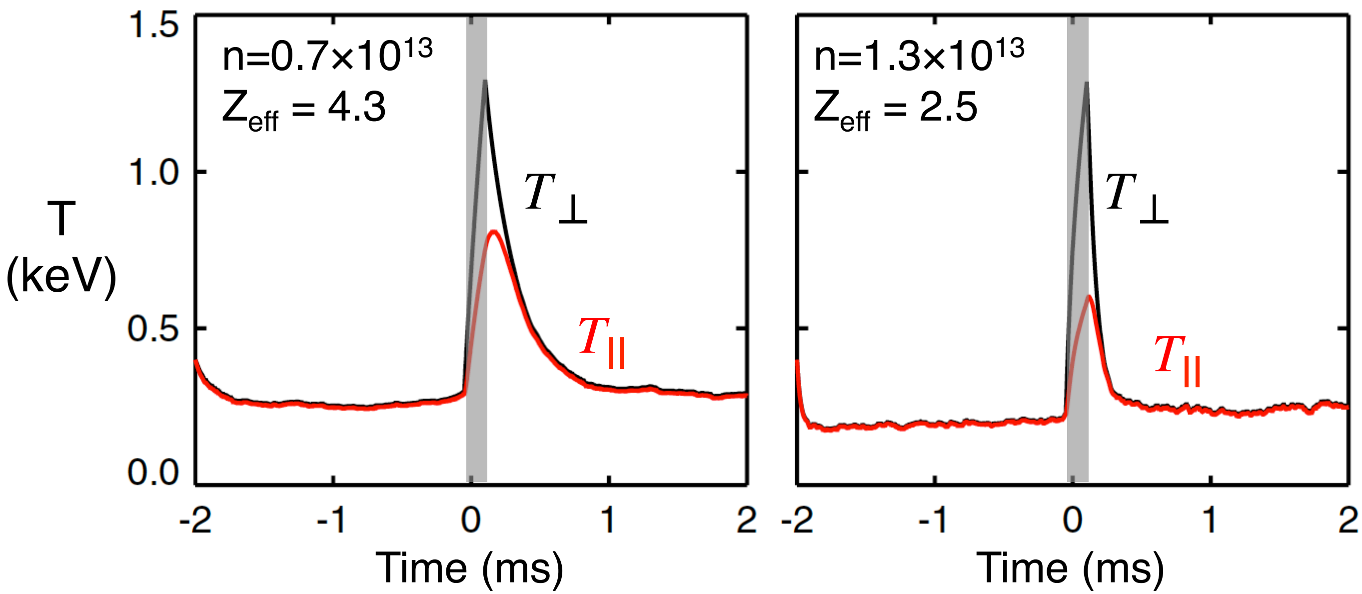
R. Magee et al, PRL 2011

Anisotropy is consistent with perpendicular heating and collisional relaxation through multiple ion species

$$\frac{dT_{\parallel,C}}{dt} = \frac{1}{k_B n_C}\left(C_{\parallel,CD}(T_{\parallel,D} - T_{\parallel,C}) + \sum_i m_i J_{\parallel,C_i}\right) - \frac{T_{\parallel,C}}{\tau}$$

$$\frac{dT_{\perp,C}}{dt} = \frac{1}{k_B n_C}\left(C_{\perp,CD}(T_{\perp,D} - T_{\perp,C}) + \sum_i m_i J_{\perp,C_i}\right) - \frac{T_{\perp,C}}{\tau} + Q_\perp$$

Anisotropic Heating Assumed

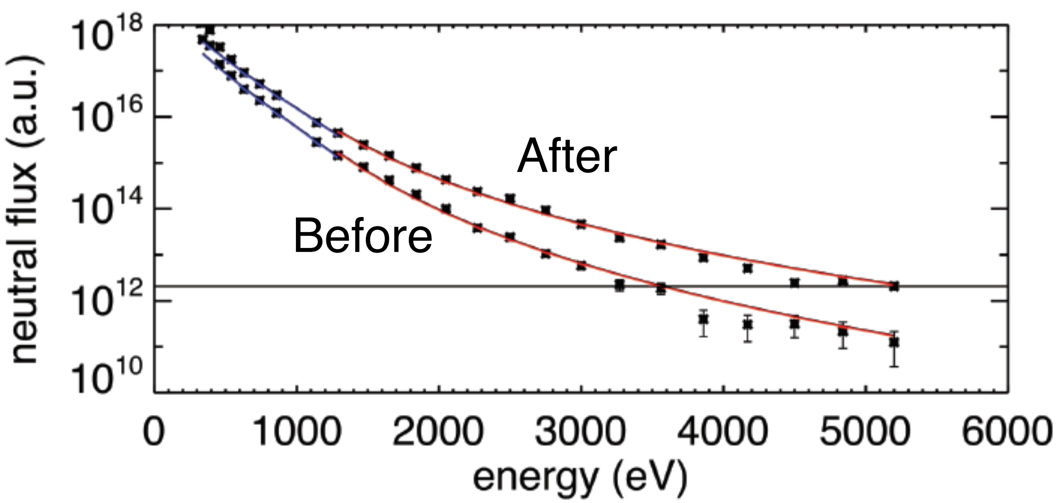


Post-sawtooth decay is faster than in MST, suggesting finite heating between events

Energetic ion tail detected by neutral particle analyzer

- Ion distribution well-fit by a Maxwellian "bulk" plus a power-law tail
- Majority ions inferred from neutral flux energy spectrum

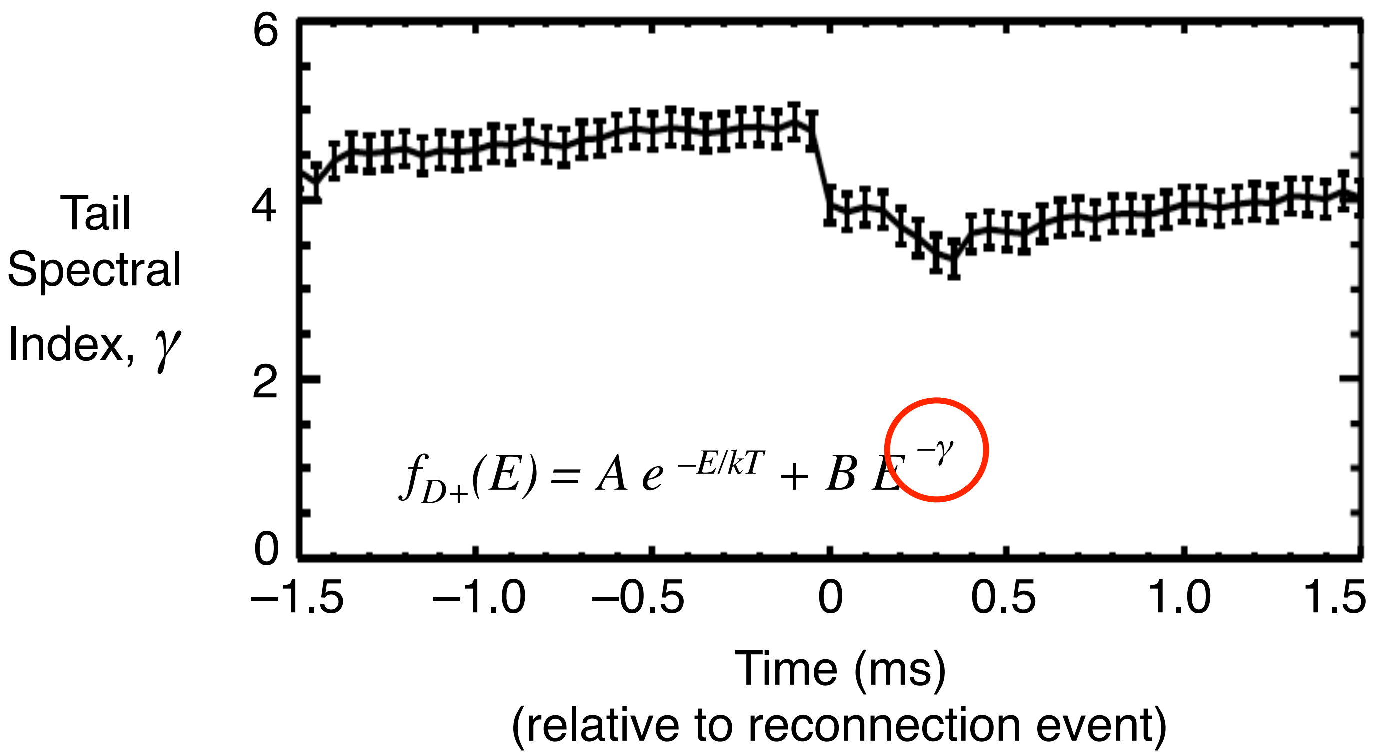
$$\Gamma_{D_0}(E) \sim \int_{-a}^{a} e^{-\int_x^a \alpha(E,l)dl} n_{D^0}(x) f_{D^+}(v,x)dx \Rightarrow f_{D+}(E) = A\, e^{-E/kT} + B\, E^{-\gamma}$$



J. Titus et al, Florida A&M Univ

Energetic tail is enhanced/reinforced at the reconnection event

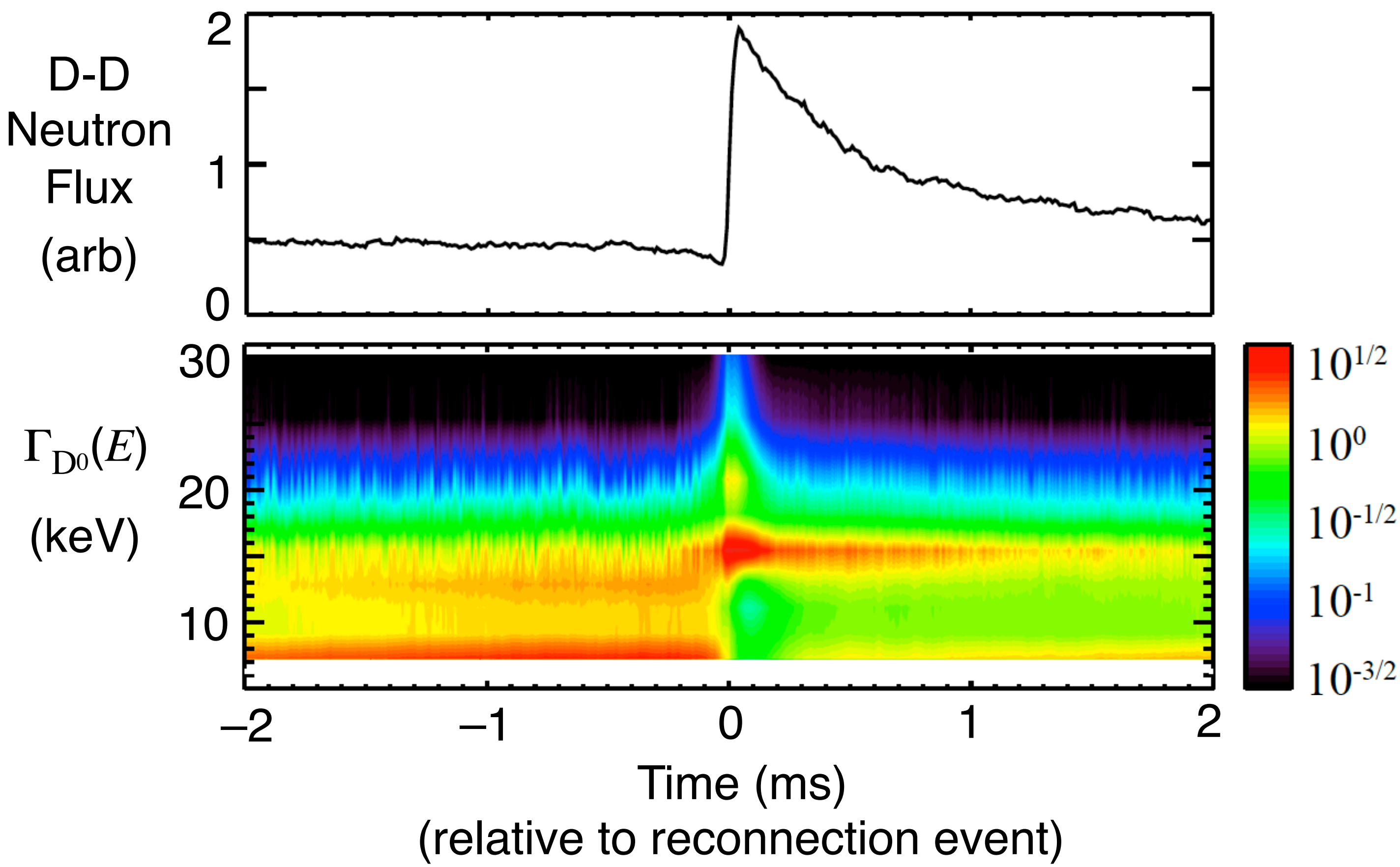
- Slow evolution of the tail following the event likely just classical slowing of the energetic ions, see neutral beam injection below



R. Magee et al, PRL 2011

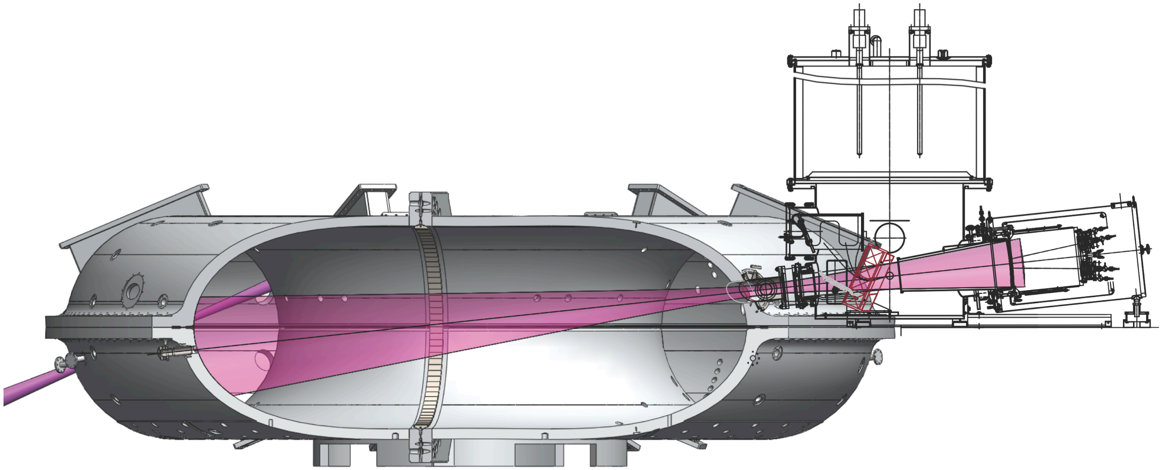
Neutron emission and new Advanced-NPA detect ions energized to at least 35 keV

- Neutron emission consistent with non-Maxwellian energetic ion tail
- Slow evolution between events likely to be classical slowing of energetic ions



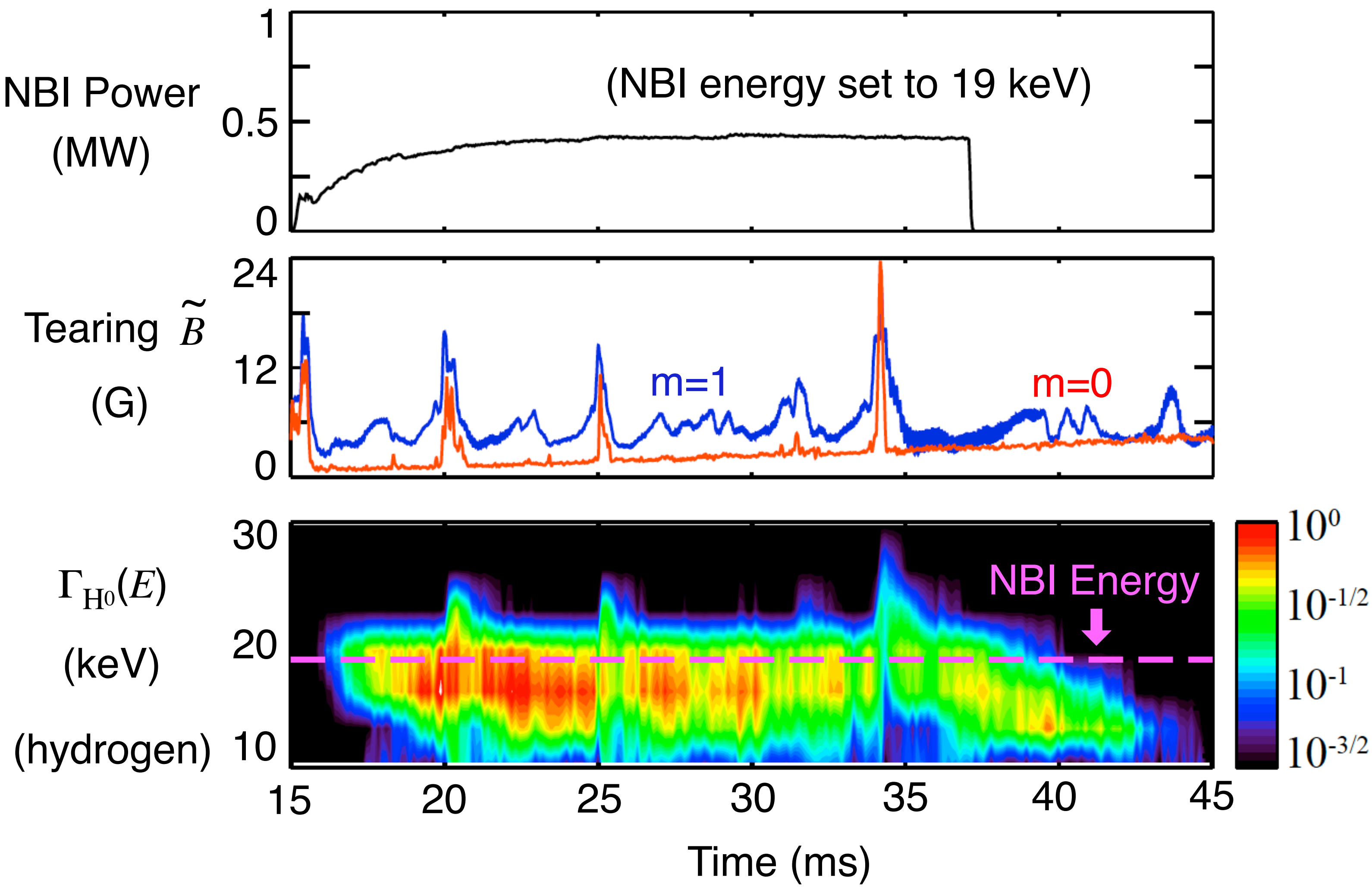
Eilerman, Reusch et al

High-power 1 MW neutral beam injector on MST



NBI Parameter	Specification
Beam energy	25 keV
Beam power	1 MW
Pulse length	20 ms
Composition	97% H, 3% D
Energy fraction (E:E/2E/3:E/18)	86%:10%:2%:2%

Acceleration of energetic “test ions” created by neutral beam injection



Eilerman, Reusch et al

Energetic ion confinement is classical

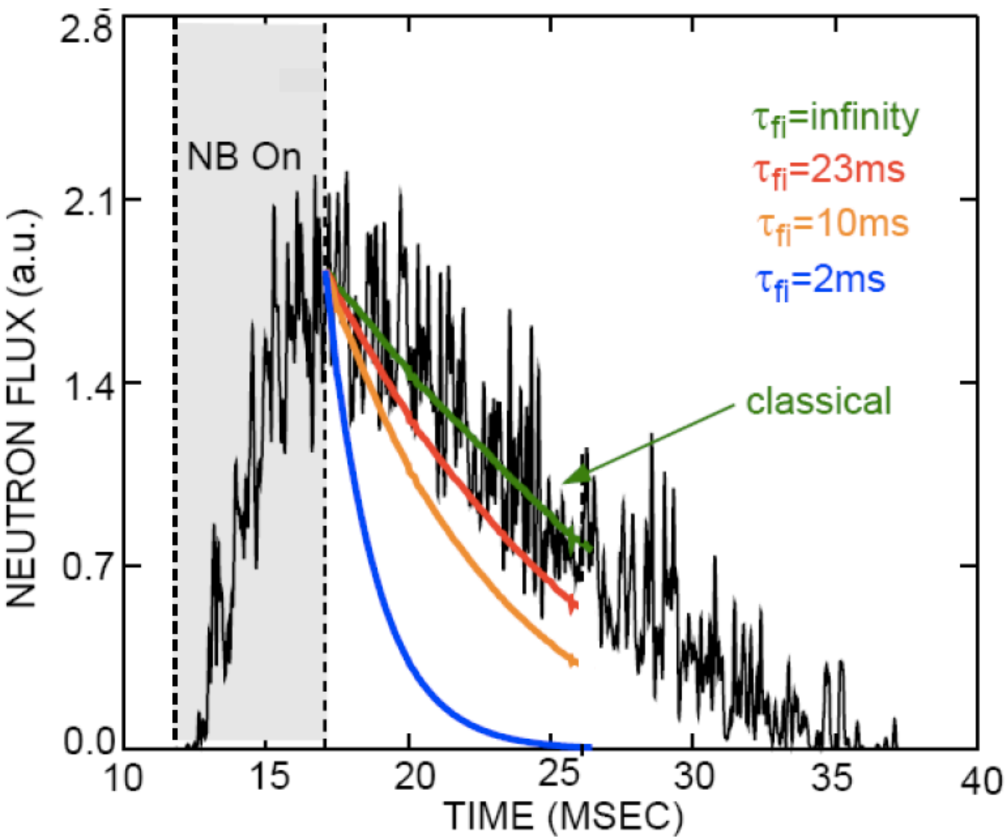
- NBI fueled with 3% deuterium to monitor D-D fusion reactions

$$\tau_n^{-1} = \tau_{fi}^{-1} + \tau_s^{-1}$$

fast ion losses (↑ τ_{fi}^{-1})

classical slowing down (function of T_e, n_e) (↑ τ_s^{-1})

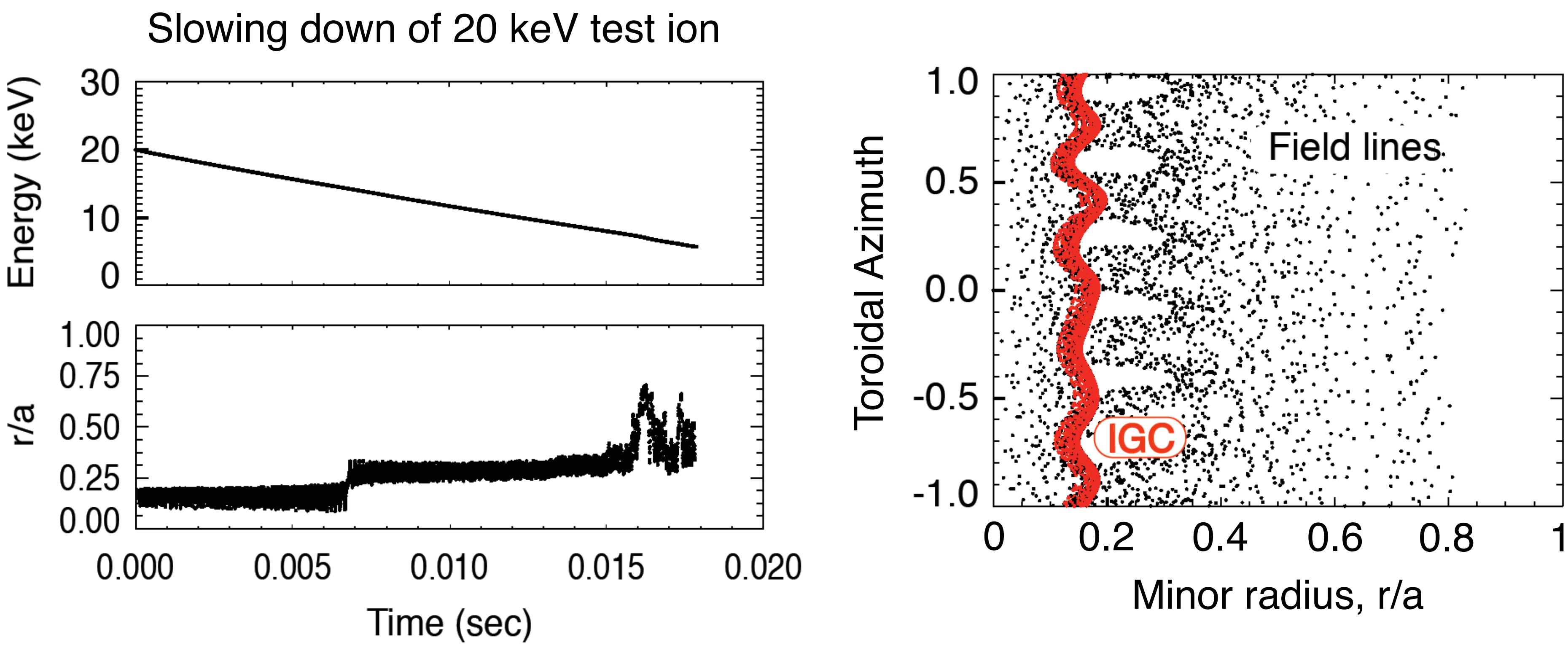
$$\tau_{fi}^{-1} = \tau_{cx}^{-1} + \tau_{turb}^{-1} + \ldots$$



D. Liu, J. Anderson et al.

Full-orbit analysis shows insensitivity of energetic ion guiding center to stochastic magnetic field

- Energetic ions classically confined, despite stochastic magnetic field
- Helps explain build-up of energetic tail created spontaneously by reconnection

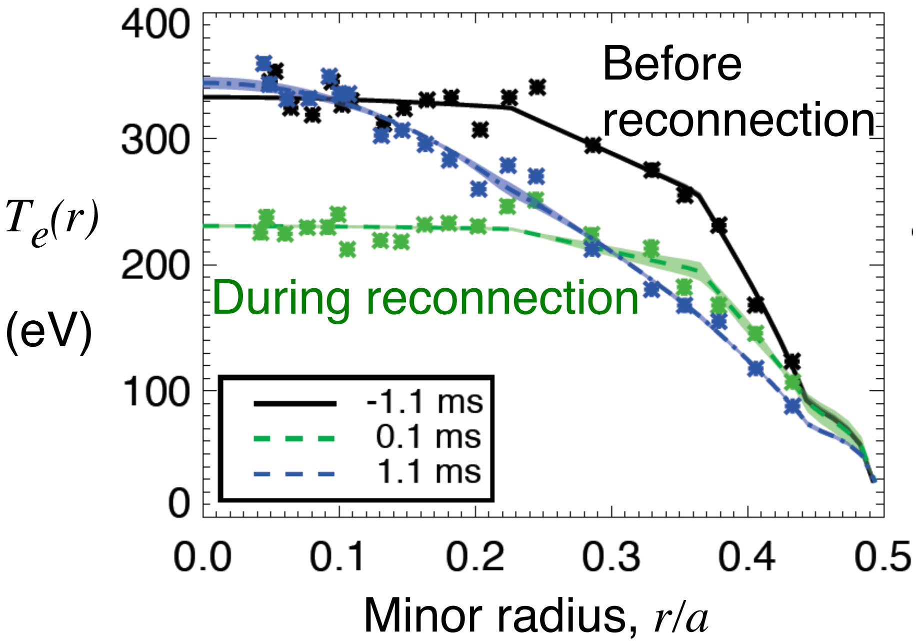


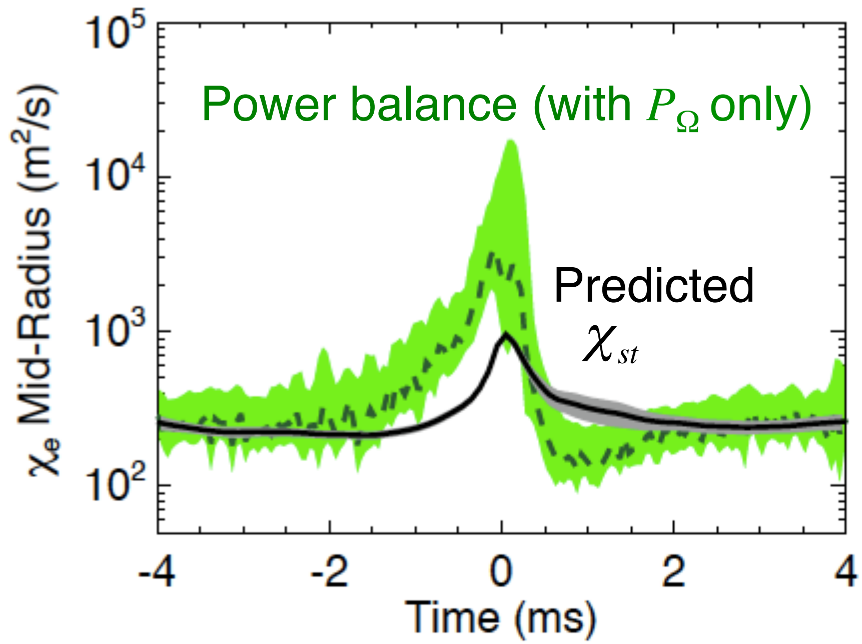
G. Fiksel et al, PRL 2005

What about electron heating from magnetic reconnection?

- Electron heat transport is consistent with $\chi_{st} = v_{th} D_m \sim \sqrt{T}\, L_{ac} \left(\tilde{B} / B\right)^2$ (Rechester-Rosenbluth / Jokipi)
- Reconnection heating power to ions is comparable to ohmic heating power, which is apparently sufficient for electrons

$$P_\Omega = \int \eta J^2\, dV \sim \frac{\partial}{\partial t} \int \tfrac{3}{2} n_i T_i\, dV \sim 5 \text{ MW}$$





(relative to reconnection event)

Reusch et al, PRL 2011

Summary

- Ion heating and acceleration associated with magnetic reconnection from tearing instability is powerful and robust in the RFP (and other toroidal plasmas like spheromaks, STs)

- Heating characteristics are consistent with gyro-resonant heating and/or stochastic/Fermi processes

- Ion confinement is relatively insensitive to stochastic magnetic diffusion, so energy transferred by reconnection is confined, hence identifiable

- Difficult to discern possible electron heating during reconnection events, since ohmic heating is large, and electron heat transport from stochastic diffusion is very large. Will look for energetic electrons during reconnection events using energy-resolved x-ray measurements.