Parallel and perpendicular ion heating in the MST RFP

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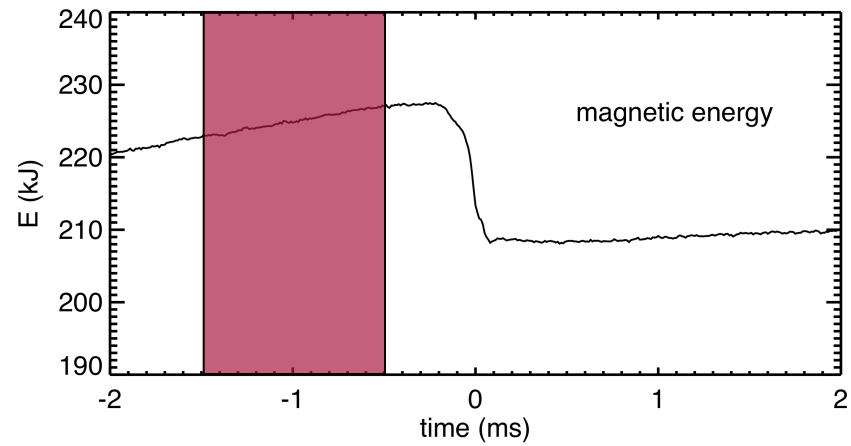
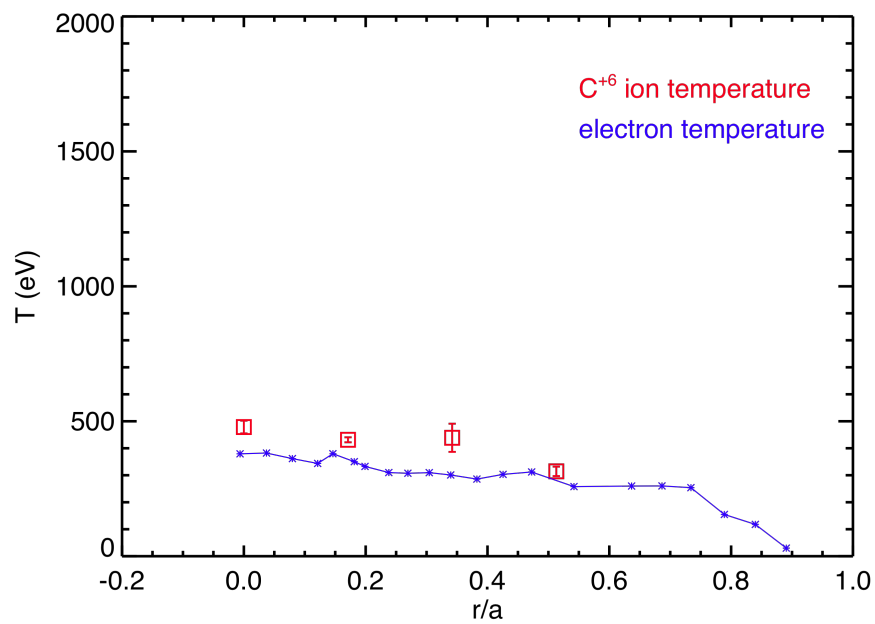
ORNL FEST seminar

Non-collisional ion heating is observed in MST

- Energy is transferred from the equilibrium B-field to ion thermal energy by an unknown mechanism

- Detailed measurements of ion distribution function may provide strong constraints to ion heating theory
  - isotropic?
  - Maxwellian?





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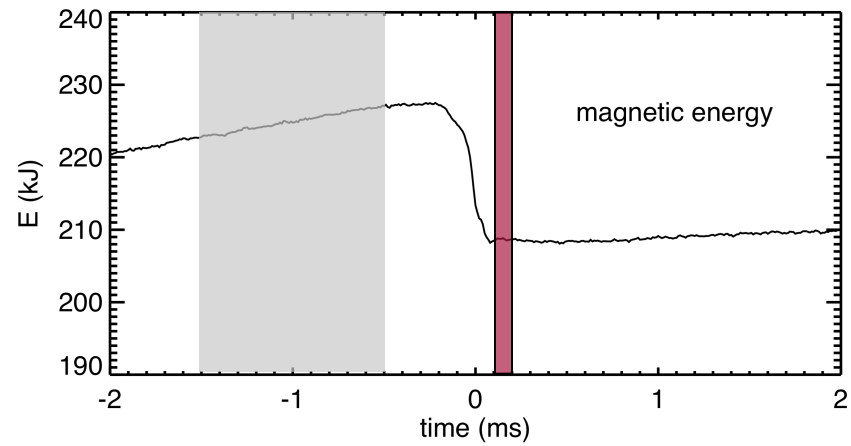
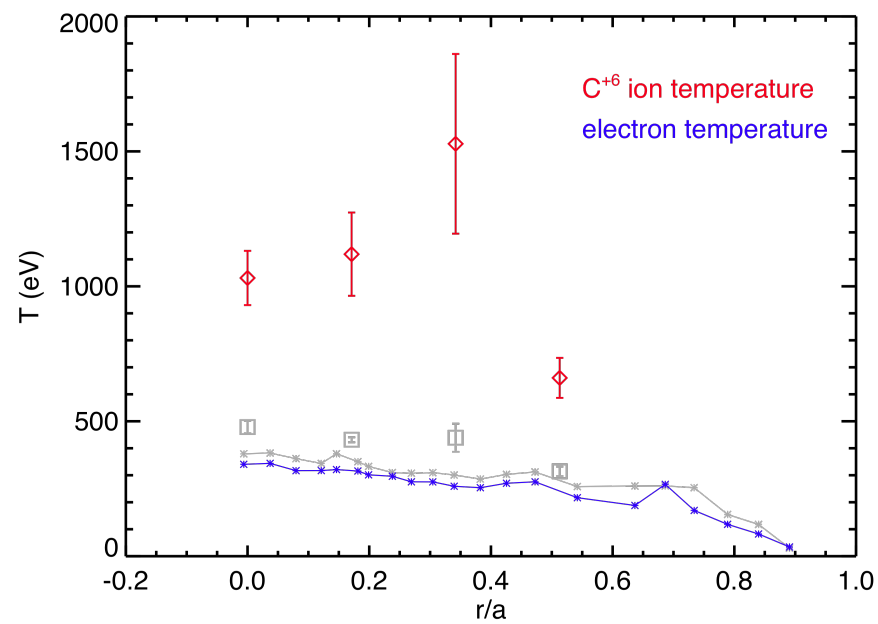
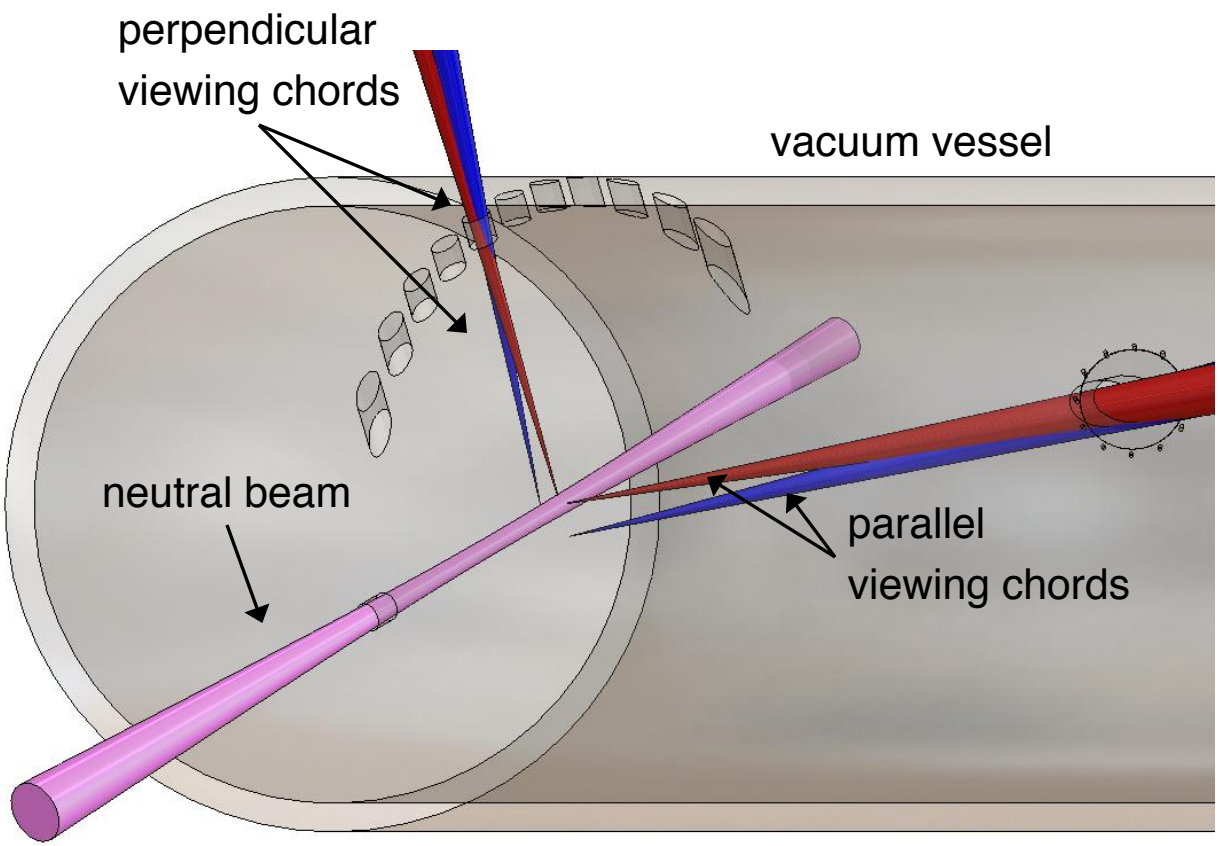




New diagnostic capability: measure T_{perp} and T_{par} in the core of MST

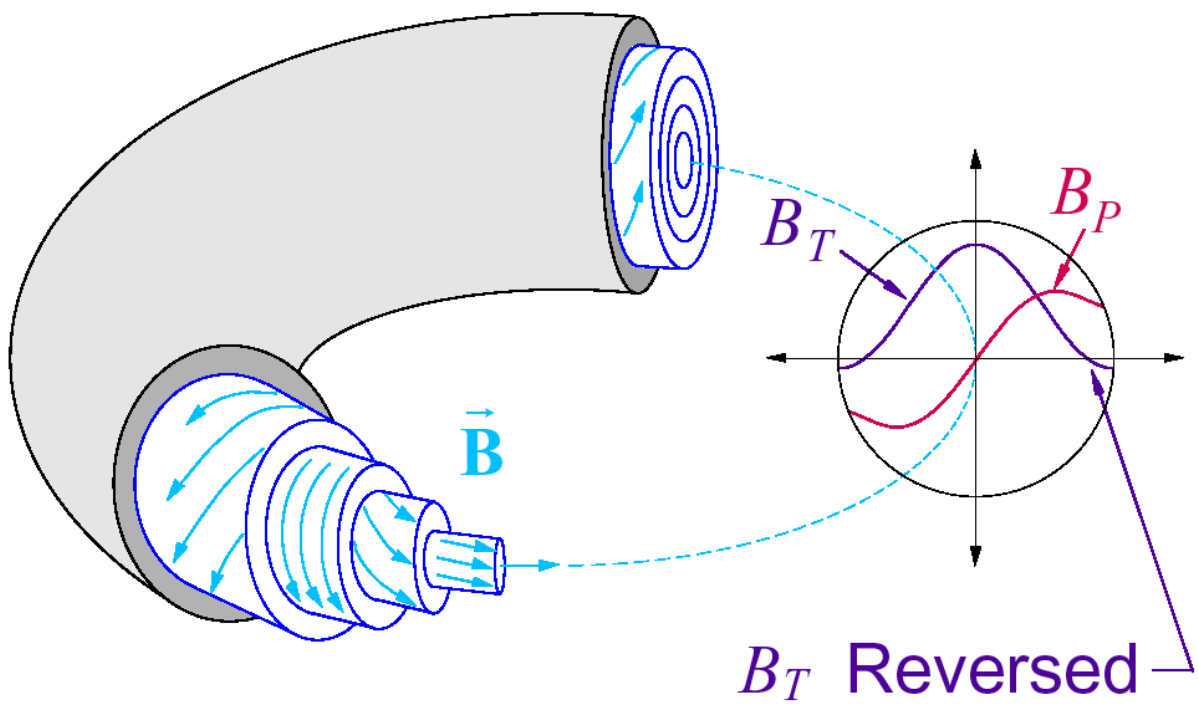
- Good time resolution (10-100 kHz)
- Good spatial resolution (1-4 cm^2)
- MST discharge reproducibility allows effective comparison



Outline

- Magnetic reconnection ion heating in MST
- CHERS
  - the diagnostic
  - T_{par} vs. T_{perp}
- DD-fusion neutrons - measurement vs. models
- Conclusions

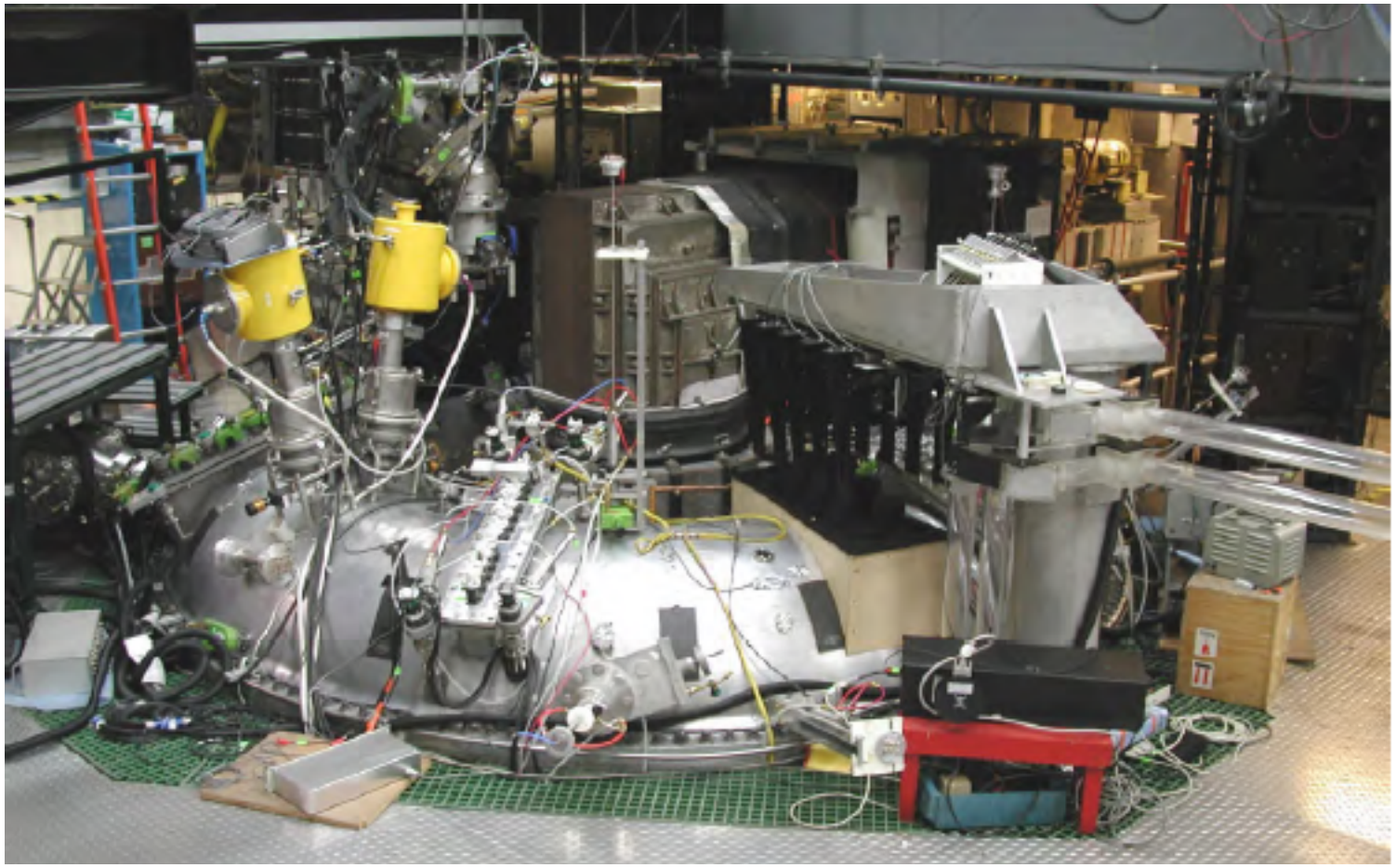
The Reversed Field Pinch is a low B toroidal confinement device



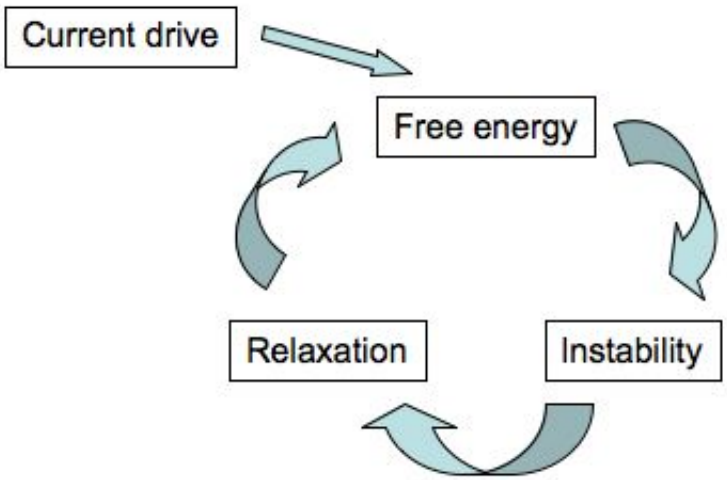
- Low magnetic field allows for self-organization
- Susceptible to tearing instability

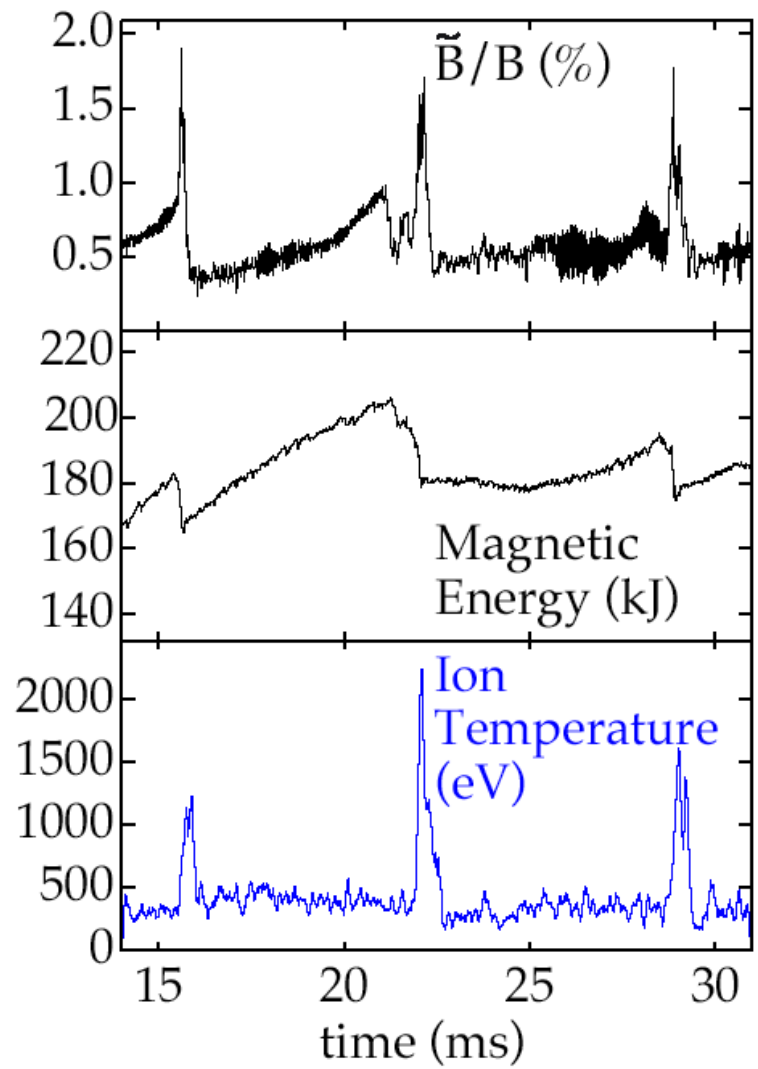
The Madison Symmetric Torus is a large, moderate current RFP

R = 1.5 m	I_p ≤ 600 kA	$n_e = 0.4 - 4.0 \times 10^{19}\ m^{-3}$	$\beta \leq 26\ \%$
a = 0.52 m	B = 0.5 T	$T_{i,e} = 0.2 - 2$ keV	



Magnetic reconnection is impulsive and semi-periodic in MST





- Large amount of power is liberated from magnetic field

  $P_{mag} \sim 10$ kJ/ 100μs = 100 MW

  $P_{ohmic} \sim 5$ MW

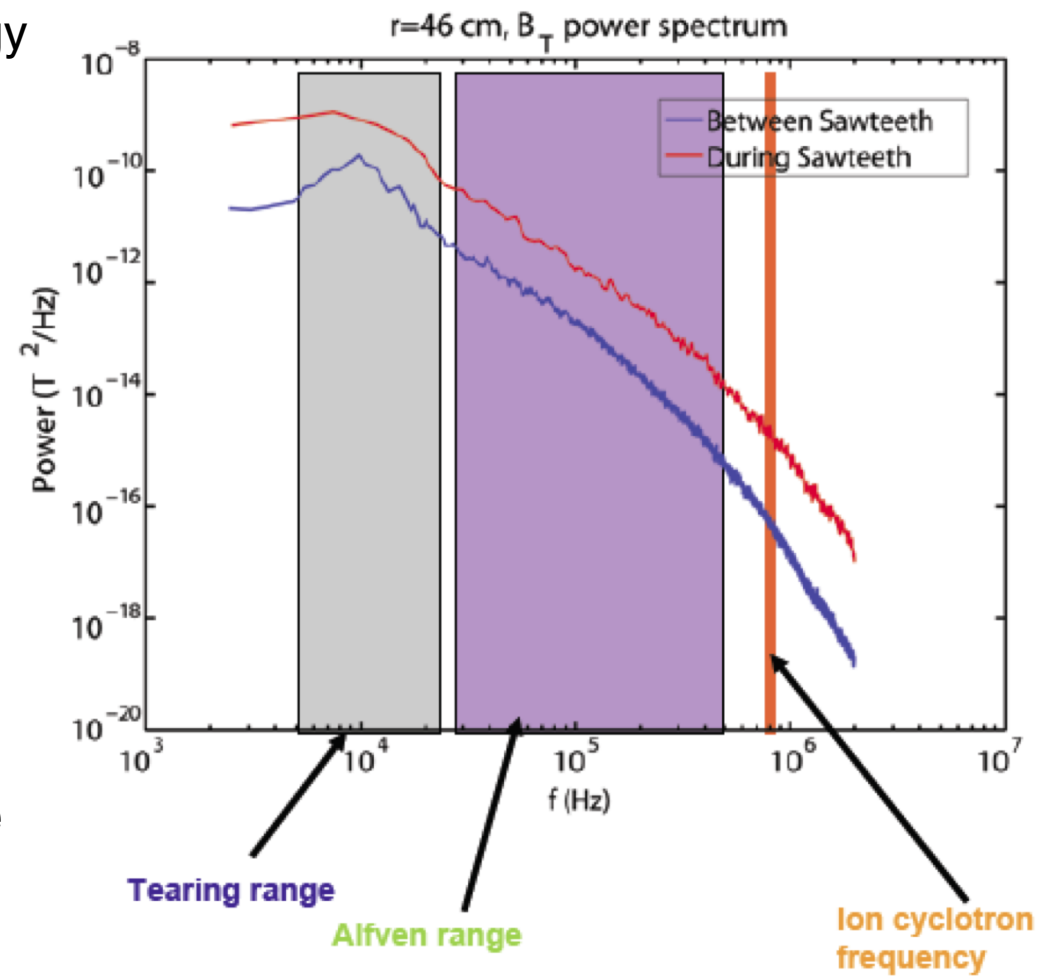
- ~10-25% appears as ion thermal energy

ICRH by cascade of tearing mode fluctuations has been a long-favored ion heating theory

- Assume magnetic fluctuation energy is converted to ion thermal energy by linear damping,

$$\frac{\partial}{\partial t} Q_\alpha = \frac{\partial}{\partial t}\left(\frac{\tilde{B}^2}{2\mu_0}\right) = \int d\omega \gamma_\alpha^{ICR} \frac{\tilde{B}^2(\omega)}{\mu_0}$$

- This heating rate is estimated to be ~ 10 eV/μs for species with q/m=1/2



Courtesy of Yang Ren

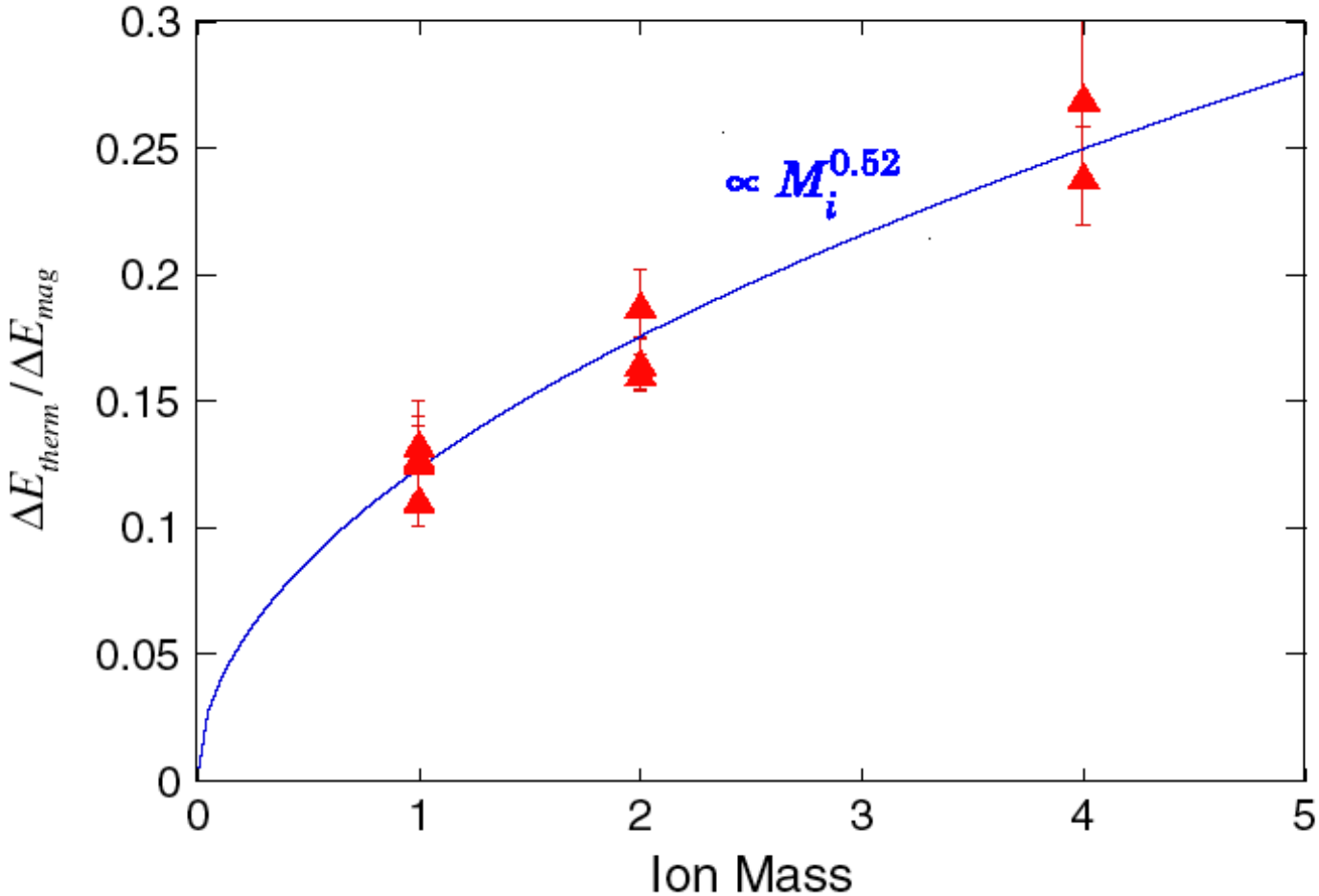
Several theoretical models exist

- ICRH of ions from turbulent cascade of magnetic fluctuations:
  - Perpendicular heating
  - species dependence $\Delta T \sim q/m$ (or $m^{0.5}$ for modified theory)

- Stochastic heating from random walk in fluctuating electric field
  - Perpendicular heating
  - species dependence $\Delta T \sim m^{0.5}$

- Viscous damping of parallel flows
  - Energy deposited in parallel degree of freedom
  - requires grad(v) $\sim v_{Ti}/\rho_i$

New result: heating efficiency ~ $m^{1/2}$

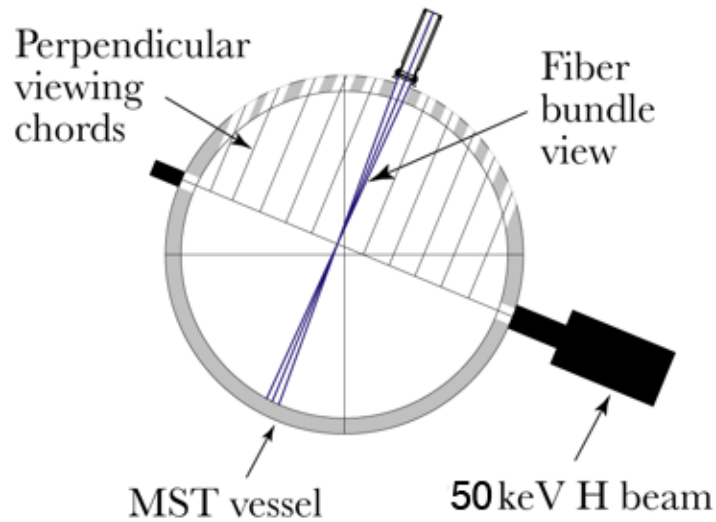


Fiksel et. al. PRL 103, 145002 (2009)

The CHERS diagnostic

CHarge Exchange Recombination Spectroscopy

1. Inject 50 keV H^0 with diagnostic neutral beam (DNB)



2. Neutrals charge exchange with C^{+6} impurities

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

3. Recombined ion (C^{+5}) promptly emits de-excitation photon

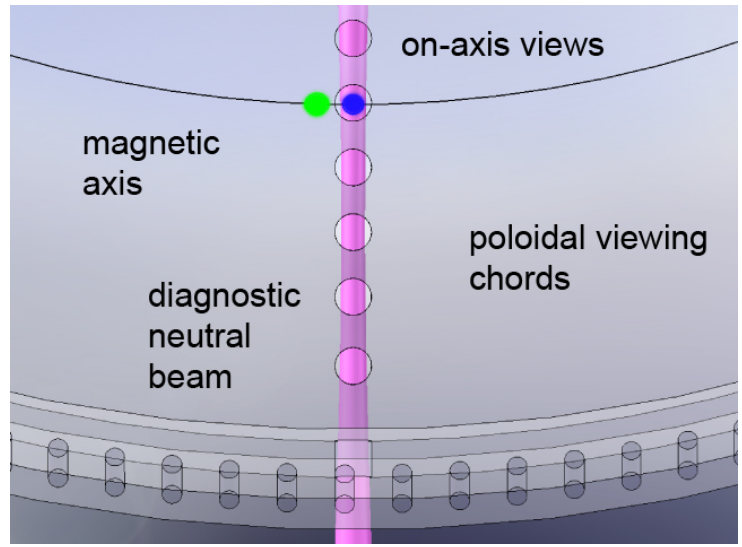
$$C^{+5*} \rightarrow C^{+5} + h\nu$$

4. *However*, electron impact excitation can also create C^{+5*}...

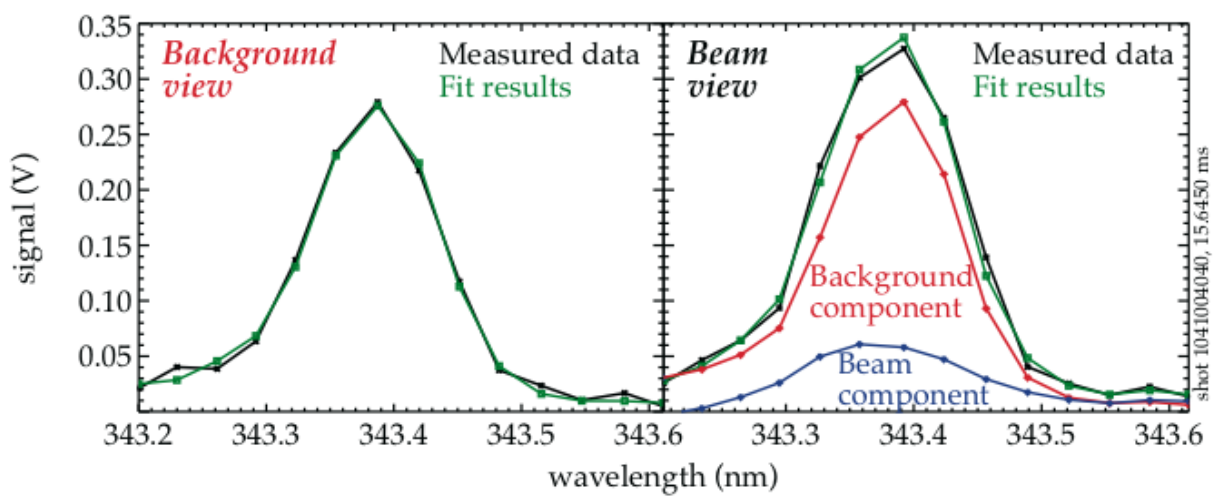
$$C^{+5} + e^- \rightarrow C^{+5*} + e^-$$

Electron impact excitation dominates signal

- A simultaneous, nearby background measurement isolates EI component



- Signal-to-background ratio is small (~0.2)



Atomic modeling of fine structure is critical for low temperatures

- *n* = 7-6 transition has 31 allowed transitions ($\Delta l=\pm 1$, $\Delta j=0,\pm 1$)

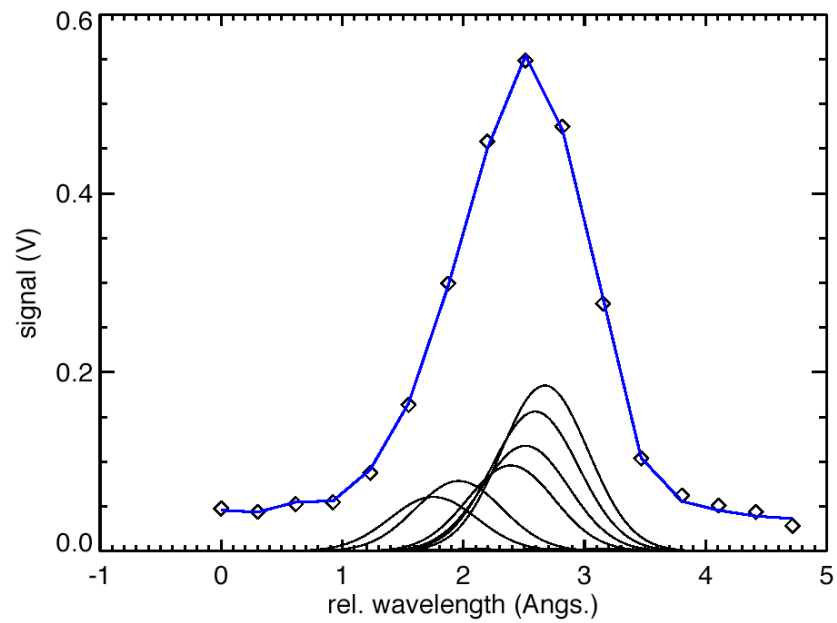
- Can be non-degenerate due to L-S coupling

- Use ADAS to determine relative poplulations

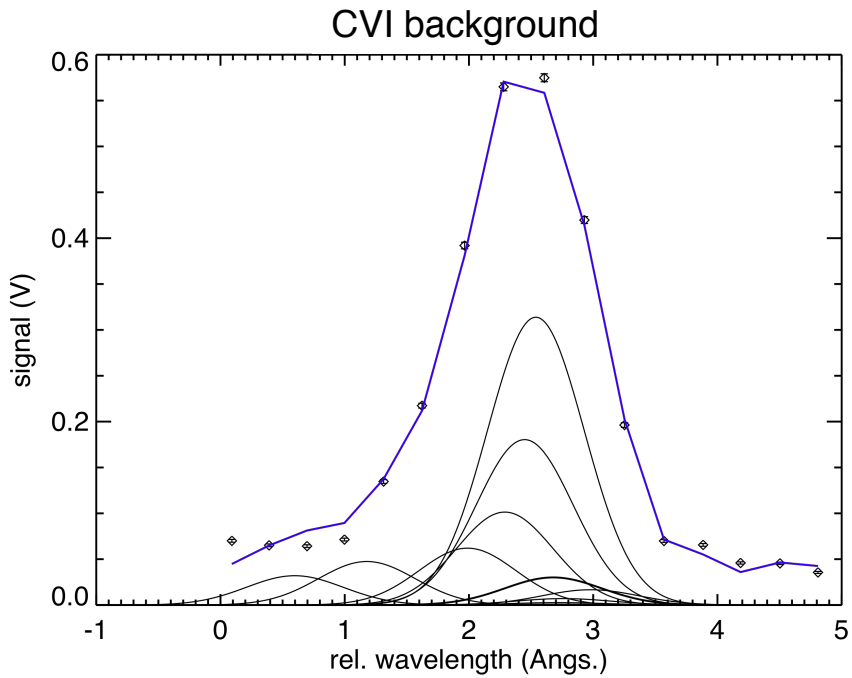
- Important for low temperatures,

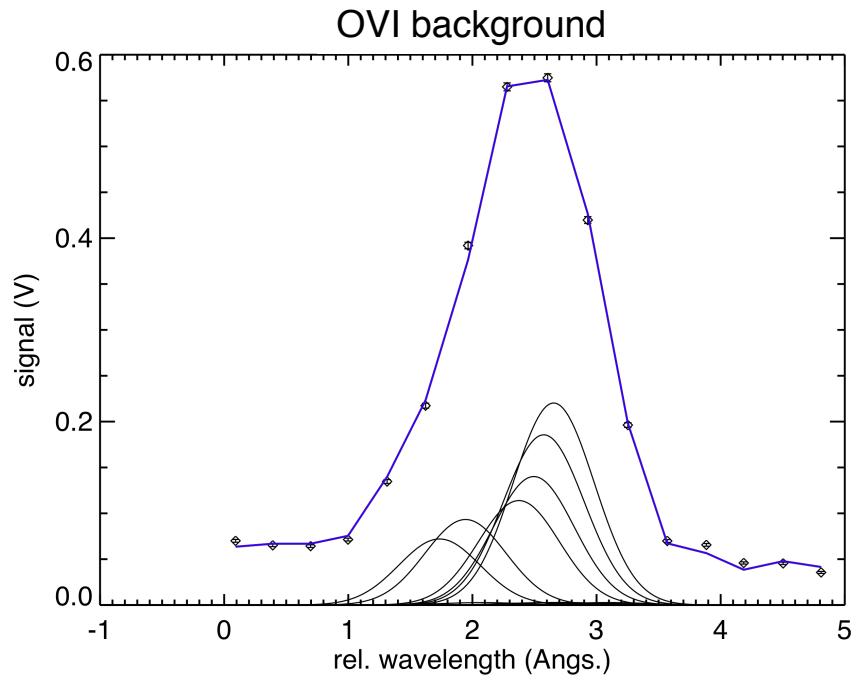
  T = 160 eV with fine structure

  T = 263 eV without



Adjusting the ratio OVI / CVI in the model has a large effect on the goodness-of-fit



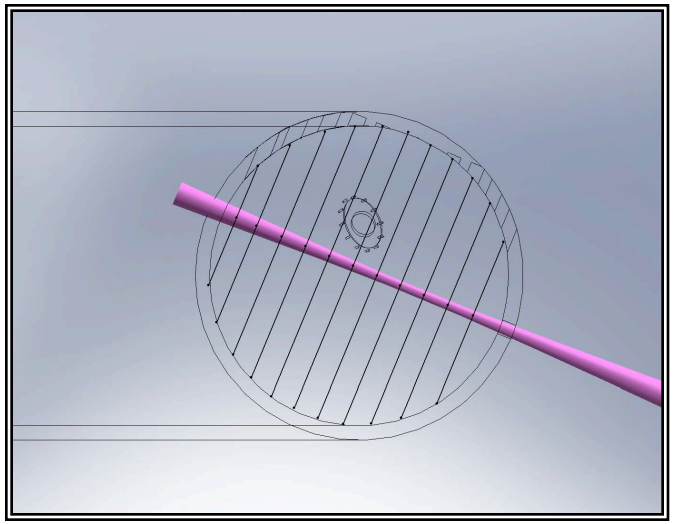


- OVI dominated background (right) fit much better than CVI dominated background (left)
- OVI / CVI ratio in model can affect inferred velocity by up to 10 km/s

Longer line-of-sight for toroidal view gives lower signal-background ratio

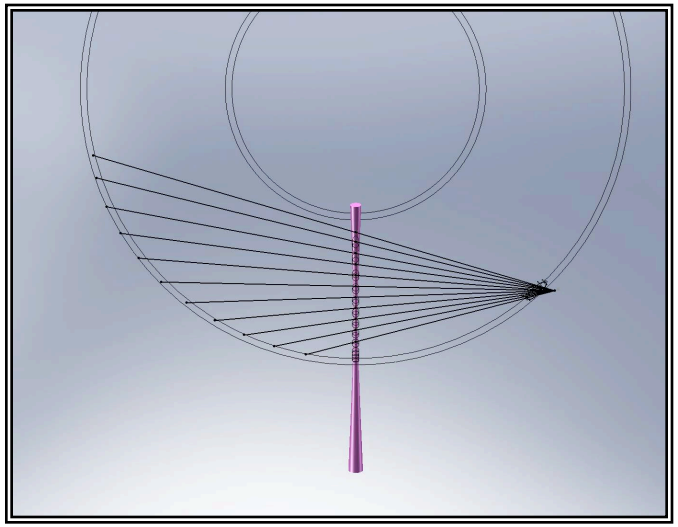
Poloidal view

- 8 discrete viewing locations
  - $-0.7 < r/a < 0.7$
- signal/ background ~ 0.25
- spatial resolution ~ 1 cm^2
- separation ~ 4 cm



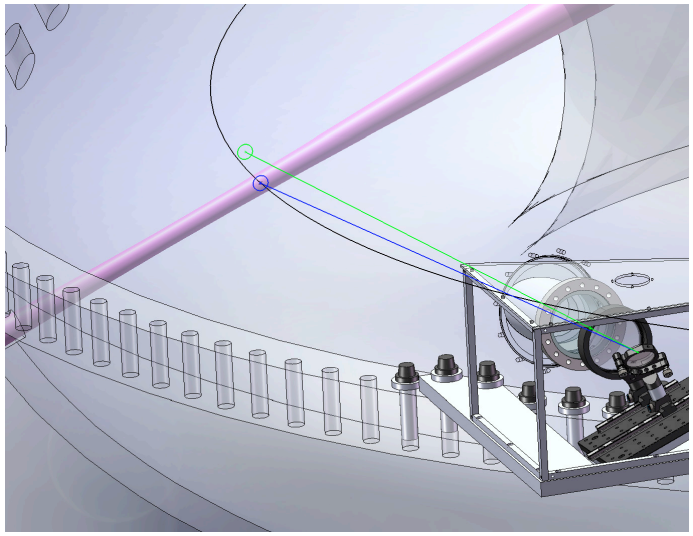
Toroidal view

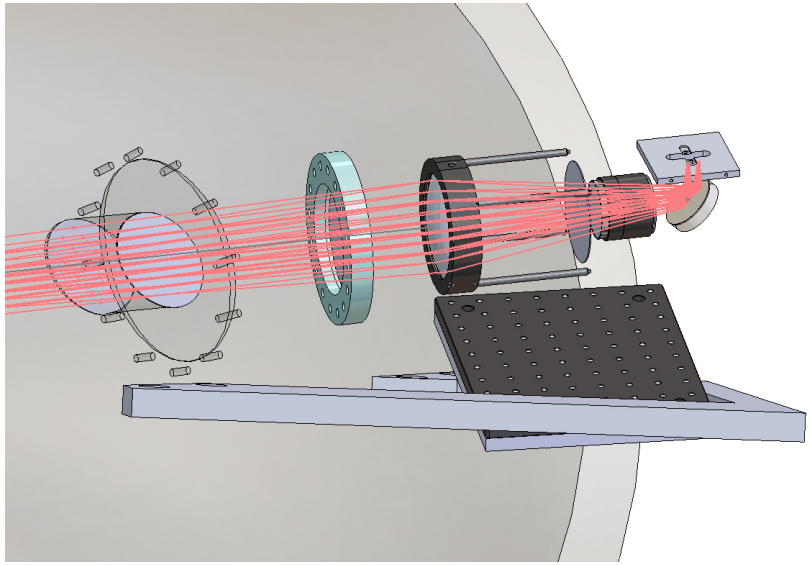
- continuous viewing
  - $-0.6 < r/a < 0.4$ (design)
- signal/ background ~ 0.1
- spatial resolution ~ 4 cm^2
- separation ~ 6 cm



Toroidal view design

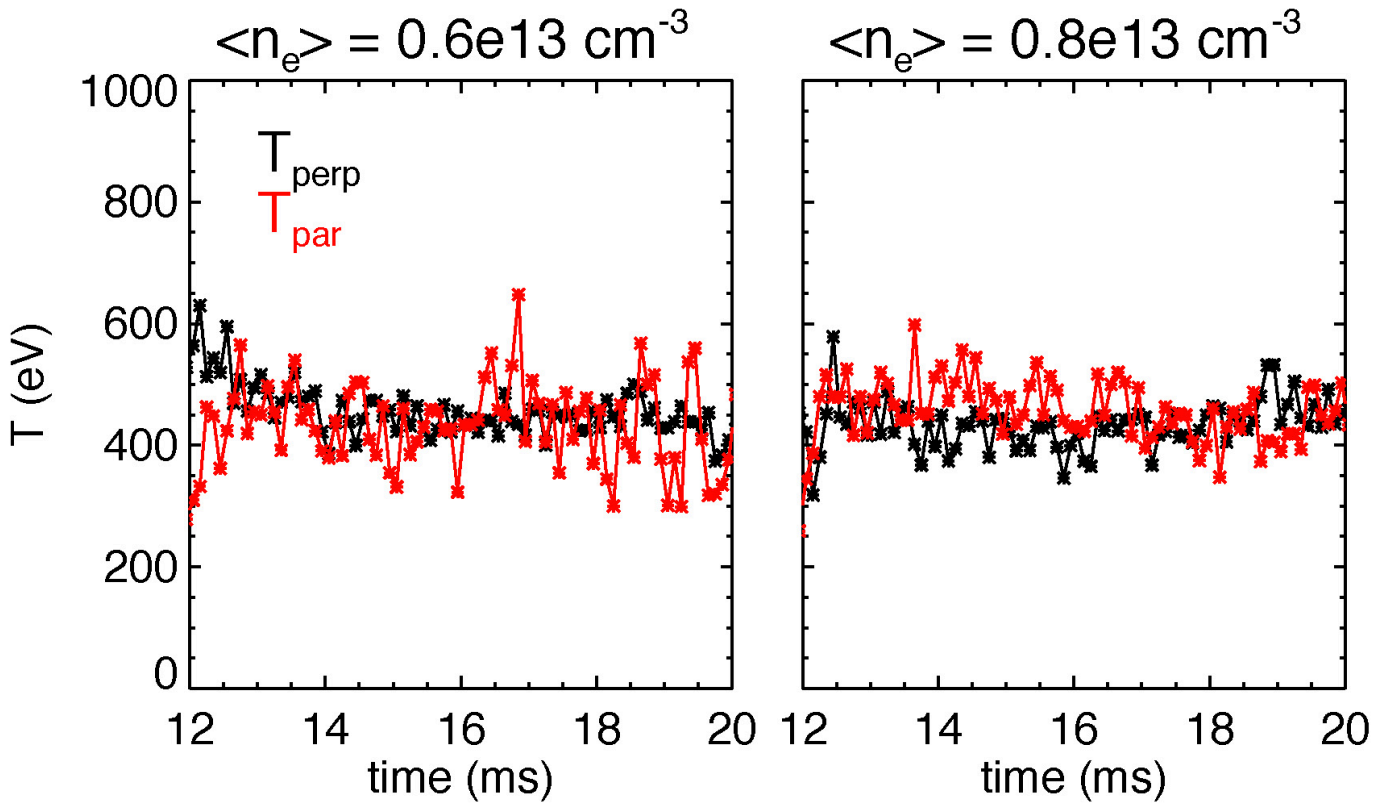
- Utilizes existing MST porthole
- Design challenges
  - non-ideal geometry
  - multiple viewing locations
  - sufficient light collection





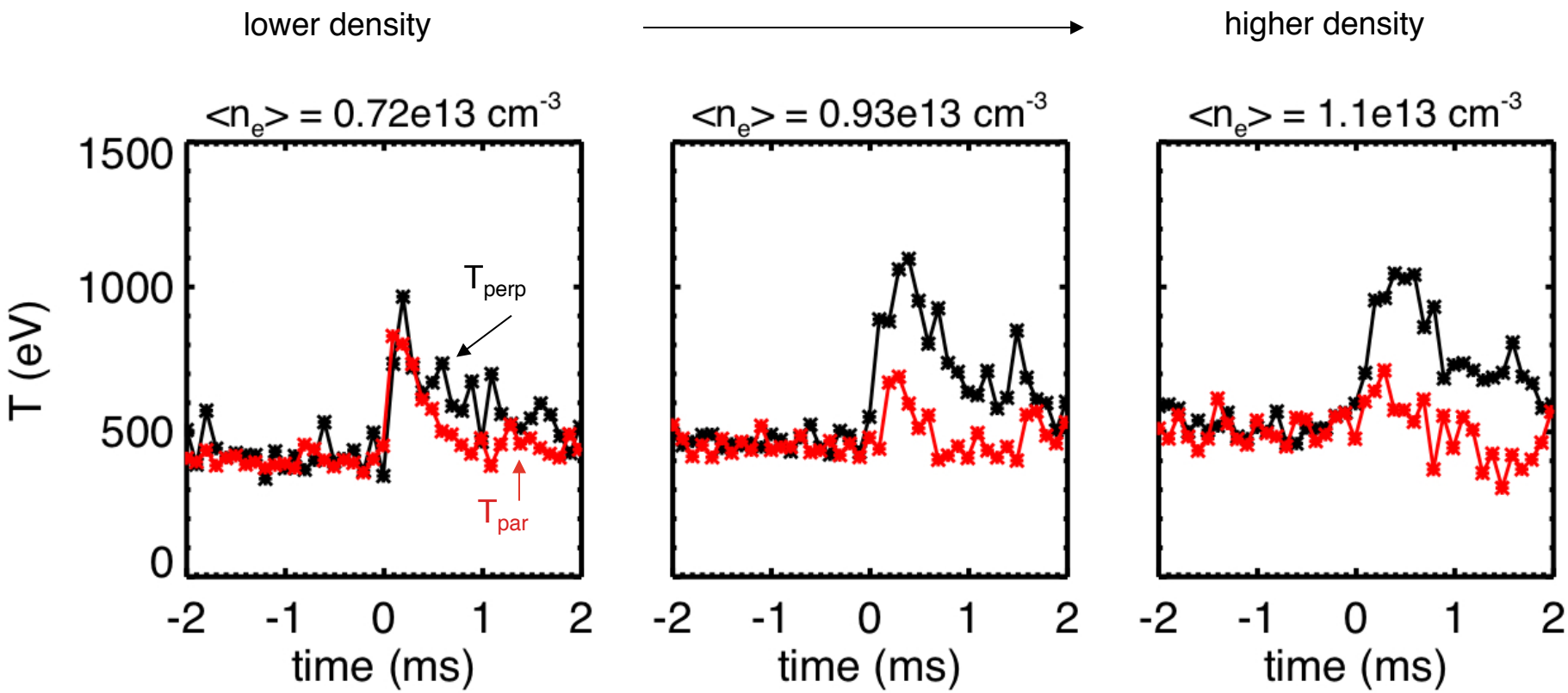
CHERS data

In improved confinement plasmas, there is no reconnection heating and $T_{perp} = T_{par}$



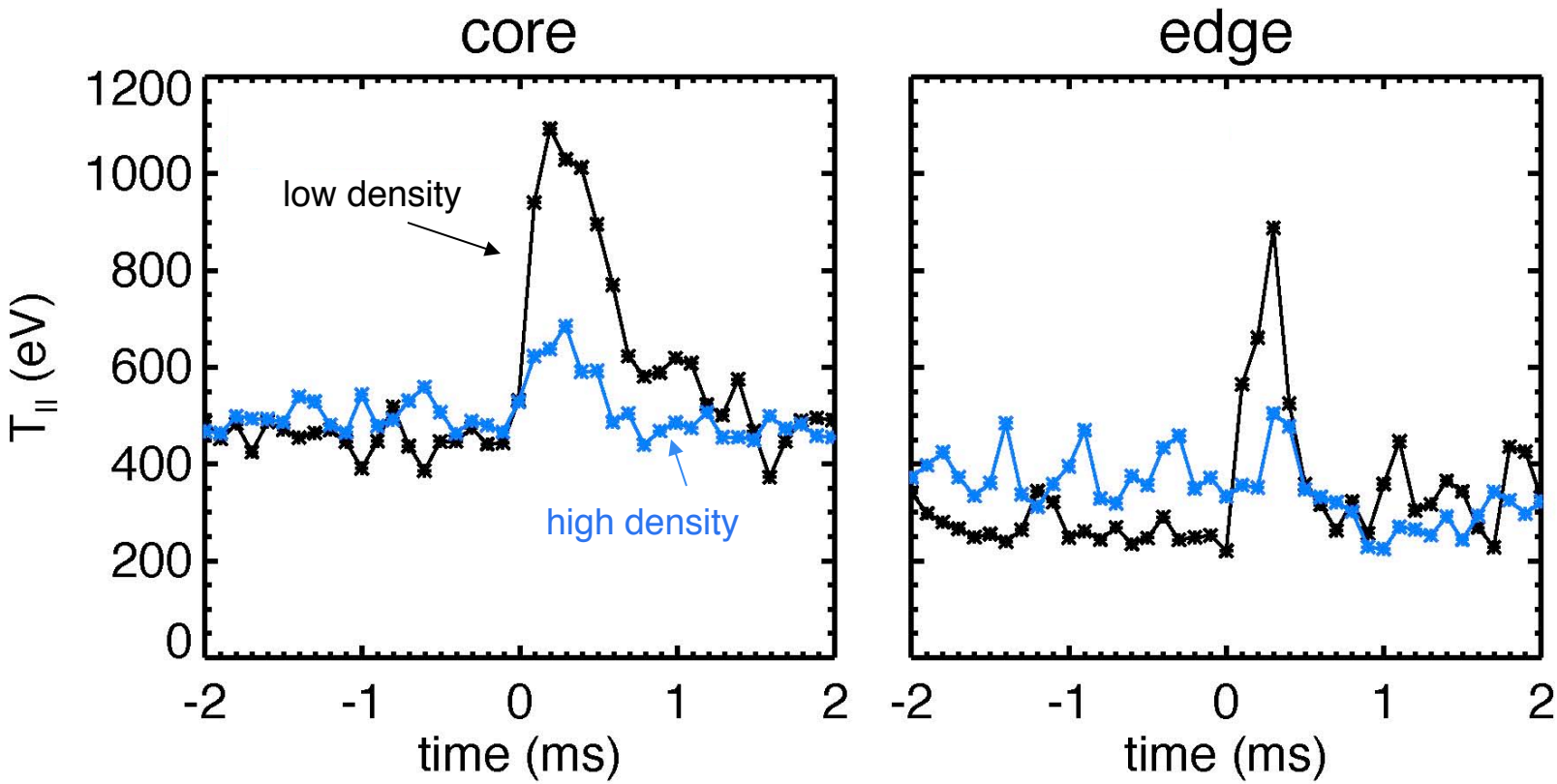
- Quiescent plasmas provide benchmark for new measurement

Parallel heating shows a density dependence that perpendicular does not



- Anisotropy persists for many collisional isotropization times, $\tau \sim 0.1$ ms

Density dependence observed wherever T_{par} is measured



- T_{par} at the reversal surface shows similar behavior to T_{par} in the core

Enhanced charge-exchange losses at high *n* may explain observation

- Assume heating mechanism acts on T_{perp} (ICRH, stochastic heating)

- T_{par} should rise due to pitch-angle scattering in a few τ_{perp}'s,
… *unless* there is a competing loss mechanism

- The charge-exchange cross-section for C^{+6} and excited neutral deuterium can be large (10^{-13} cm^2),

$$\tau^*_{cx} = (n^*_d \, \sigma^*_{cx} \, v_c)^{-1} = 100 \, \mu s$$

Comparable to scattering time!

- Furthermore, neutral fraction increases with plasma density

Neutron detection

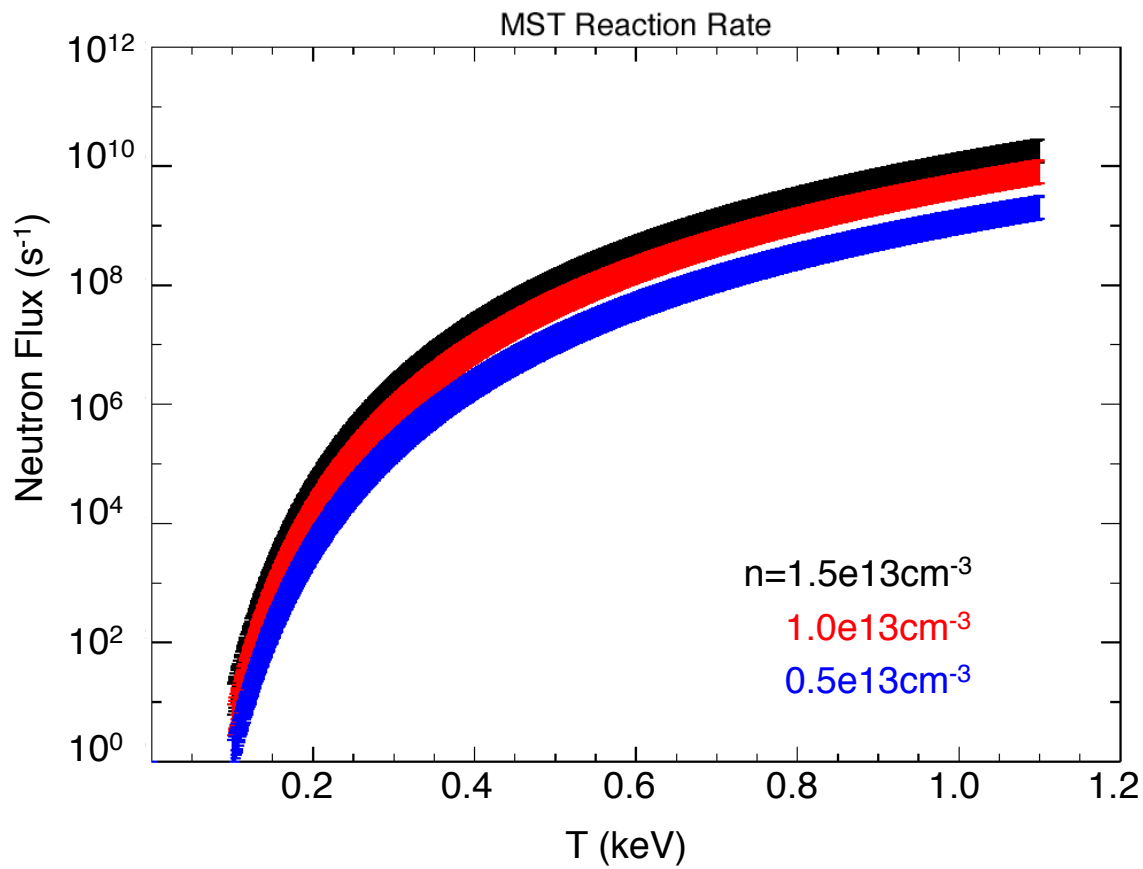
Neutron flux depends on ion density and energy

- Deuterium plasmas produce fusion neutrons,

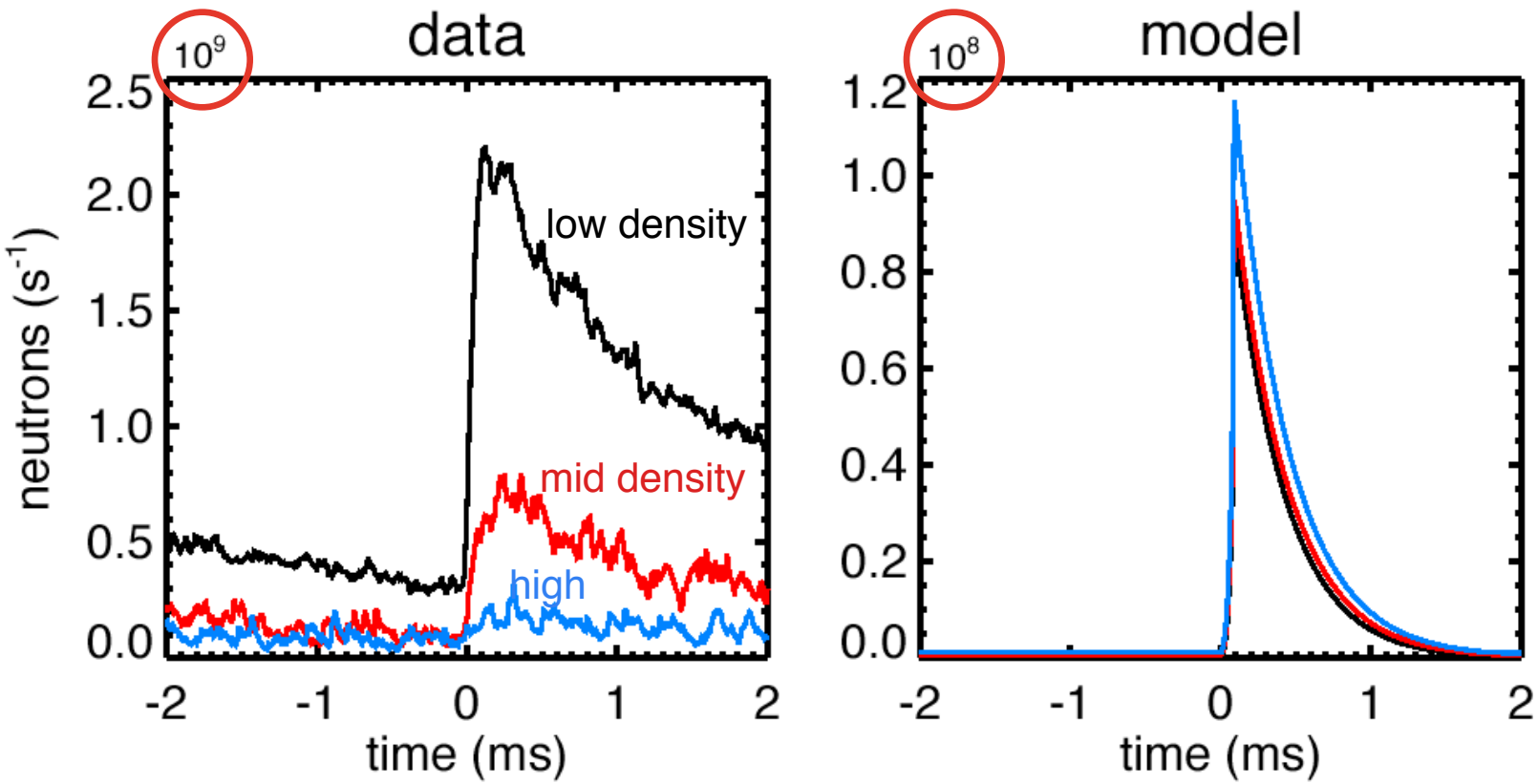
$$D + D \rightarrow He^3 + n$$
$$\rightarrow T + p$$

- We can calculate neutron flux based on measured values of n_i and T_i, assuming a Maxwellian distribution,

$$\Phi \sim n_i^2 \overline{\sigma v}(T_i)$$



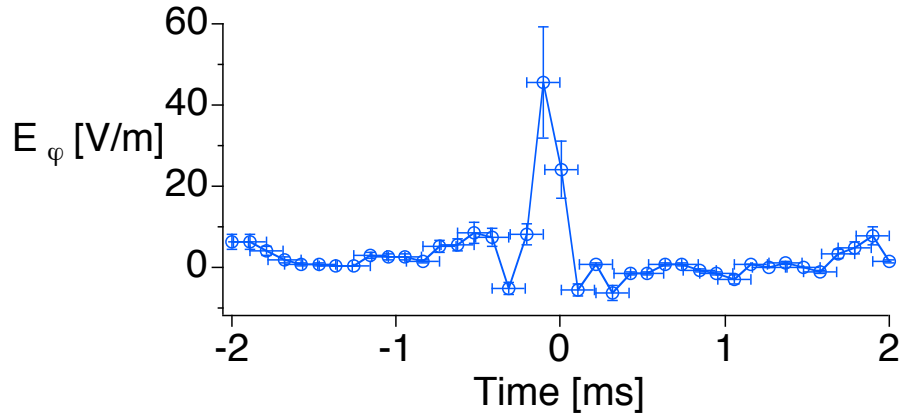
Neutron flux measurements do not agree with predictions using Maxwellian assumption



- 3 differences between data and (2 temperature) Maxwellain model:
  - data show low density neutron flux x10 higher than model
  - data show neutron flux decreasing with density
  - data show a longer decay constant

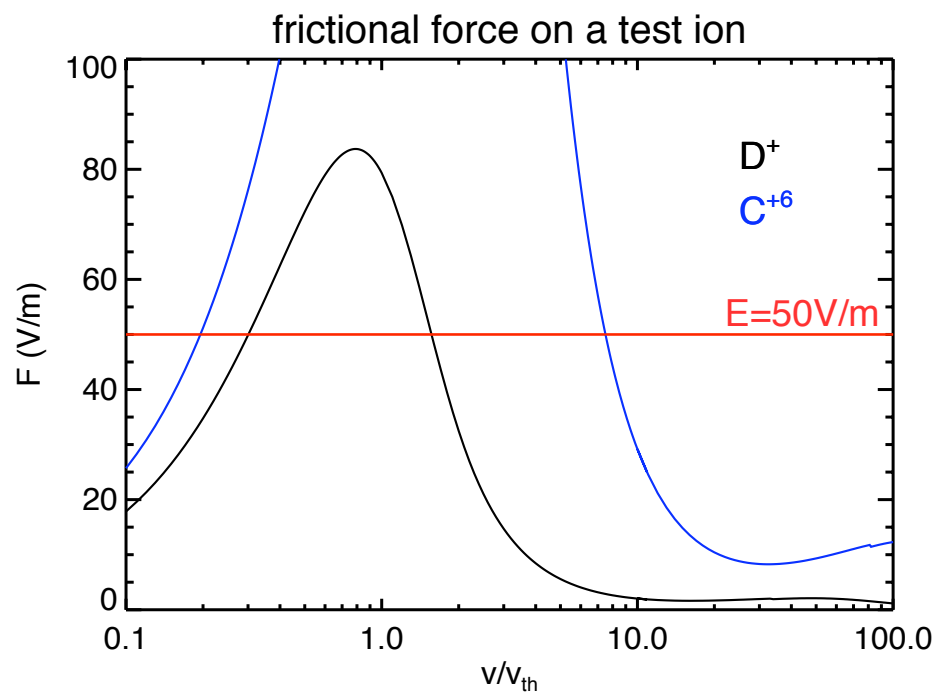
Large electric fields are induced during reconnection

- A large parallel E-field is measured during the event



- In equilibrium, ion acceleration is balanced by the electrons, but in the presence of impurities or trapped particles, there can be an imbalance.

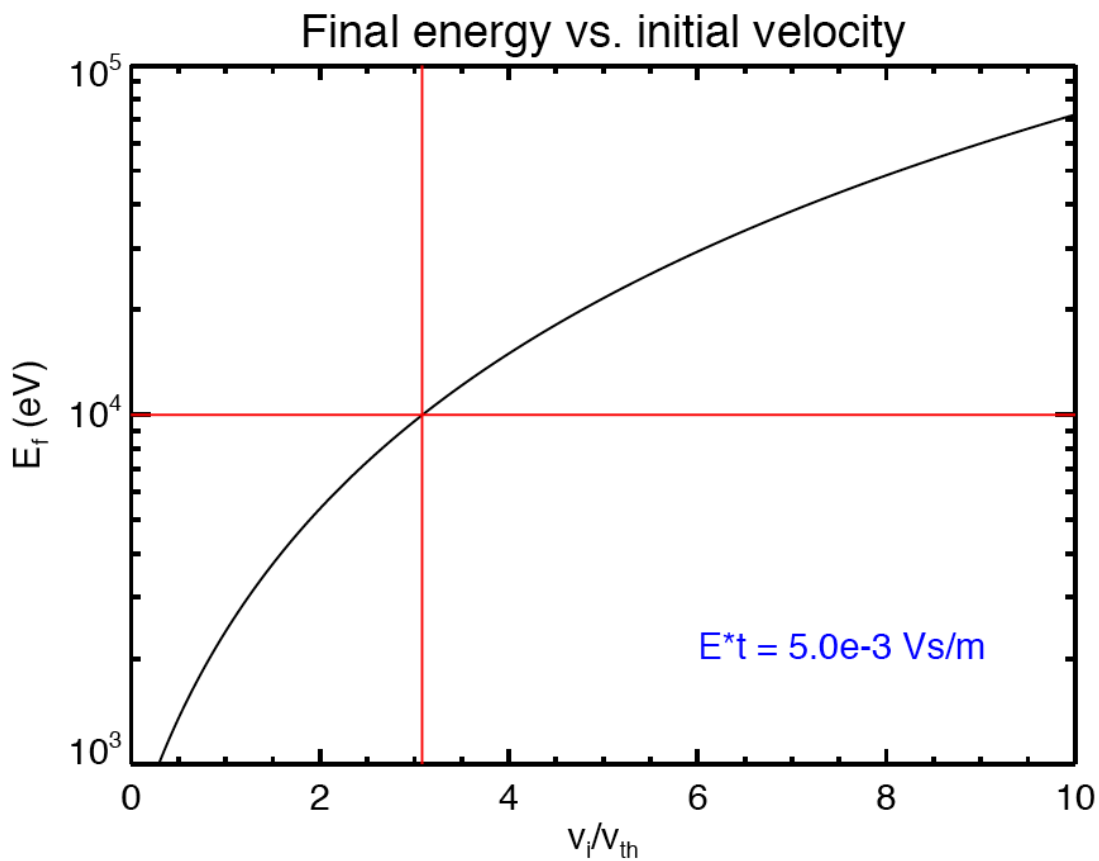
- Calculation based on e-i and i-i collisions shows that E can overcome friction for test D (not true for C^{+6})



Final energy is quadratic in initial energy

- The rich get richer!

- Neglecting friction, an ion with $v_i=3v_{th}$ can reach 10 keV in a single event



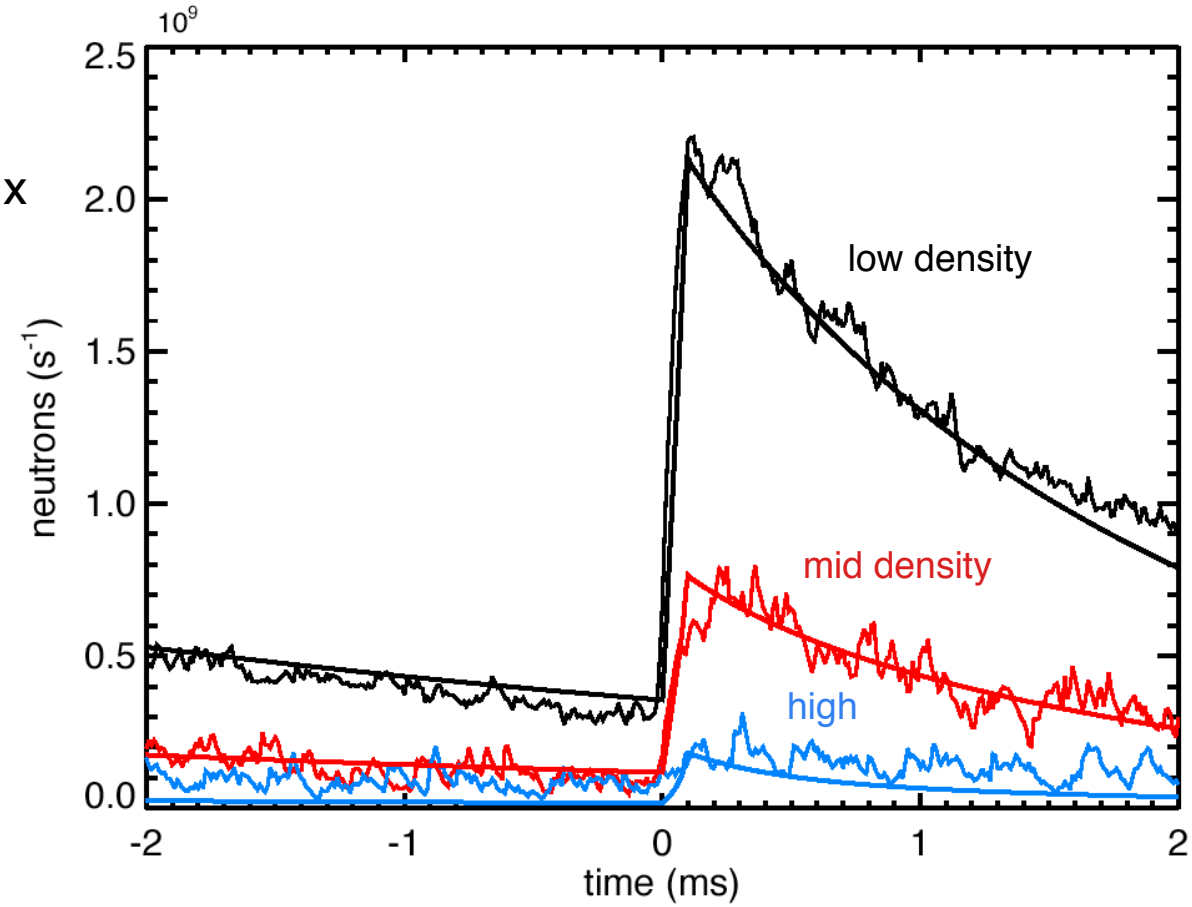
Measured neutron flux is consistent with suprathermal ion population

- Small number of suprathermal ions (E=17keV) can produce large neutron flux

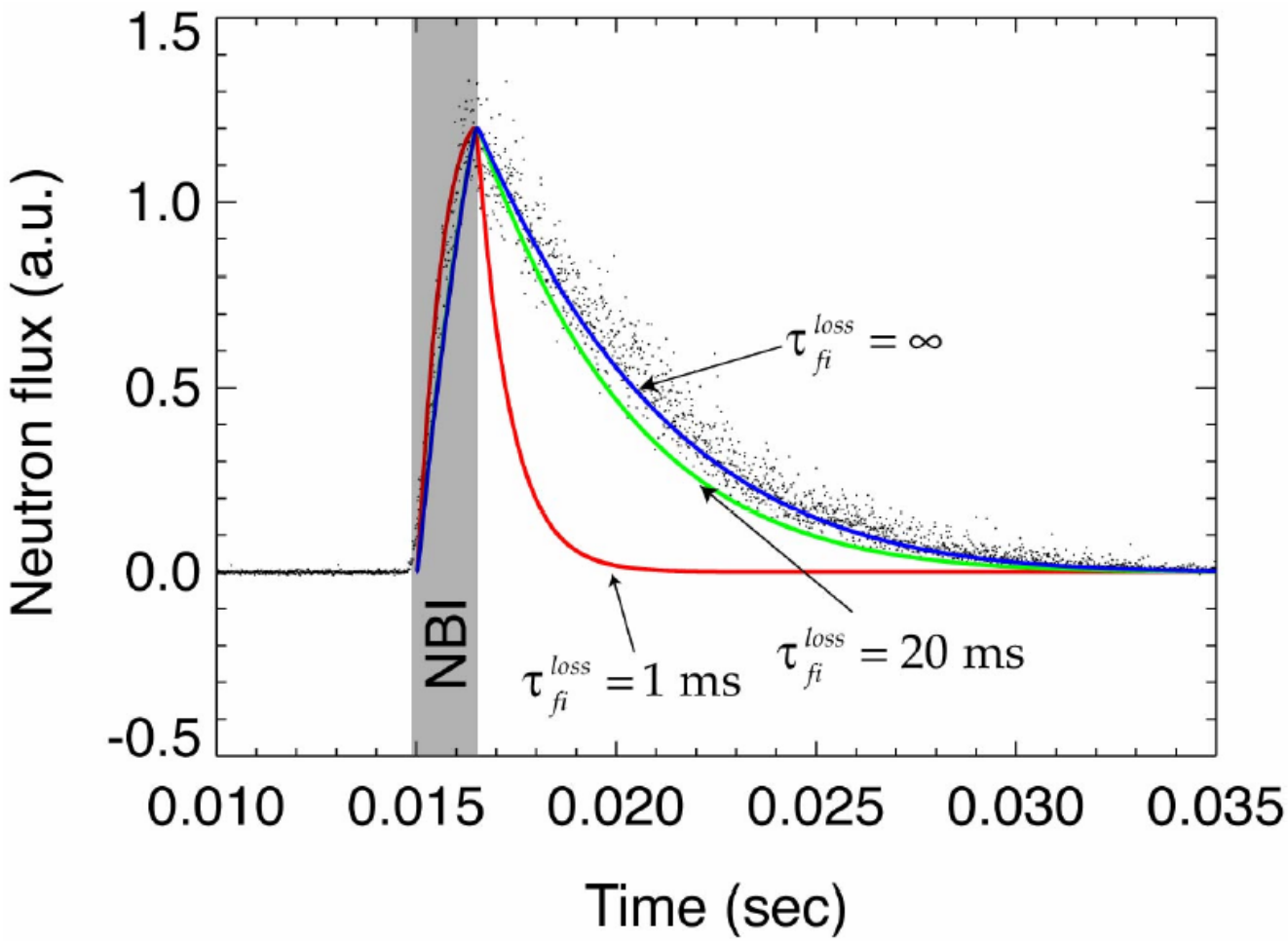
n_{fi} = 6%

= 1%

= 0.1%



NBI experiments show fast ions (E>7keV) are well-confined



Fiksel et. al. PRL 95, 125001 (2005)

Summary

- Several theoretical models for anomalous ion heating in the RFP exist. New observational constraints are needed.

- Parallel ion heating shows a strong density dependence that perpendicular does not. This may (or may not) be one such constraint.

- Neutron flux measurements can not be explained by thermal fusion. They are consistent with fusion from a small population of fast ions that do not exist in high density plasmas.

- There is no indication that fast ions are contaminating the C^{+6} temperature measurement.

Future work

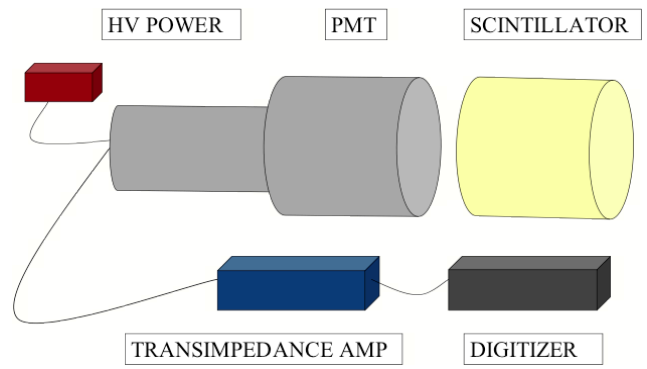
- Increase the time resolution of the T_{par} measurement to 100 kHz. This can be accomplished by:
  - Increasing the beam current of the diagnostic neutral beam (power supply was upgraded Jan. ’10)
  - Averaging spectral data before fitting to improve photon statistics

- Make off-axis toroidal measurements so that both T_{perp} and T_{par} profiles can be reconstructed.

The End

Neutron detector

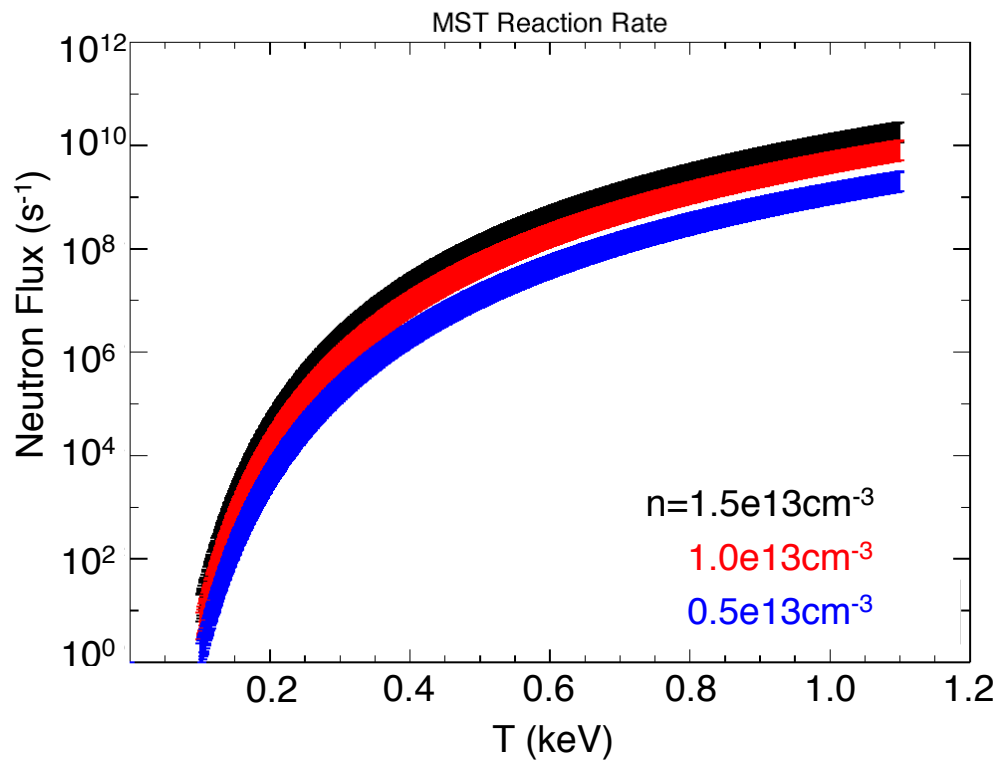
- Scintillation detector measures volume averaged neutron flux



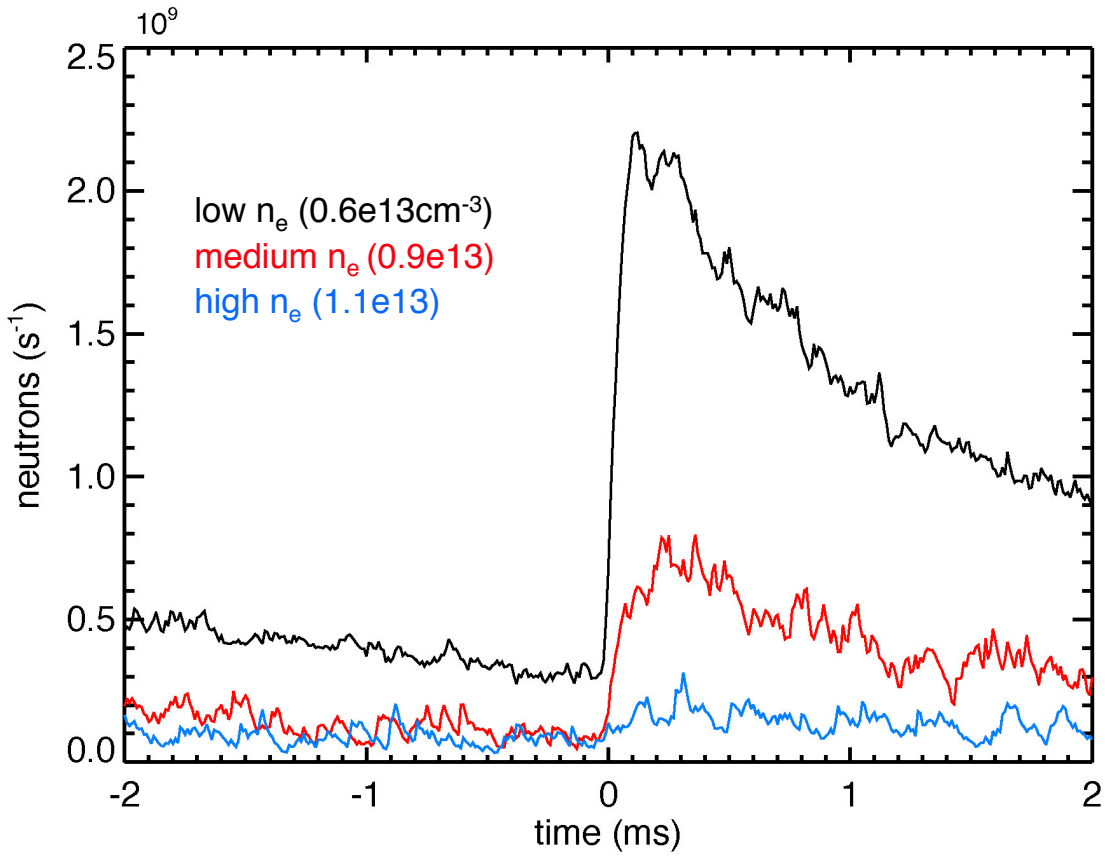
- The dd-fusion cross-section is very sensitive to ion energy

- Neutron flux ~ n^2,

$$\Phi = \frac{1}{2} n^2 < \sigma v > V$$



Low density plasmas show larger neutron flux than high

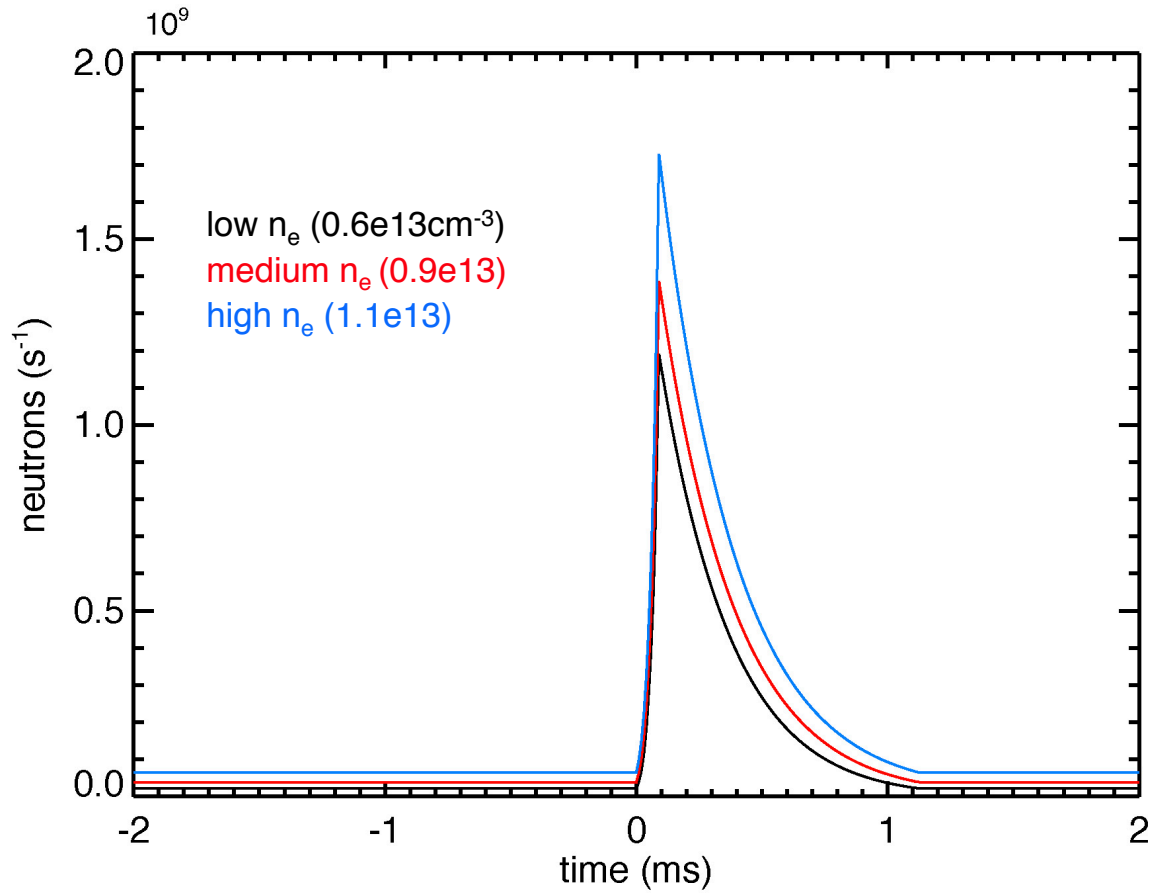


- Because $<\sigma v>$ is a very steep function of energy, its possible that lower T_{par} inhibits neutron production in high density plasma

Measured anisotropy is not large enough to explain observation

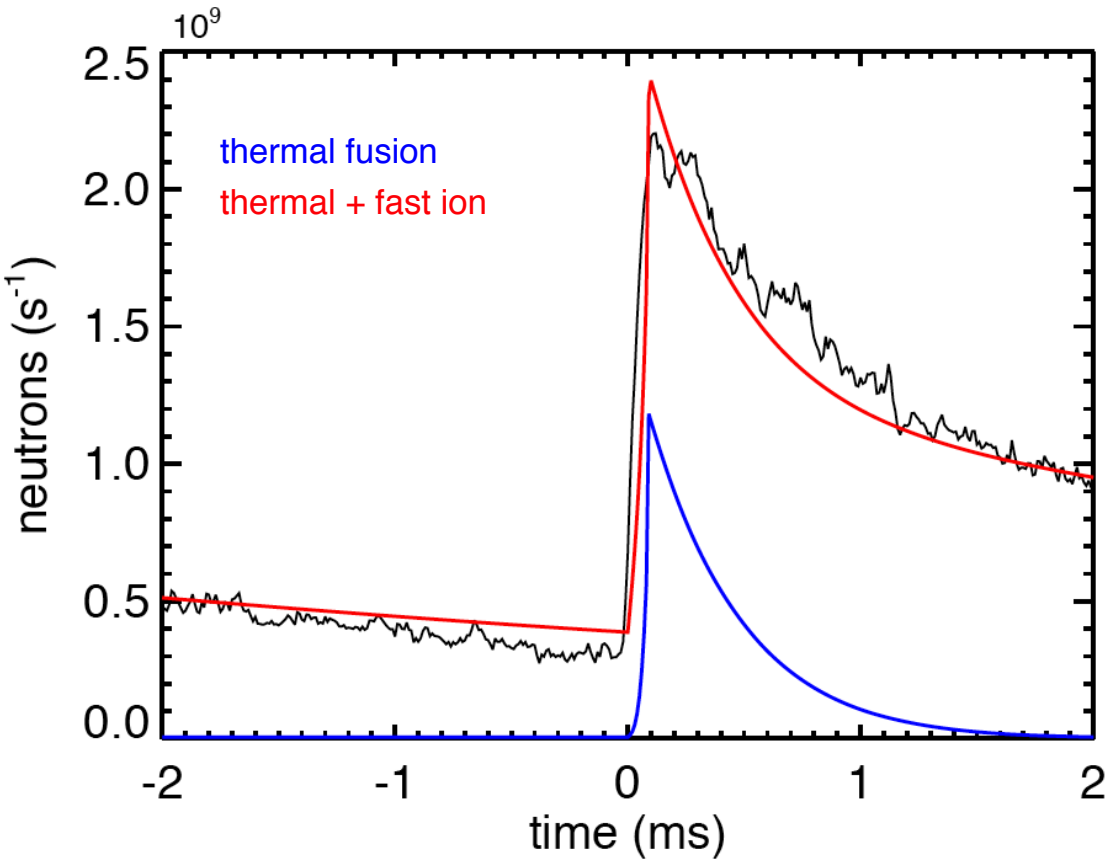
- In calculation, high density plasmas radiate more neutrons than low

- The measured flux is a factor of ~10 higher than the calculated flux



Measured neutron flux is consistent with thermal fusion plus a fast ion component

- Model parameters:
  - T_i = 0.4 keV before crash
  - T_i = 0.85 keV at crash
  - $n_{fi} = 0.015\ n_i$
  - E_{fi} = 17 keV



Calculating dd-fusion rate from anisotropic distribution

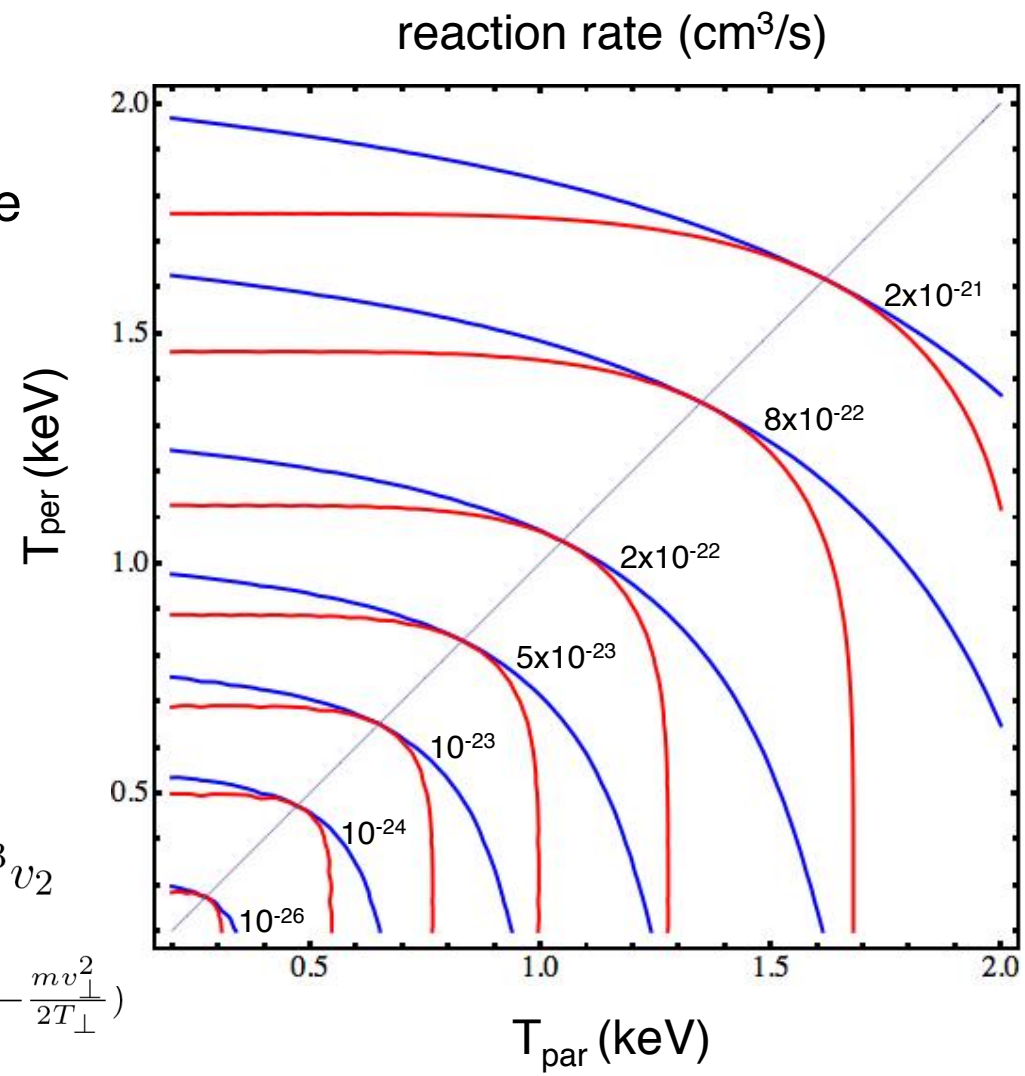
- Approximating a distribution with T_{par} ≠ T_{per} as two isotropic Maxwellians (red) overestimates the reaction rate,

$$R = \frac{2}{3} < \sigma v >_{T_\perp} + \frac{1}{3} < \sigma v >_{T_\parallel}$$

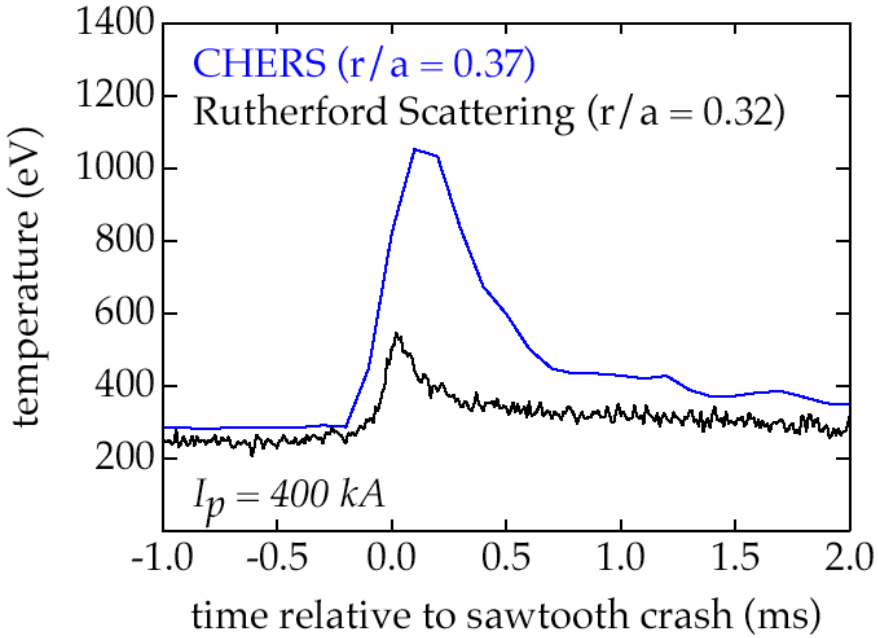
- Integrating the anisotropic *f(v)* yields the correct rate (blue),

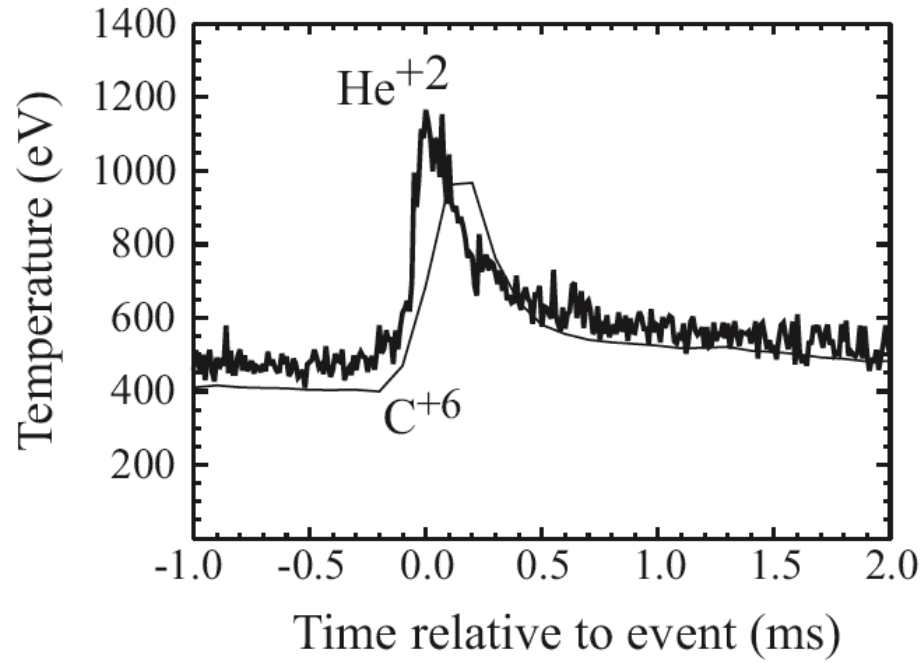
$$R = \int\int f(\vec{v}_1) f(\vec{v}_2) \sigma(|\vec{v}_r|) |\vec{v}_r| d^3 v_1 d^3 v_2$$

$$\text{where } f = \left(\frac{m}{2\pi T_\parallel}\right)^{\frac{1}{2}} \left(\frac{m}{2\pi T_\perp}\right) e^{\left(-\frac{m v_\parallel^2}{2T_\parallel} - \frac{m v_\perp^2}{2T_\perp}\right)}$$



Previous result: heating is species dependent





- Impurities heated more strongly than bulk in deuterium plasma, but temperatures agree well in helium plasma
- Difficult to distinguish between species dependent heating mechanisms and species dependent loss mechanisms (e.g. charge exchange)

S. Gangadhara, et. al. Physics of Plasmas 15, 056121 (2008)

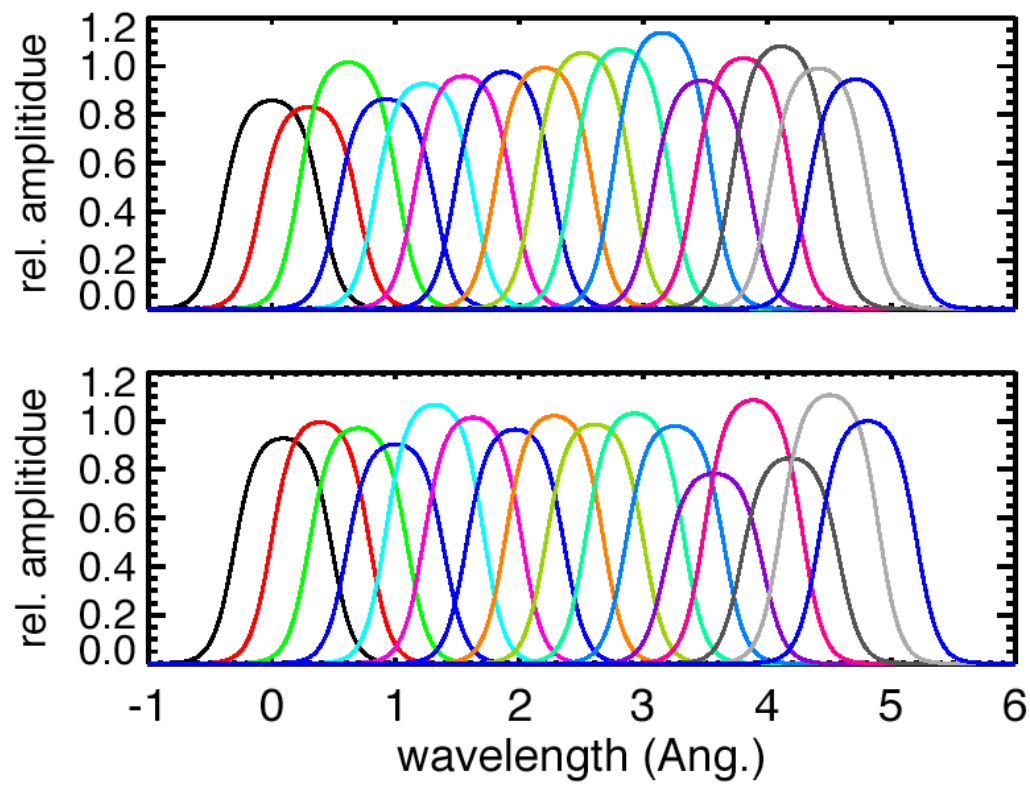
Spectrometer can measure T = 0.1-2.0 keV

- Instrumental broadening and the wavelength range of the spectrometer limit the temperature measurement,

$$kT_i = m_i\left(\frac{c\sigma}{\lambda_0}\right)^2$$

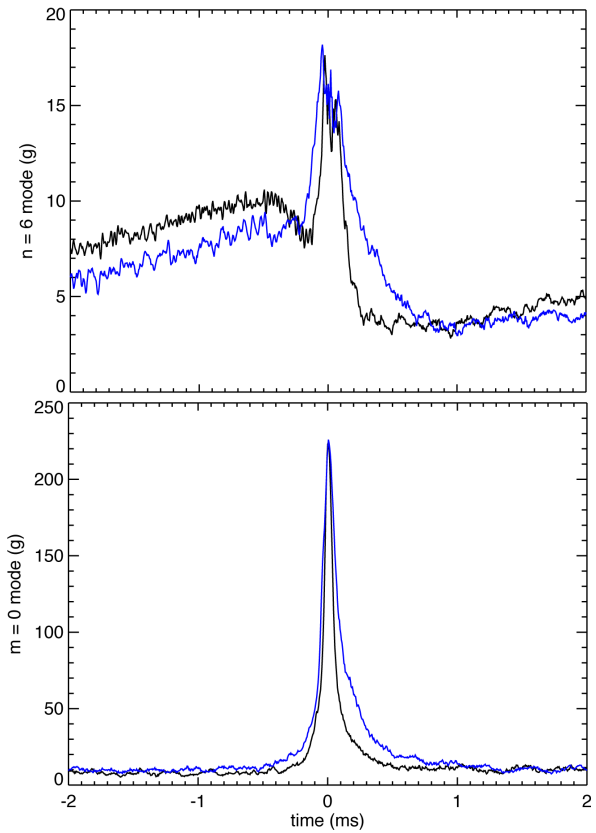
$$\sigma \approx 0.3 - 1.5\ A$$

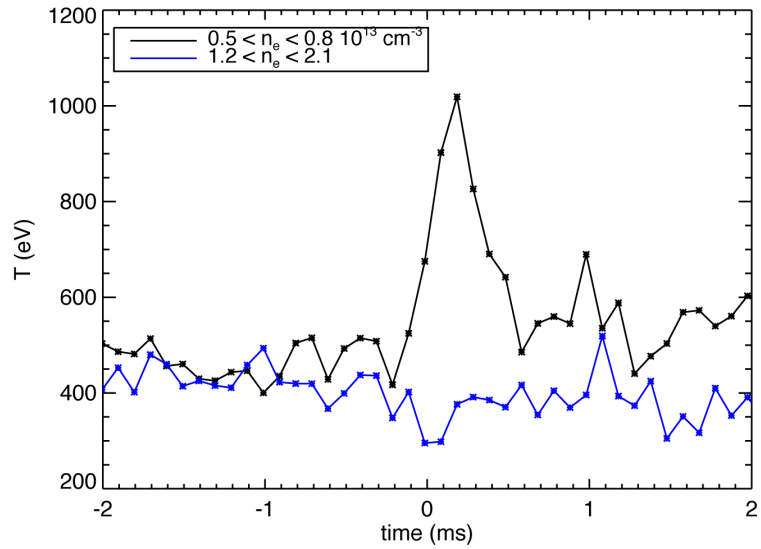
$$\Rightarrow T_i \approx 0.1 - 2.0\,keV$$

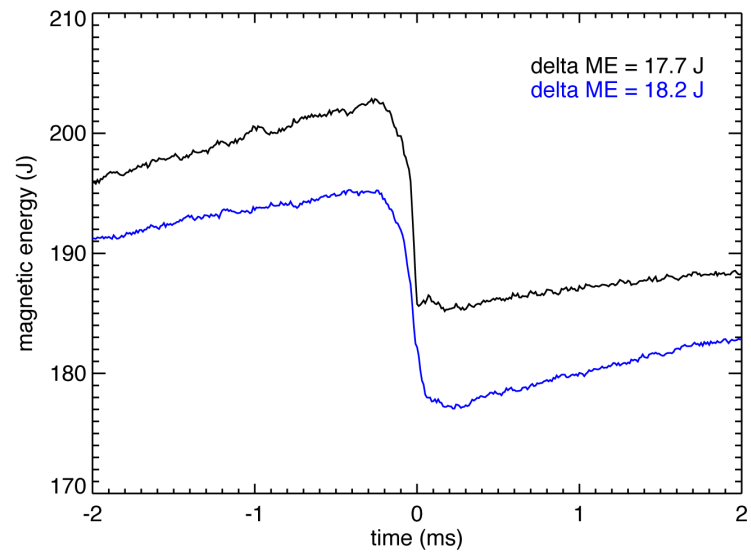


Magnetics

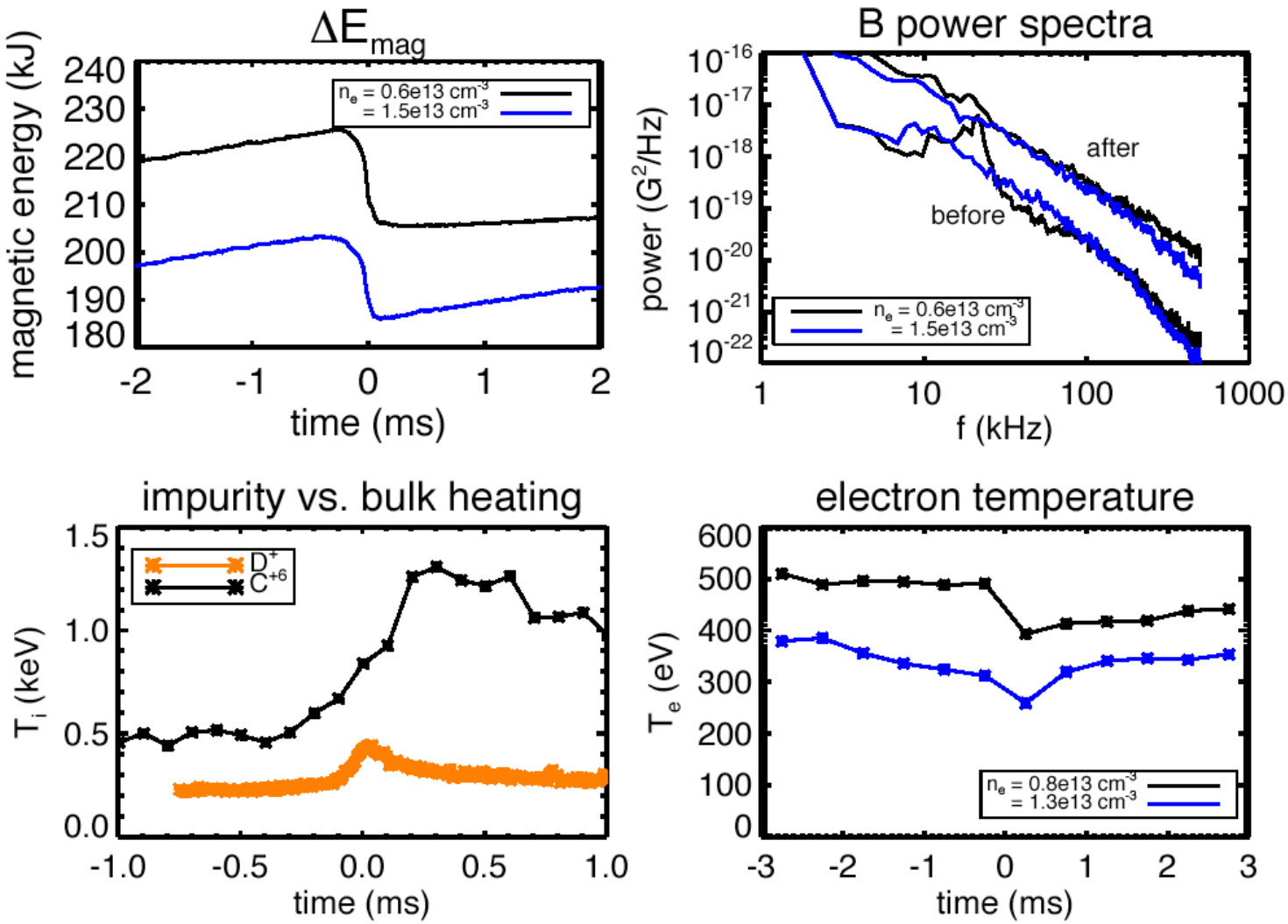
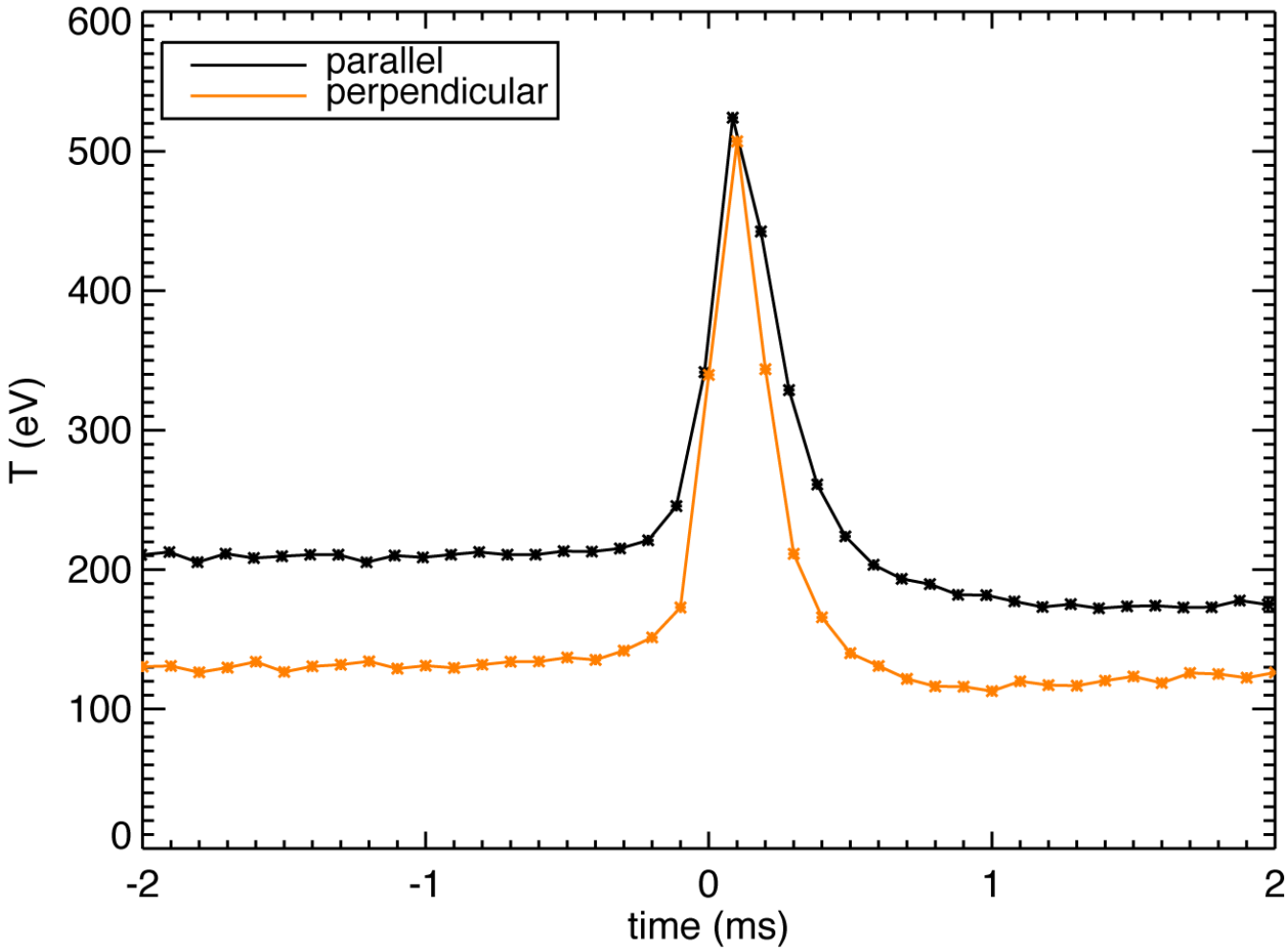
- Magnetic activity is similar for two ensembles







Ancillary


ΔE_mag
magnetic energy (kJ)
240
230
220
210
200
190
180
-2
-1
0
1
2
time (ms)
n_e = 0.6e13 cm^-3
= 1.5e13 cm^-3
B power spectra
power (G^2/Hz)
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
after
before
n_e = 0.6e13 cm^-3
= 1.5e13 cm^-3
1
10
100
1000
f (kHz)
impurity vs. bulk heating
T_i (keV)
1.5
1.0
0.5
0.0
D^+
C^+6
-1.0
-0.5
0.0
0.5
1.0
time (ms)
electron temperature
T_e (eV)
600
500
400
300
200
100
0
n_e = 0.8e13 cm^-3
= 1.3e13 cm^-3
-3
-2
-1
0
1
2
3
time (ms)

Passive Temperature