Thermal electron and fast ion transport throughout the sawtooth cycle in the MST RFP

J. A. Reusch

THE UNIVERSITY
of
WISCONSIN
MADISON

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Acknowledgements

J.K. Anderson, V. Belykh, D.J. Den Hartog, F. Ebrahimi, S. Eilerman, C.B. Forest, G. Fiksel, J.J. Koliner, L. Lin, D. Liu, R. O'Connell, M.D. Nornberg, E. Parke, S. Polosatkin, D.D. Schnack, H.D. Stephens, Y. Tsidulko, and the MST Team

U.S. DEPARTMENT OF ENERGY

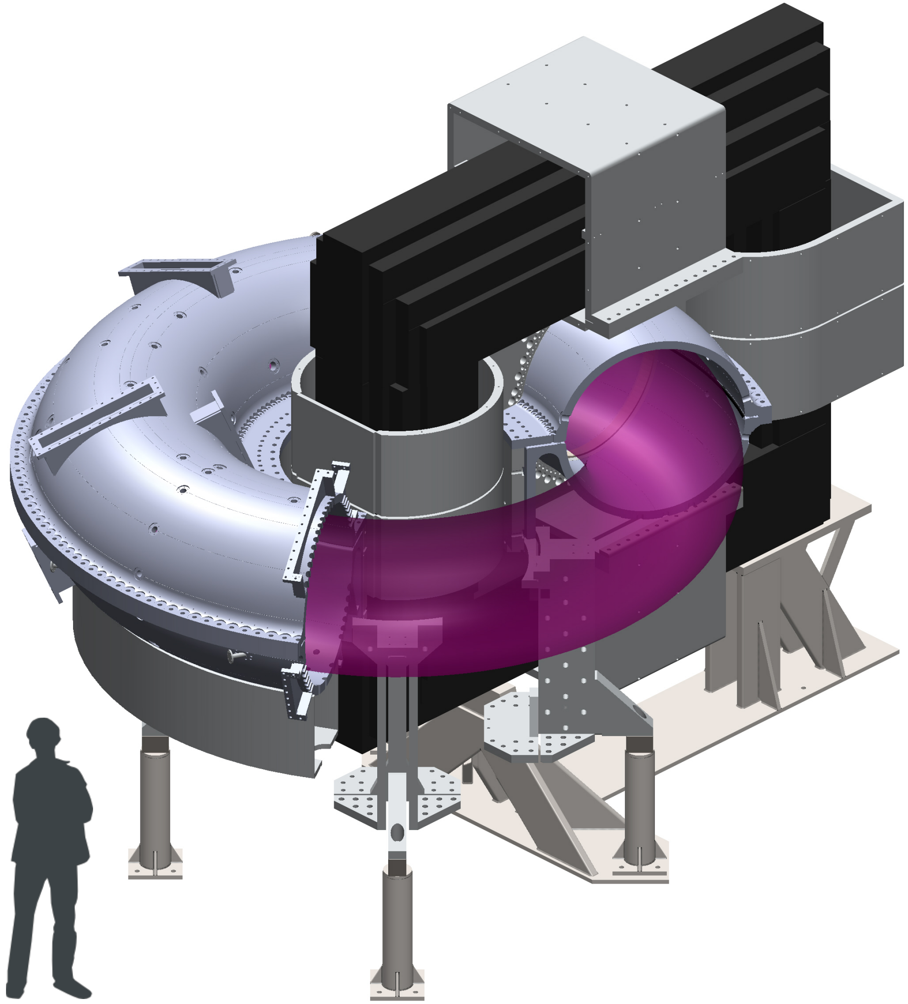
NSF

Outline

- Introduction
  - Description of MST
  - Sawteeth in MST
- Measured and Simulated χ_e in MST
  - Measuring T_e and χ_e in the experiment
  - Stochastic χ_e from Nonlinear MHD simulations of MST
- Fast ion dynamics in MST
  - Effect of broad spectrum tearing modes on fast ions
  - Simulated and measured fast ion energization during sawteeth
- Summary and Conclusions

The Madison Symmetric Torus is a large Reversed Field Pinch.

- Major Radius: R = 1.5 m
- Minor Radius: r = 0.52 m
- Plasma Current < 0.5MA
- Electron Density ~ $1\text{x}10^{19}$ m^{-3}
- |B(0)| < 0.5 T
- Current flattop ~ 20 ms



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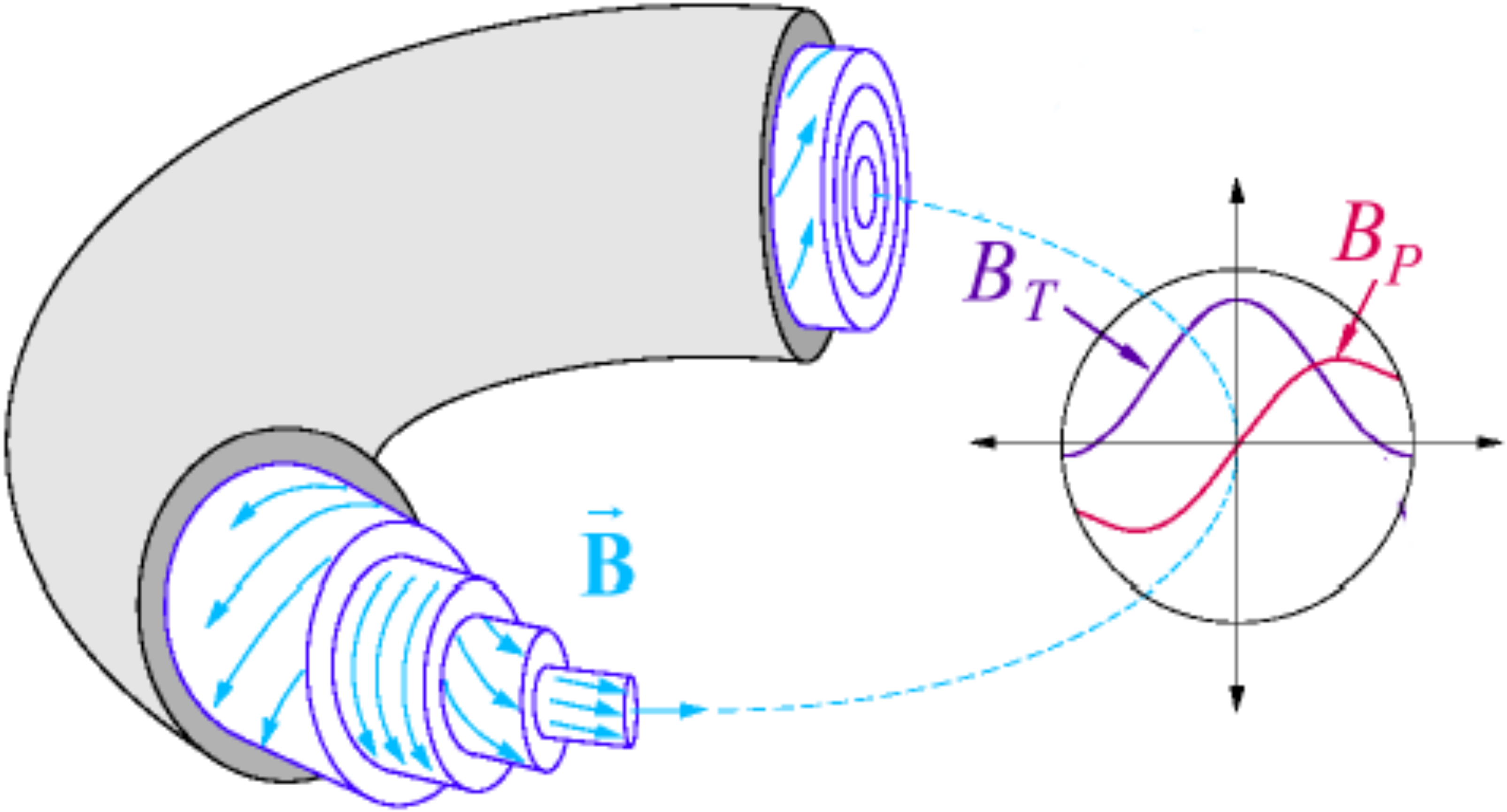
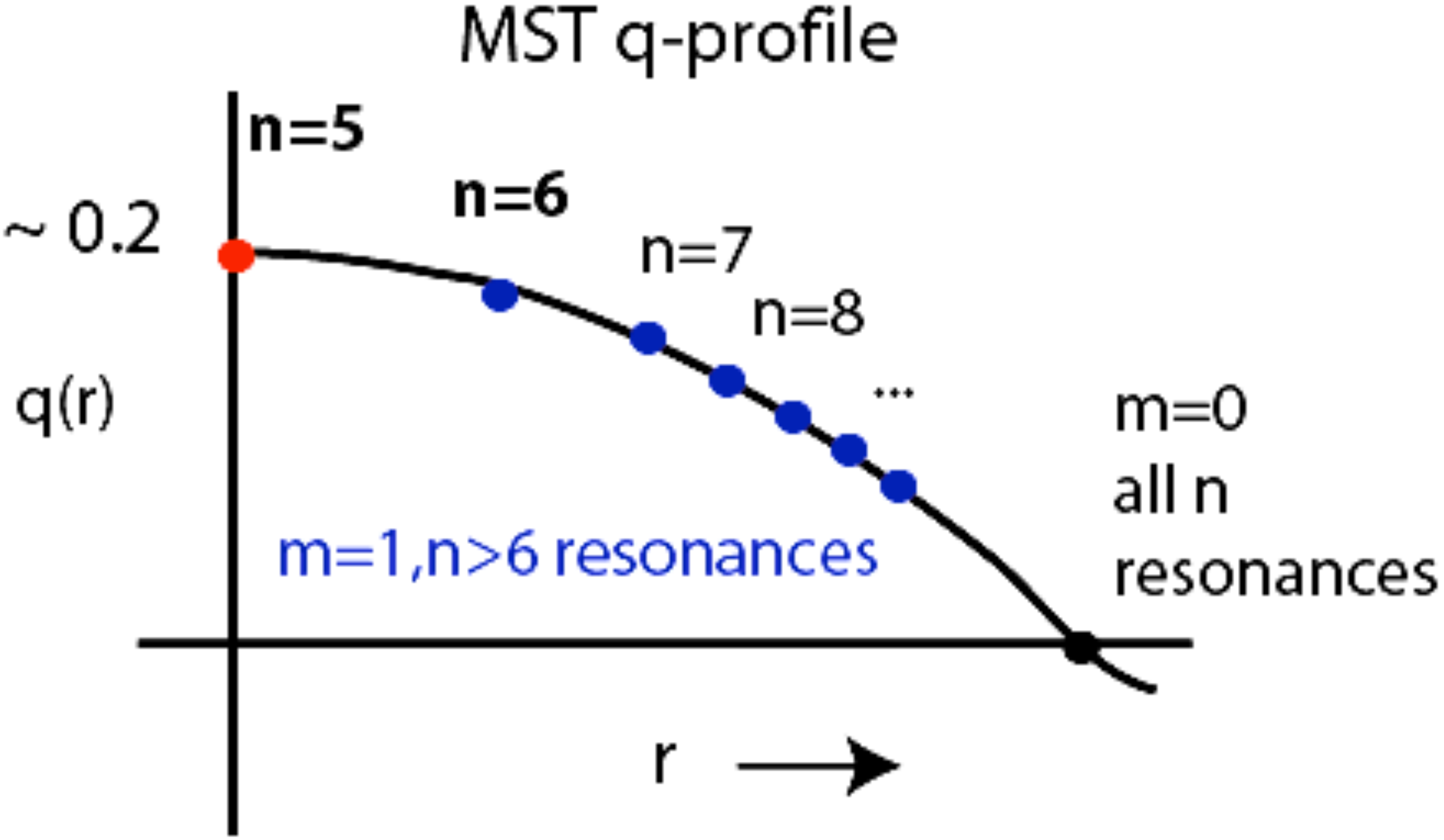


Closely spaced tearing mode resonances in MST can lead to stochasticty.

- Safety factor: $q(r) = rB_t/RB_p$
- Magnetic modes resonant where q=m/n



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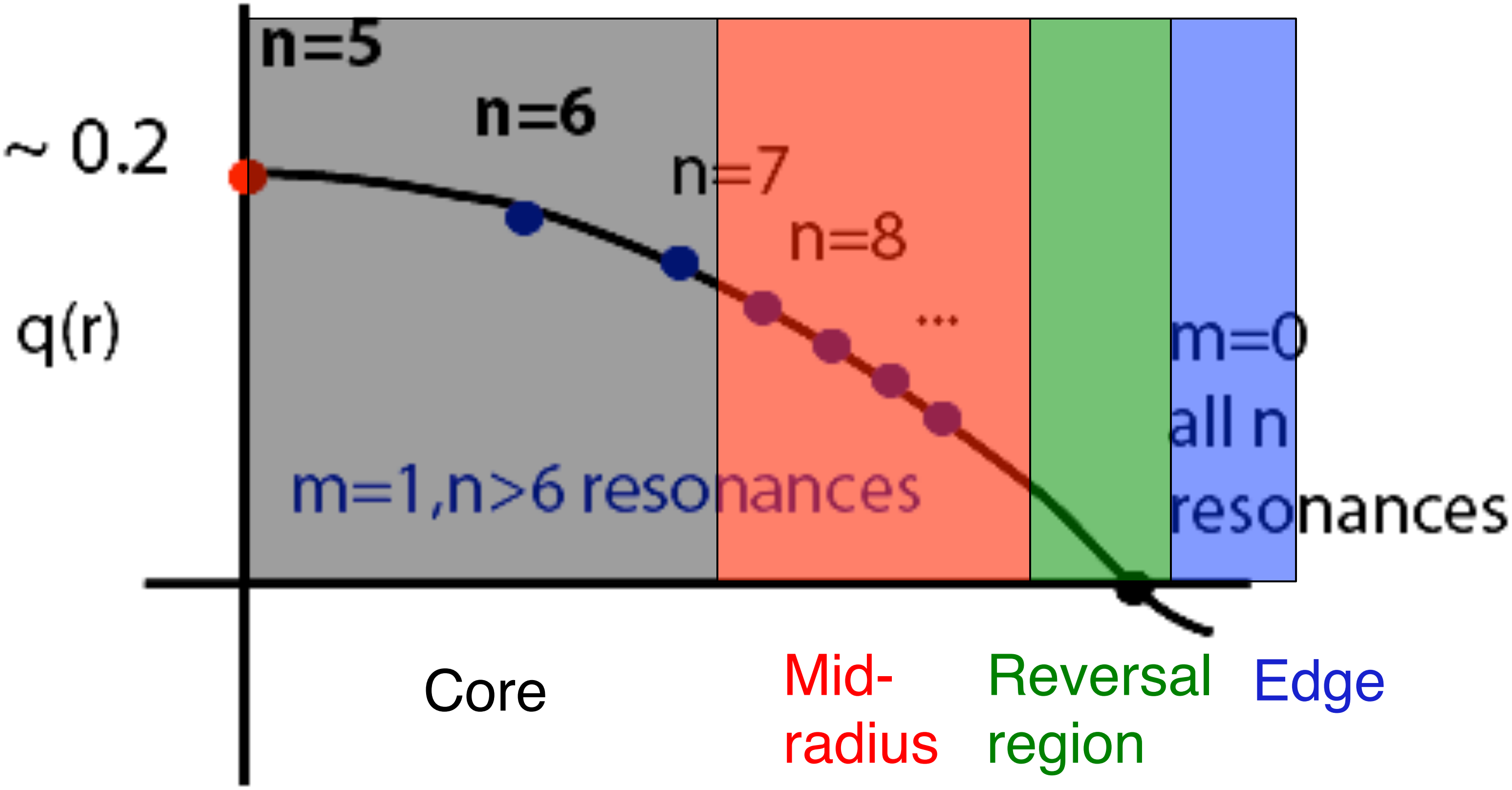
MST q-profile



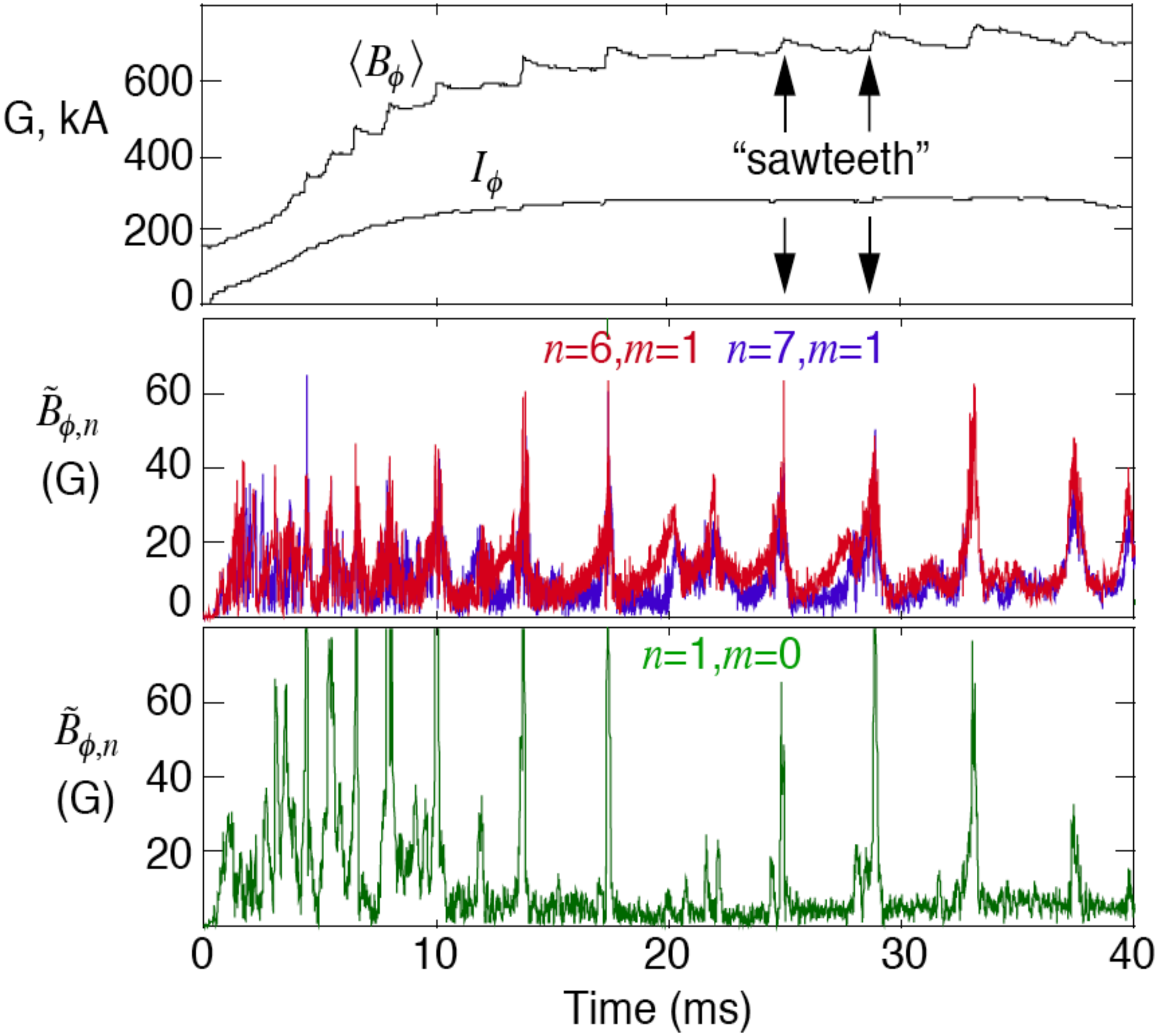
Core

Mid-
radius

Reversal
region

Edge

Quasi-periodic impulsive reconnection events (sawteeth) are a common feature in MST discharges.

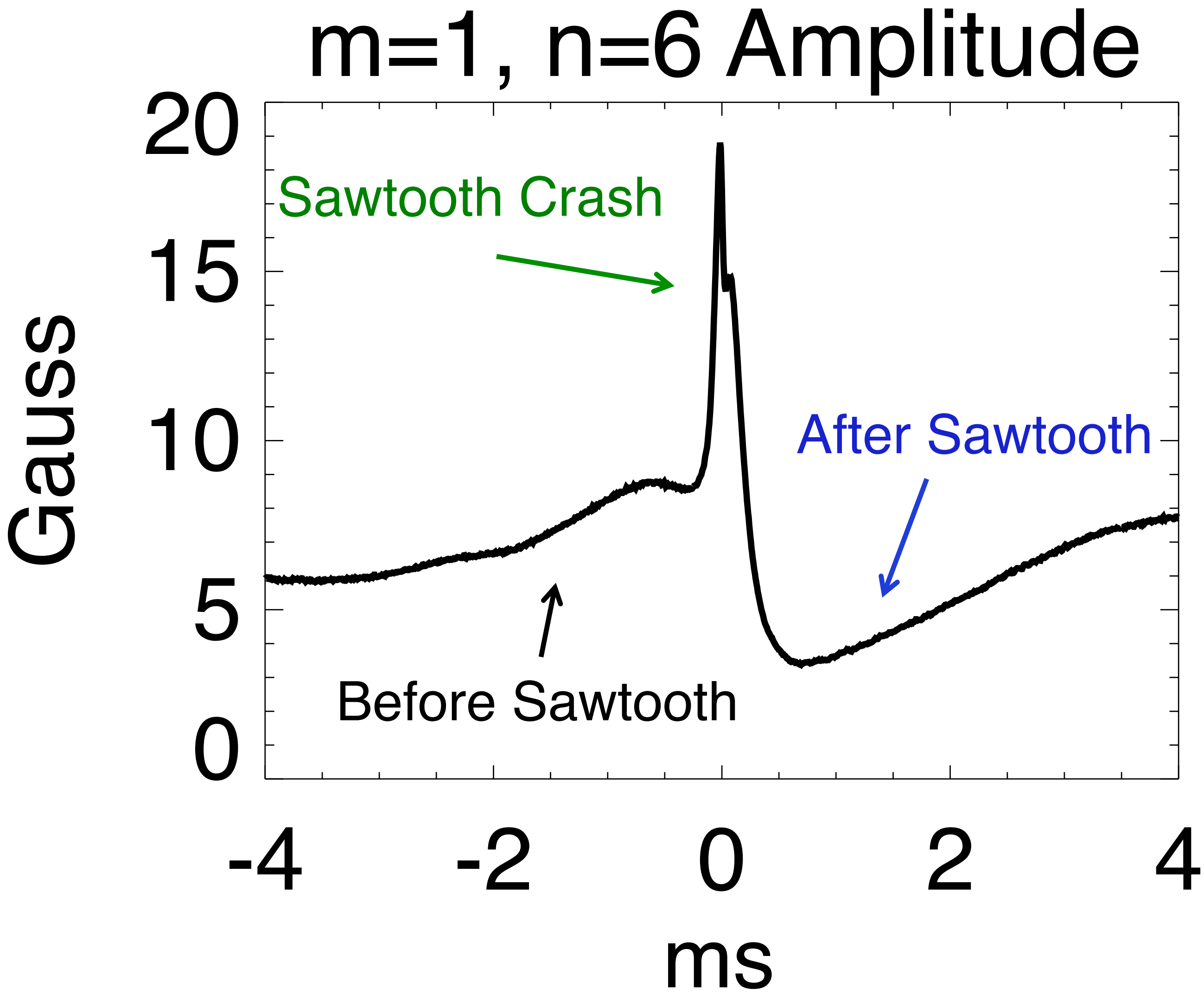


Core-resonant m=1 modes are largest, calculated to be linearly unstable from gradient $\nabla_r (J_{\|}/B)$

Edge-resonant m=0 modes are linearly stable, excited by nonlinear coupling to m=1 spectrum

Parallel current density profile is flattened, causing a substantial toroidal flux generation

The sawtooth cycle has three distinct phases.



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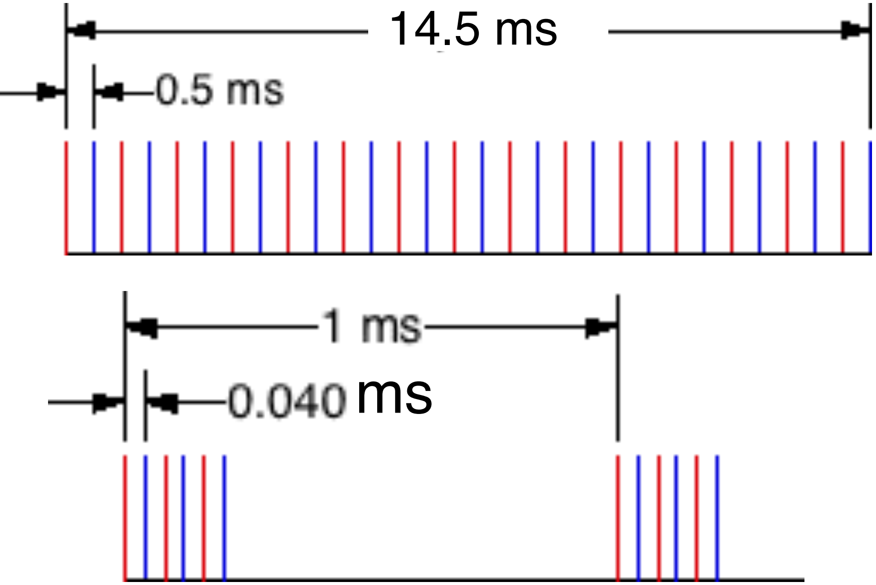
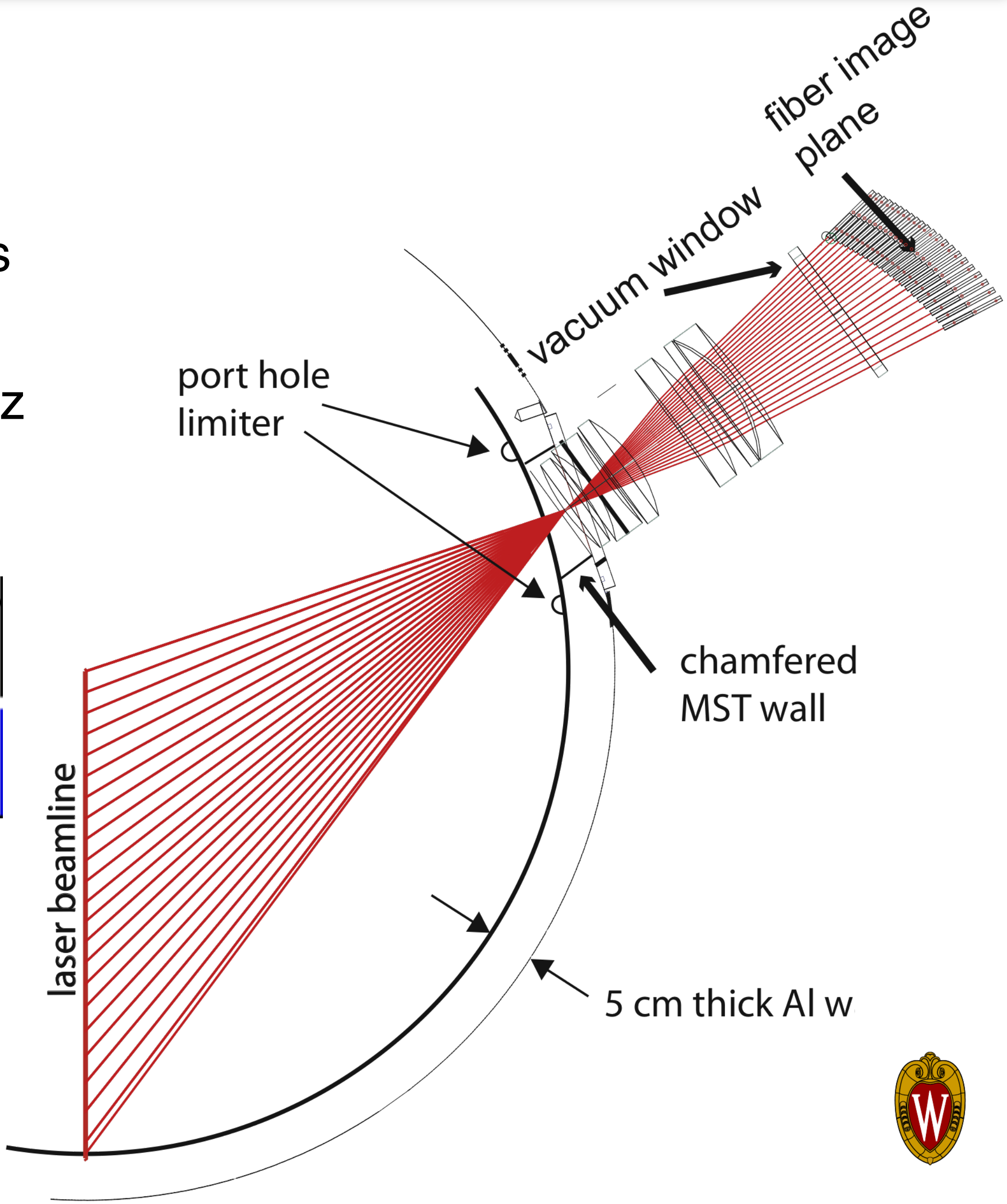
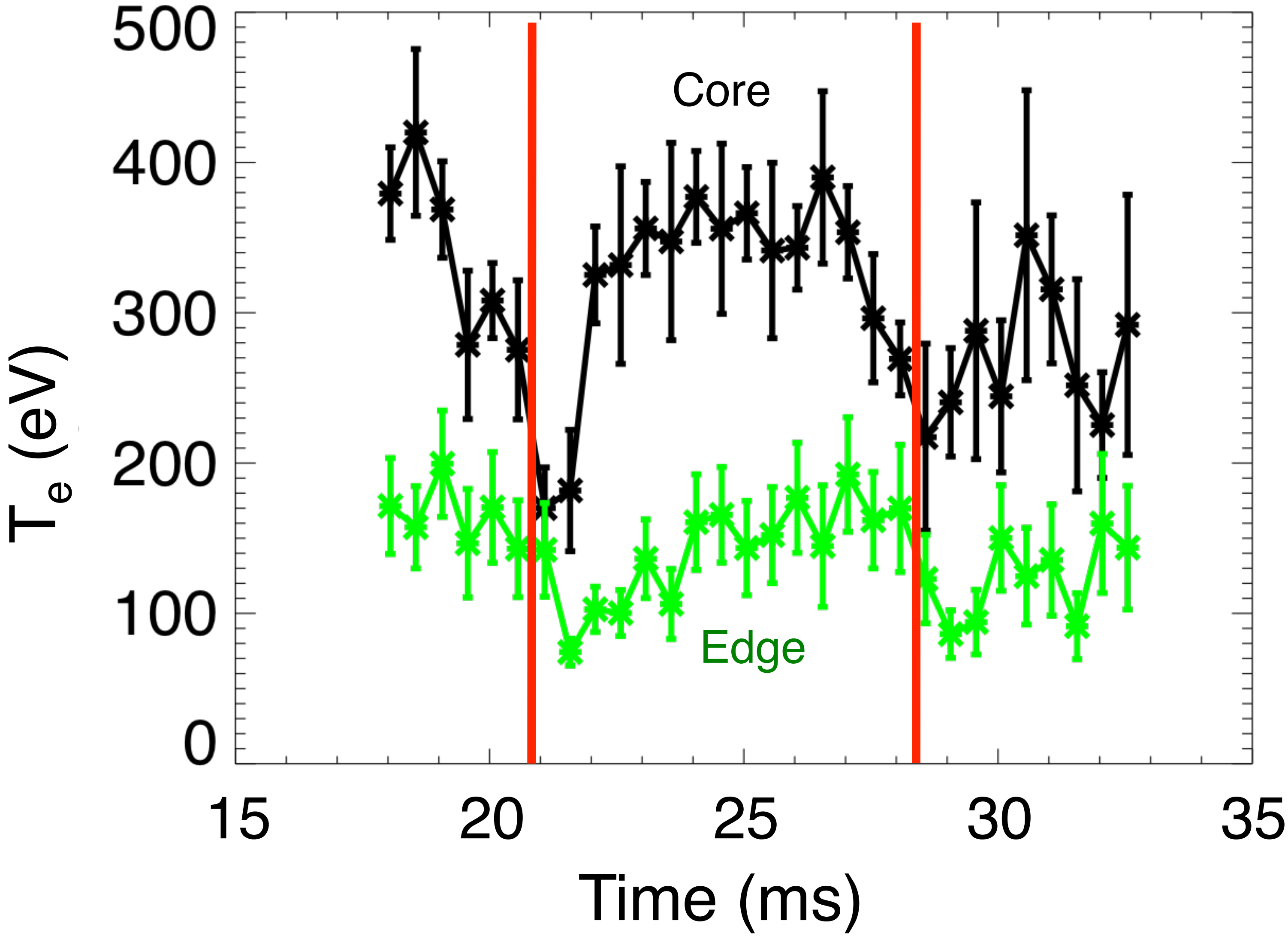
T_e is measured on MST with a multi-point multi-pulse Thomson scattering system.

- Thomson scattering system specs:
  - 21 spatial points
  - 2 interleaved Nd:YAG lasers
  - 30 pulses at 2kHz
  - 5 bursts of 6 pulses at 25kHz per discharge





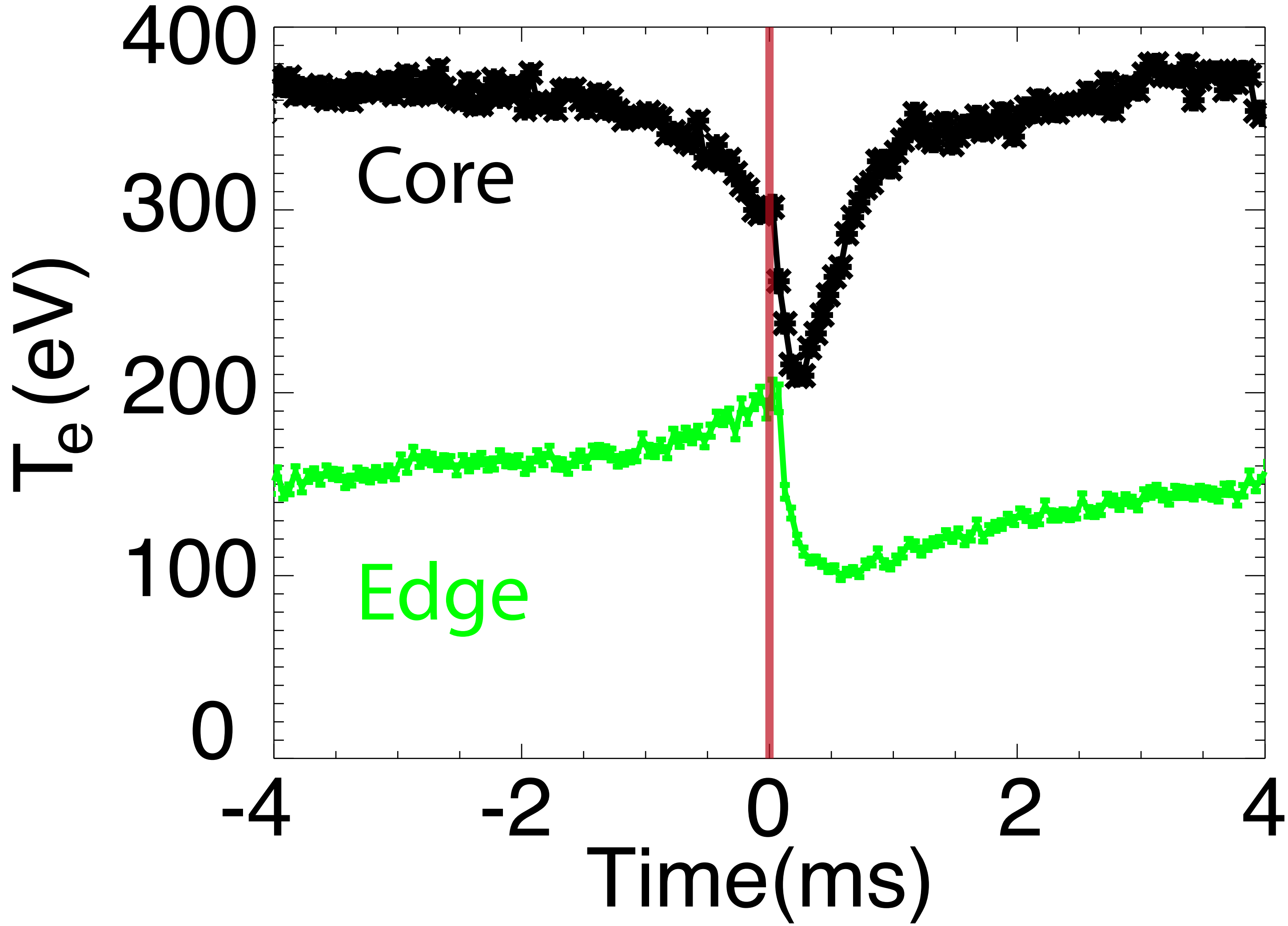
2kHz operation resolves the sawtooth cycle.



- Can use sawteeth as markers in time for averaging

Sawtooth ensembling allows the electron temperature profile evolution to be found at high time resolution.

- 20 kHz time resolution used for this work
- Time resolution chosen such that all points had > 20 measurements

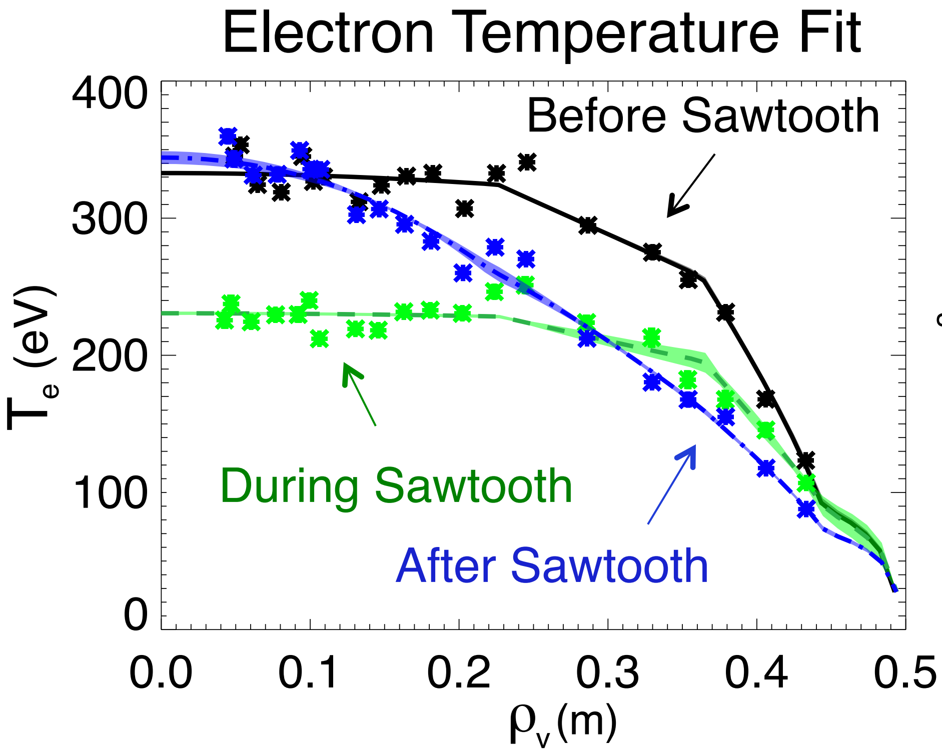


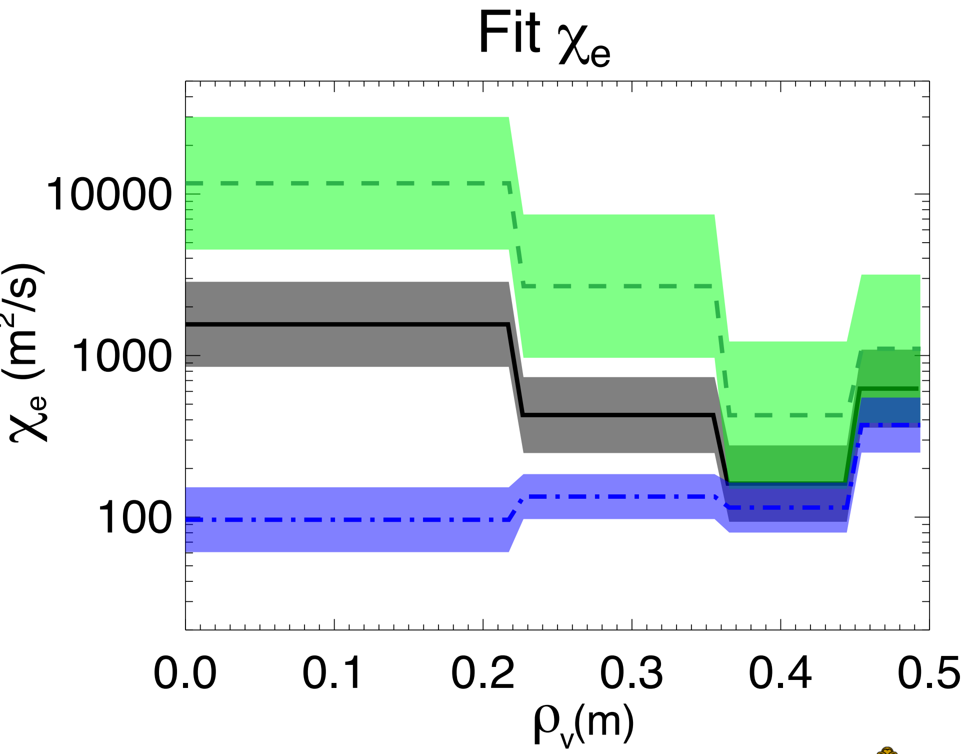
Characteristic values of the electron thermal diffusion are found for different regions of MST.

- Electron thermal diffusion (χ_e) fit by solving:

$$1.5\,\partial(n_e T_e)/\partial t = \nabla(n_e \chi_e \nabla T_e) + \eta J^2 - Sink$$

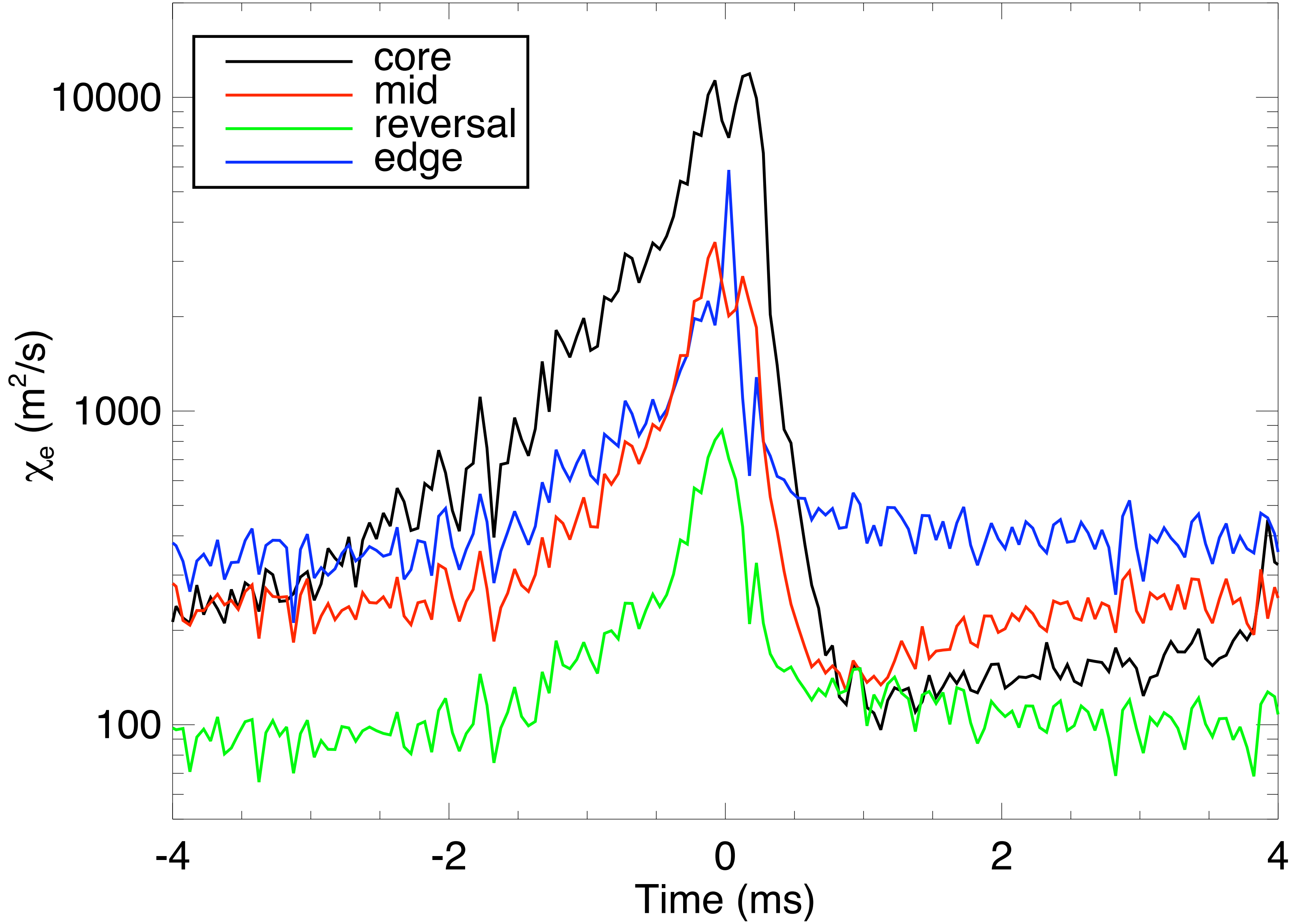
for T_e and comparing to measurements





Profile information from MSTFit (J.K. Anderson, *et al.*, Nuclear Fusion **44**, **(2004)** 162-171)

The fit χ_e changes by orders of magnitude through the sawtooth cycle.



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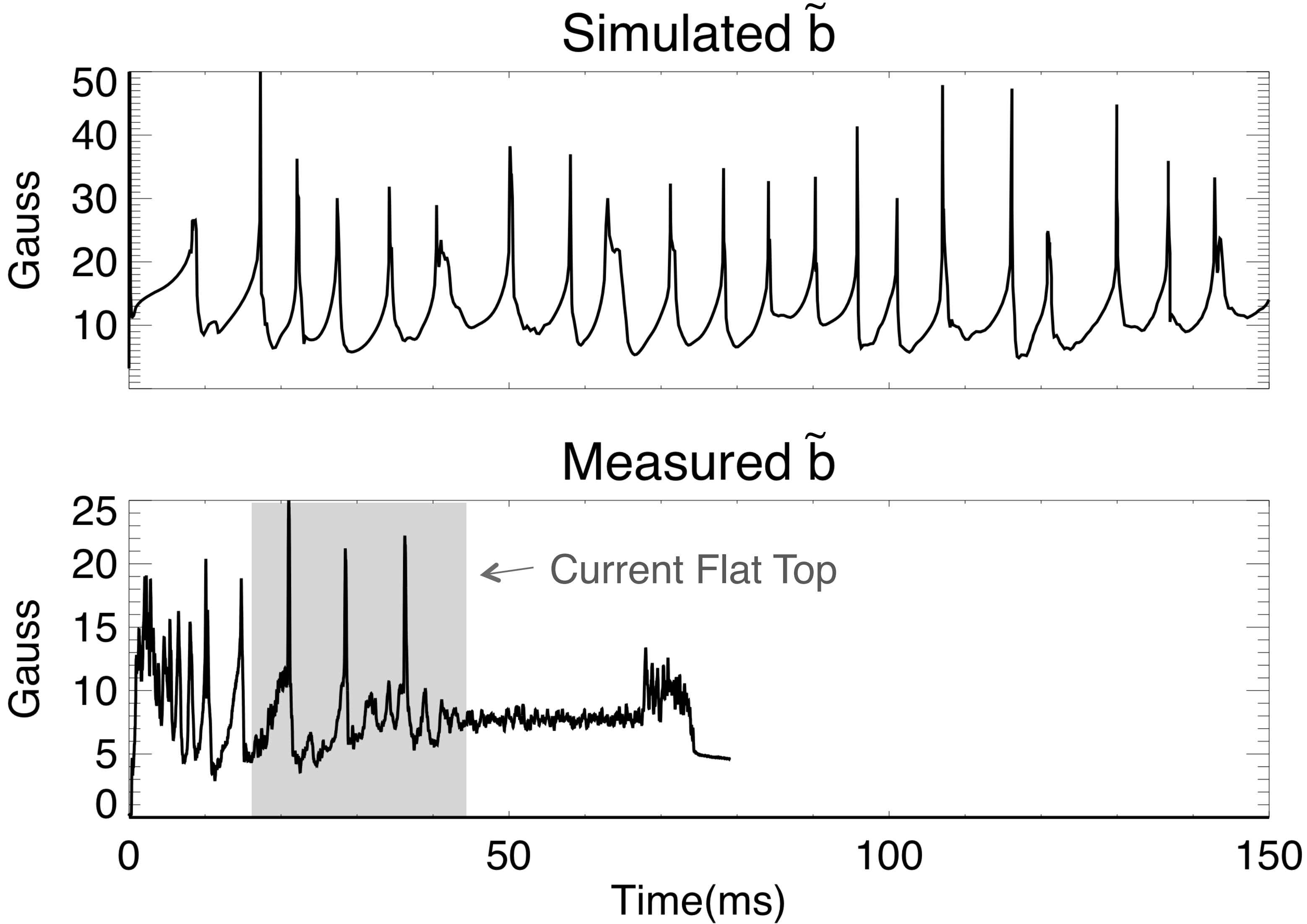
Single fluid, 3D, nonlinear, resistive MHD simulations reproduce the MST sawtooth cycle well.

- Cylindrical, force-free MHD model was used (DEBS* code run with zero β)
- Pinch parameter ($\Theta = B_p(a)/\langle B_t \rangle$), resistivity profile, and Lundquist number from MST ($S=3.8\text{x}10^6$) are used
- High Prandtl number used to damp sub grid scale fluctuations ($Pr_m \sim 200$)
- Simulations reproduce sawtooth period, duration, and equilibrium evolution of MST well
- Magnetic mode amplitudes are higher than in MST

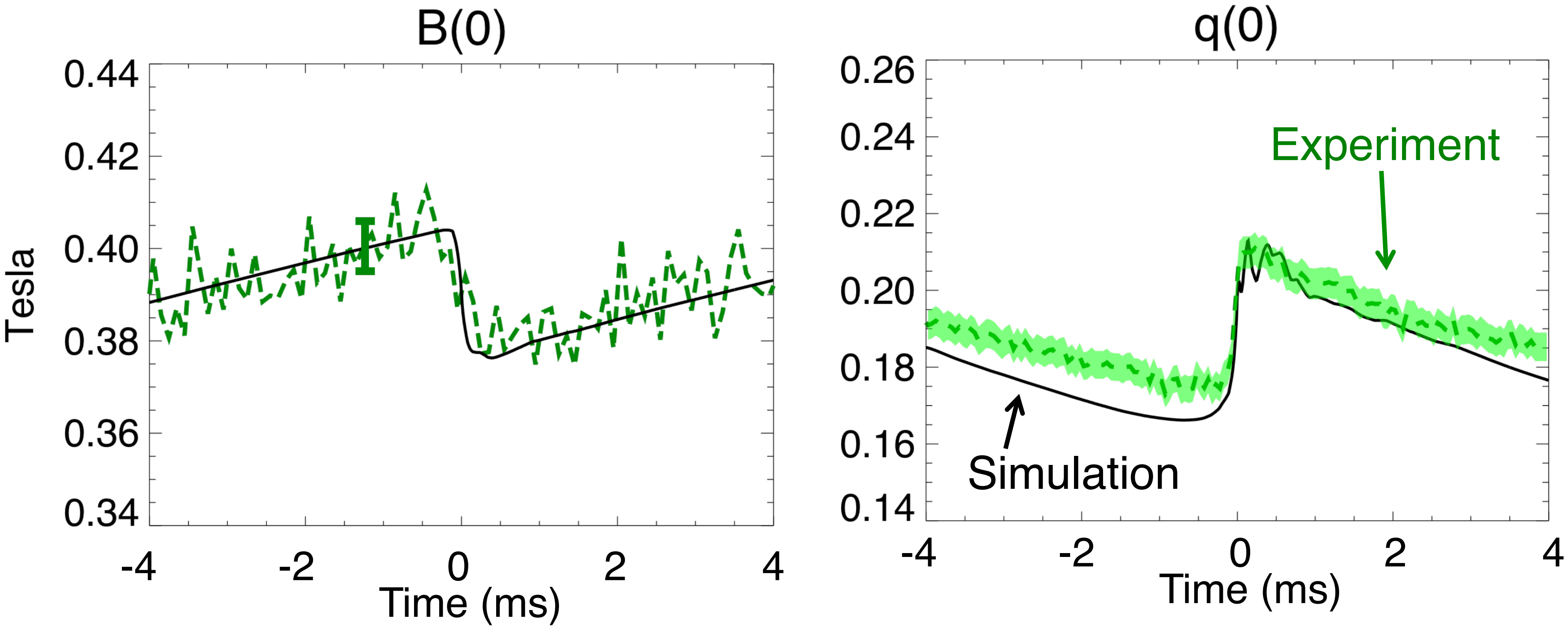
*D.D. Schnack, *et al.*, J. Comput. Phys. **70, 330 (1987)**

These simulations produced large, well defined sawteeth similar in period and duration to MST.

- Code produces sharp, quasi-periodic sawteeth
  - Quantities of interest were sawtooth ensembled

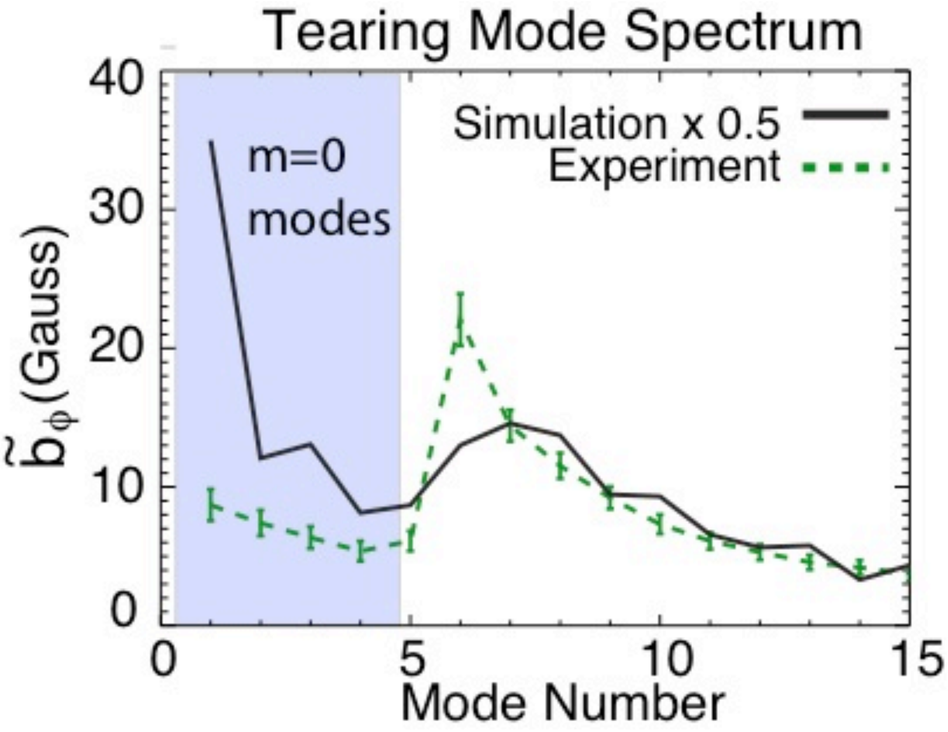


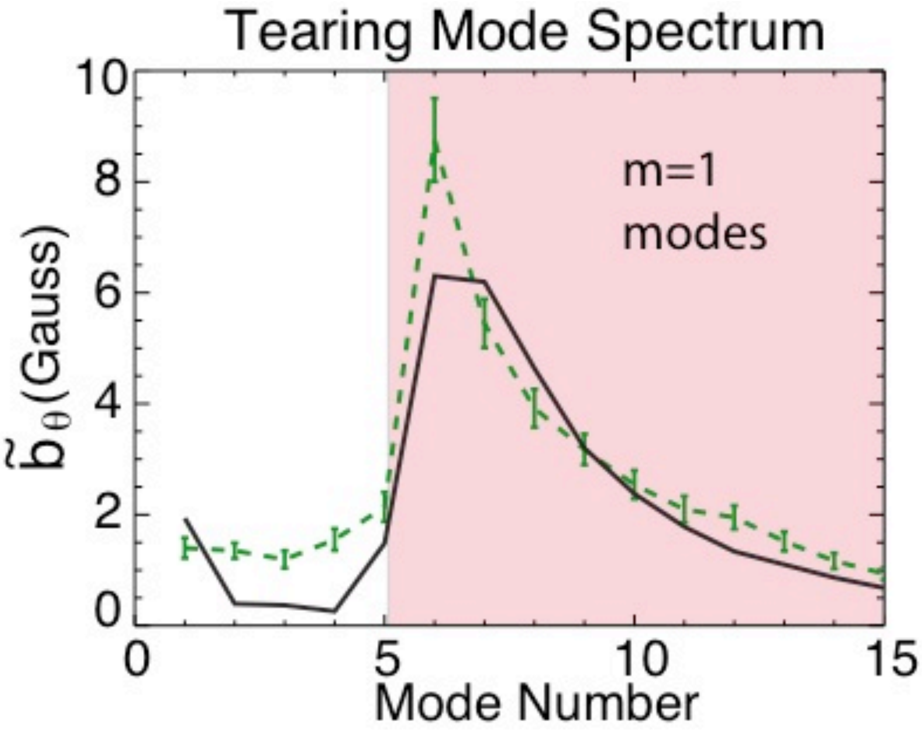
The simulated evolution of the magnetic equilibrium through the sawtooth cycle matches MST.



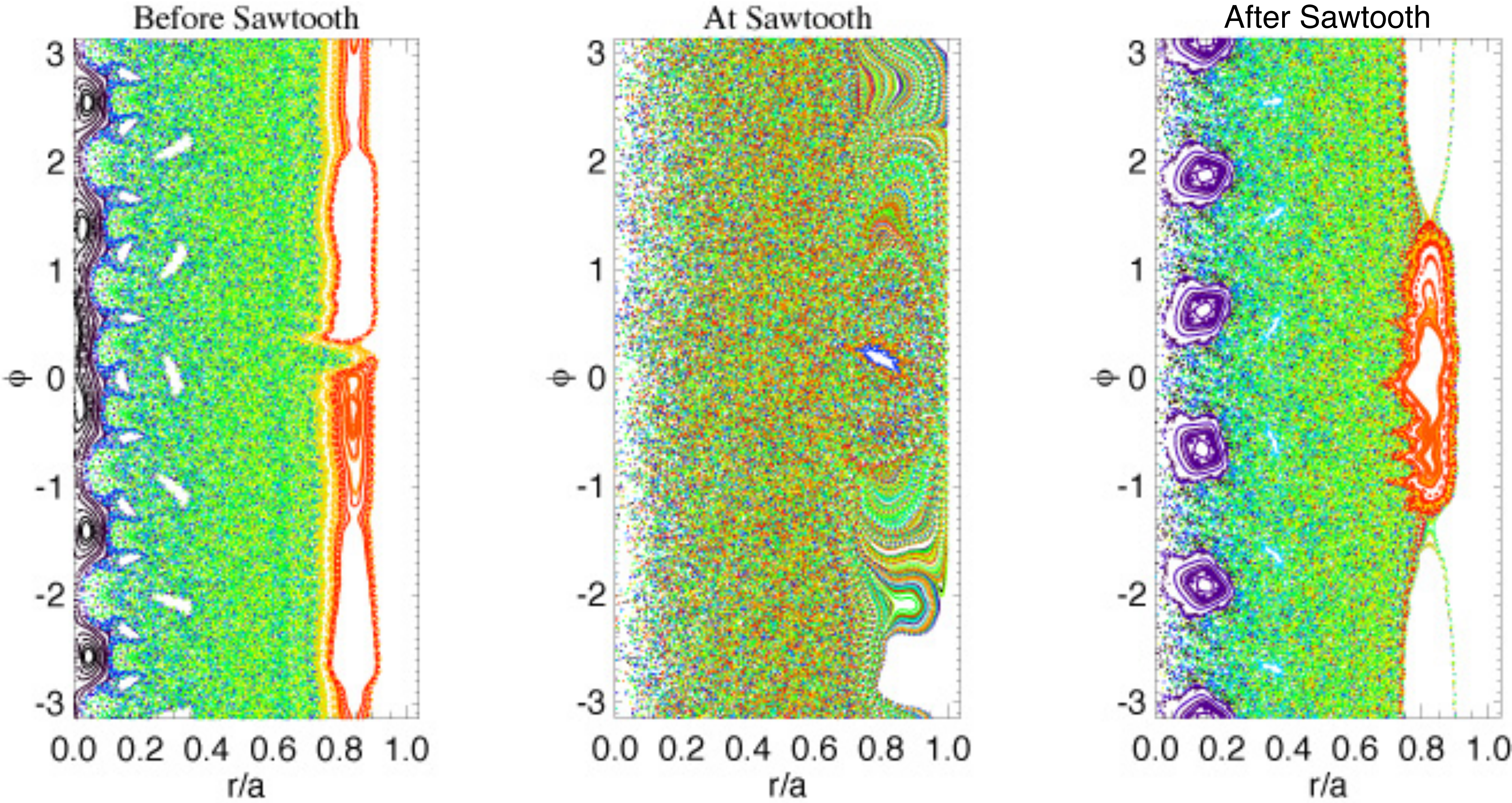
Measured magnetic mode spectrum is reasonably well reproduced by the simulation.

- Edge magnetic pick up coil data compared to synthetic diagnostic
- Simulated mode amplitudes ~2x larger than measured





By scaling the mode amplitudes and tracing magnetic field lines, D_{mag} and χ_e can be evaluated.



Tracking the magnetic field wander allows direct computation of D_{mag} and from this χ_e

- The magnetic diffusion is defined as:

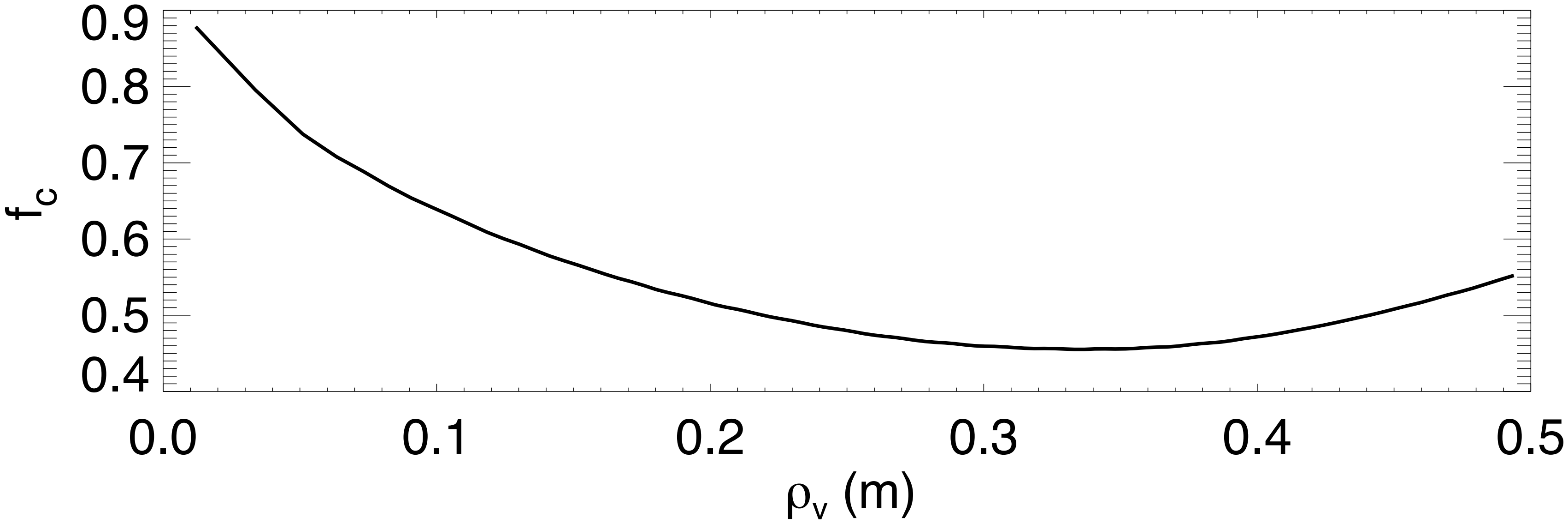
$$D_{mag} = \frac{\left\langle \left(r - r_0\right)^2 \right\rangle}{2L}$$

- The electron thermal diffusion is:

$$\chi_{MD} = V_{||} D_{mag} \approx V_{th,e} D_{mag}$$

Trapped particles, which do not carry heat along field lines*, must also be accounted for.

- The trapped particles in MST can be more than half the electron density making the circulating fraction less than 0.5**



- The effective electron thermal diffusion can be defined as:

$$\chi_{eff} \approx f_c V_{th,e} D_{mag}$$

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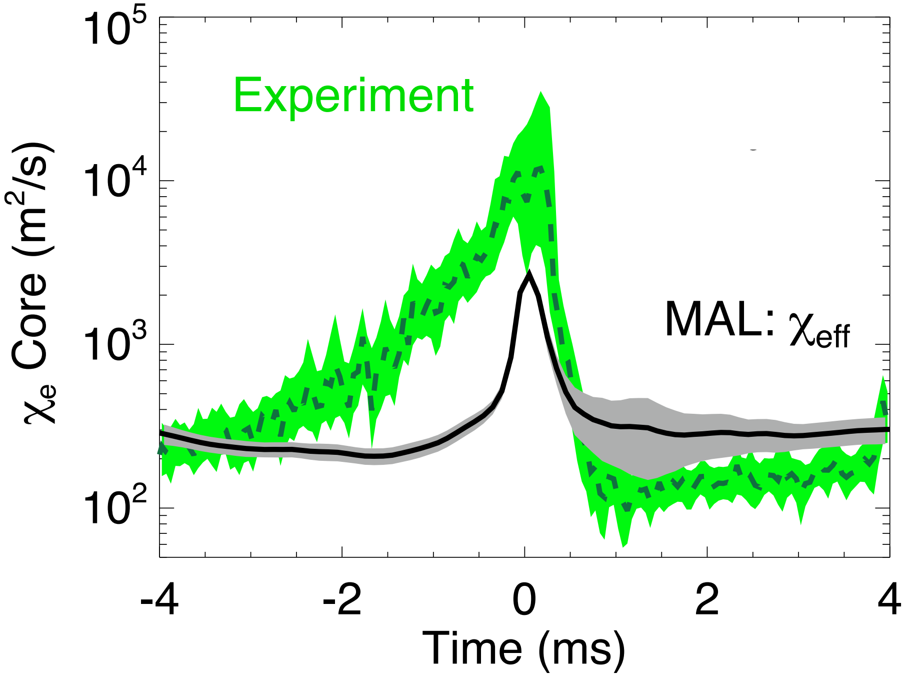
*B.D.G. Chandran, *et al.*, Astrophysical Journal, **525**, (1999) p. 638-650

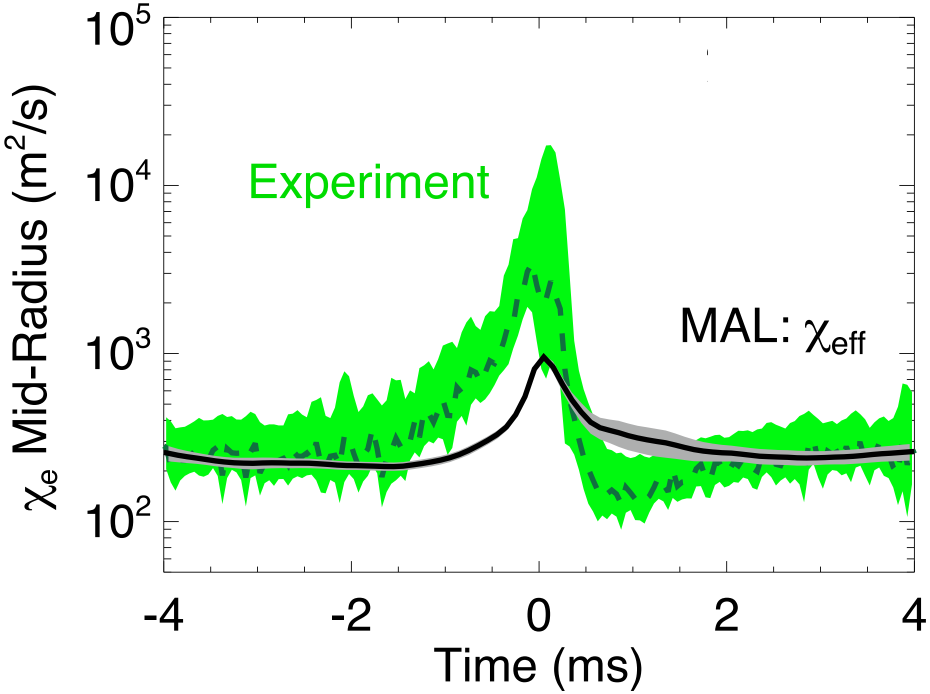
J.K. Anderson, *et al.*, Nuclear Fusion **44 (2004) p.162-171

Stochastic transport accounts for a significant amount of the observed χ_e in the core and mid-radius



- χ_e in the mid-radius is due to magnetic stochasticity throughout sawtooth cycle

- In the core, other effects (islands, electro-static transport) are still important



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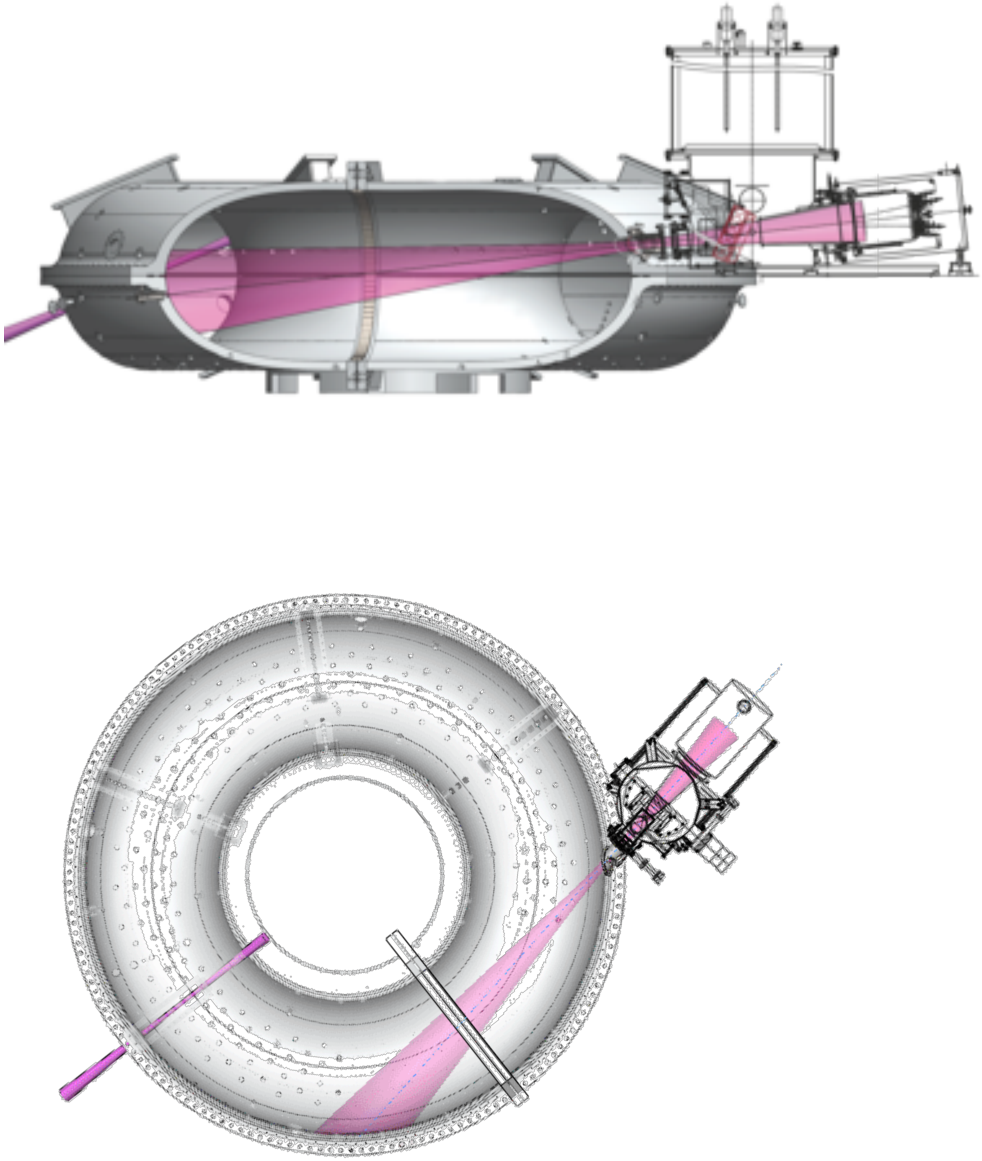
MST now has a 1MW, 25keV neutral beam injector for performing fast ion studies.

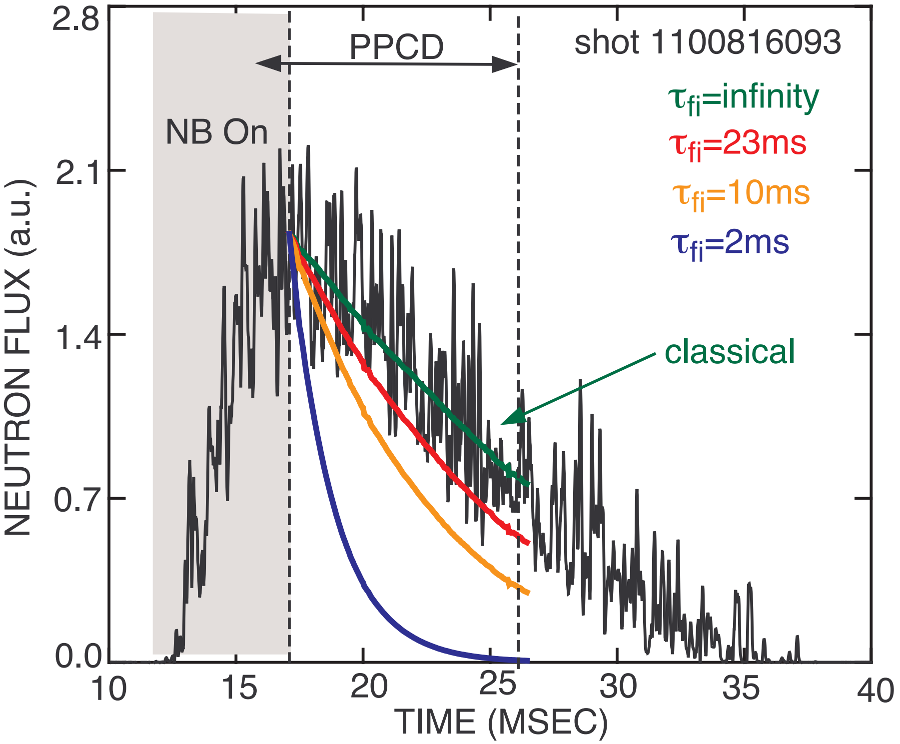


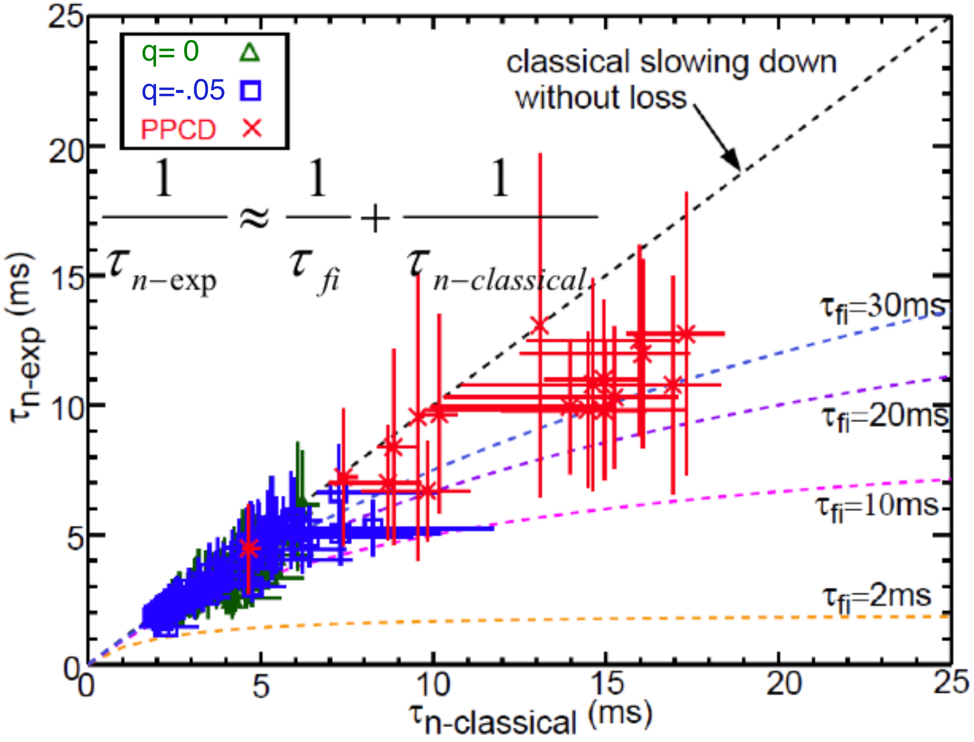
- Tangential injection to maximize deposition.

NBI Parameter	Specification
Beam Energy	25 keV
Beam Power	1 MW
Pulse Length	20 ms
Composition	95-97% H, 3-5% D Or 100% D
Energy Fraction (E:E/2:E/3:E/18)	86%:10%:2%:2%

- Co-current or counter current injection by reversing Ip
- Fast ion diagnostics:
  - Scintillator based neutron detector
  - 20 channel neutral particle analyzer

Fast ions are well confined in the presence of a broad spectrum tearing modes in MST





*Courtesy of D. Liu

The full orbit RIO code traces particles through the full time evolving 3D field output from simulation

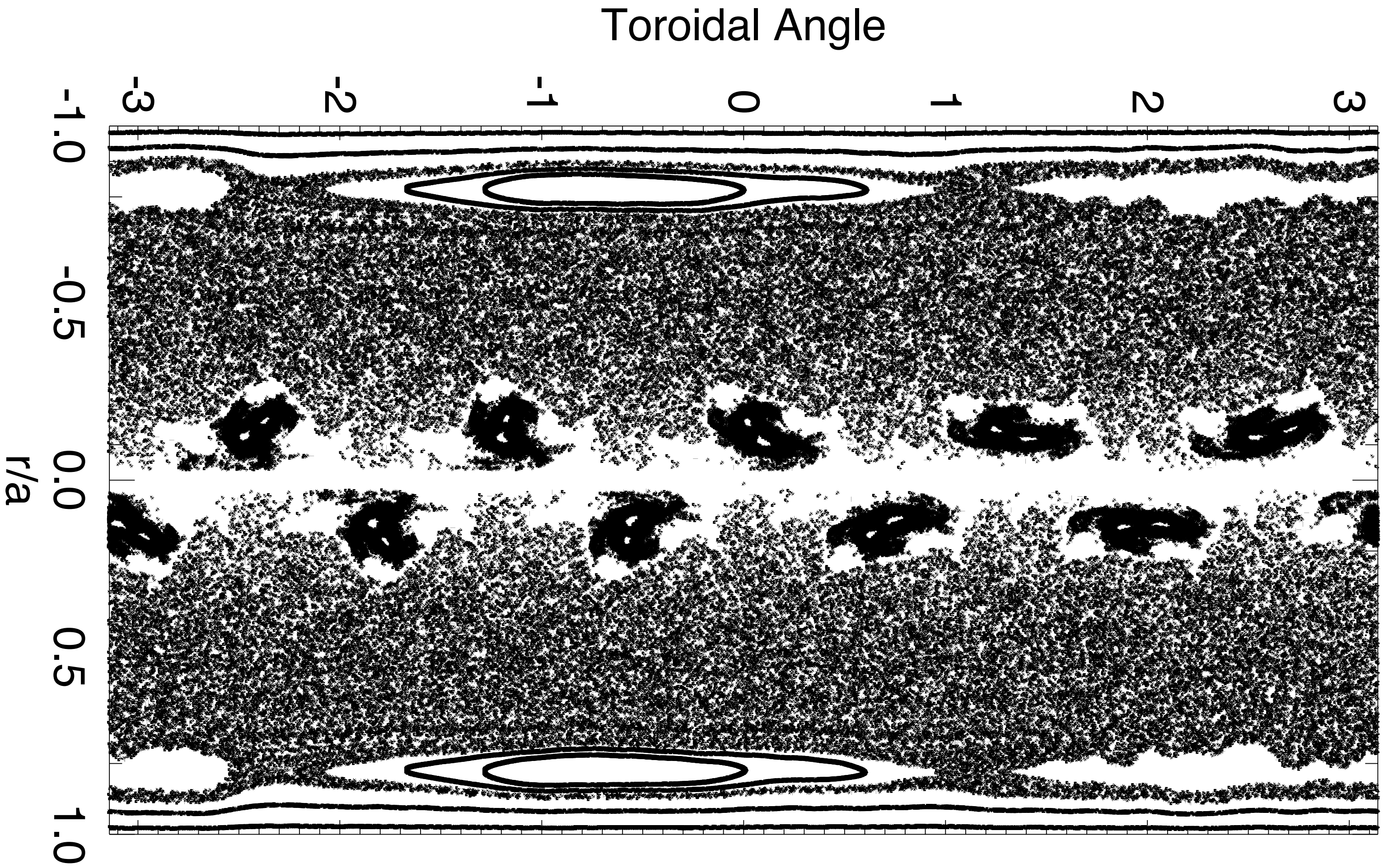
- RIO evolves the Lorentz equation in a Hamiltonian framework

- Can take into account slowing down, pitch angle scattering, and charge exchange effects due to a static background plasma

- The equilibrium and fluctuating magnetic and electric fields from simulation can be used

- Generalized coordinate system is used allowing particle tracing in cylindrical or toroidal configurations

Fast ions are decoupled from the magnetic field due to drift orbit effects



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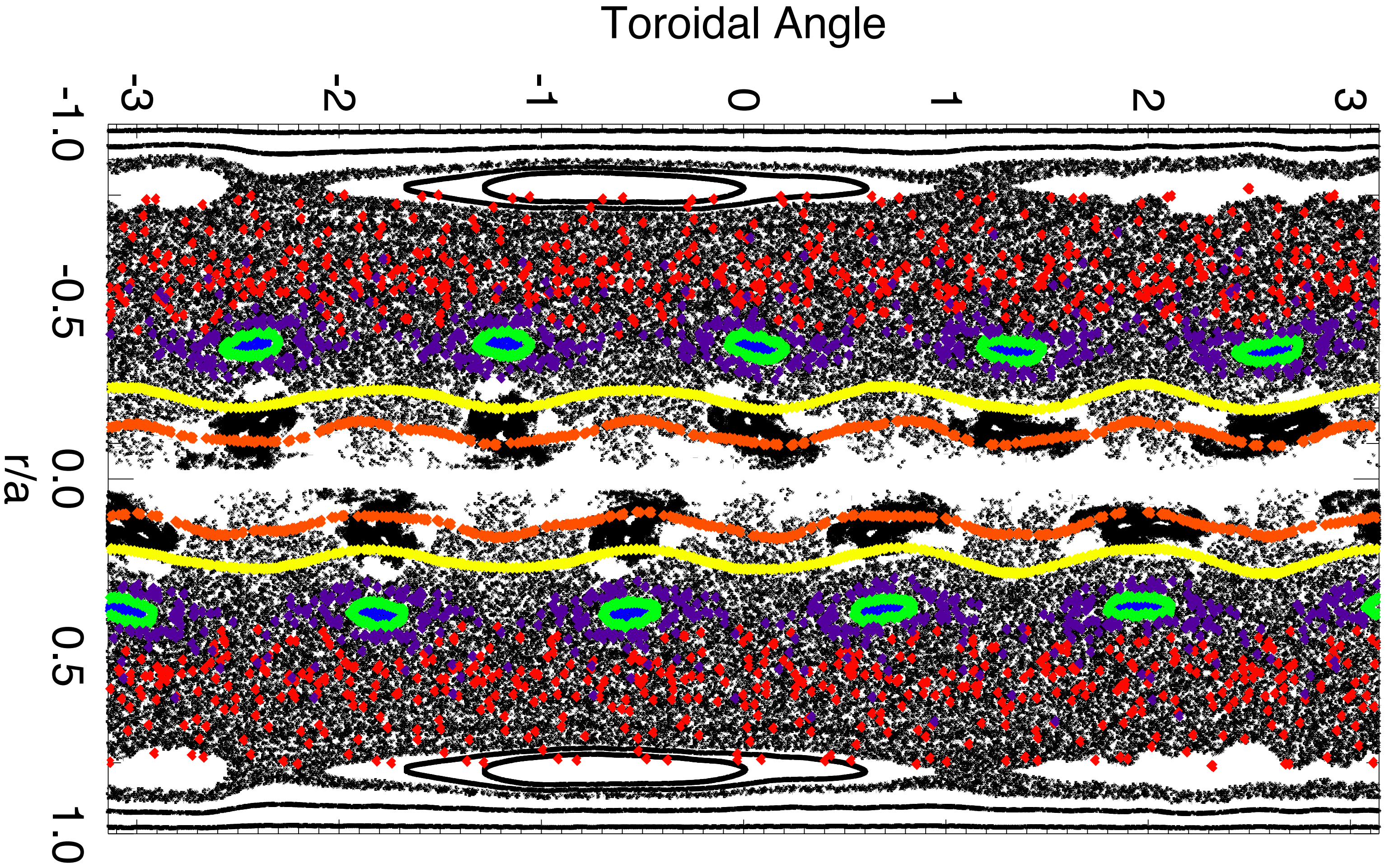


Curvature and Grad-B drifts cause the fast ions to have an effective q different from magnetic q in the RFP

- Fast ion resonances happen at rational values of f_ϕ/f_θ:

$$q_{fi}^{gc} = \frac{f_\phi}{f_\theta} = \frac{rV_\phi^{gc}}{RV_\theta^{gc}}$$

$$\vec{V}^{gc} = V_{\|}\vec{b} + \frac{V_{\|}^2}{\omega_{ci}}\frac{\vec{B}\times\vec{\kappa}}{|B|} + \frac{V_{\perp}^2}{2\omega_{ci}}\frac{\vec{B}\times\vec{\nabla}B}{|B^2|} + \frac{\vec{E}\times\vec{B}}{|B^2|}$$

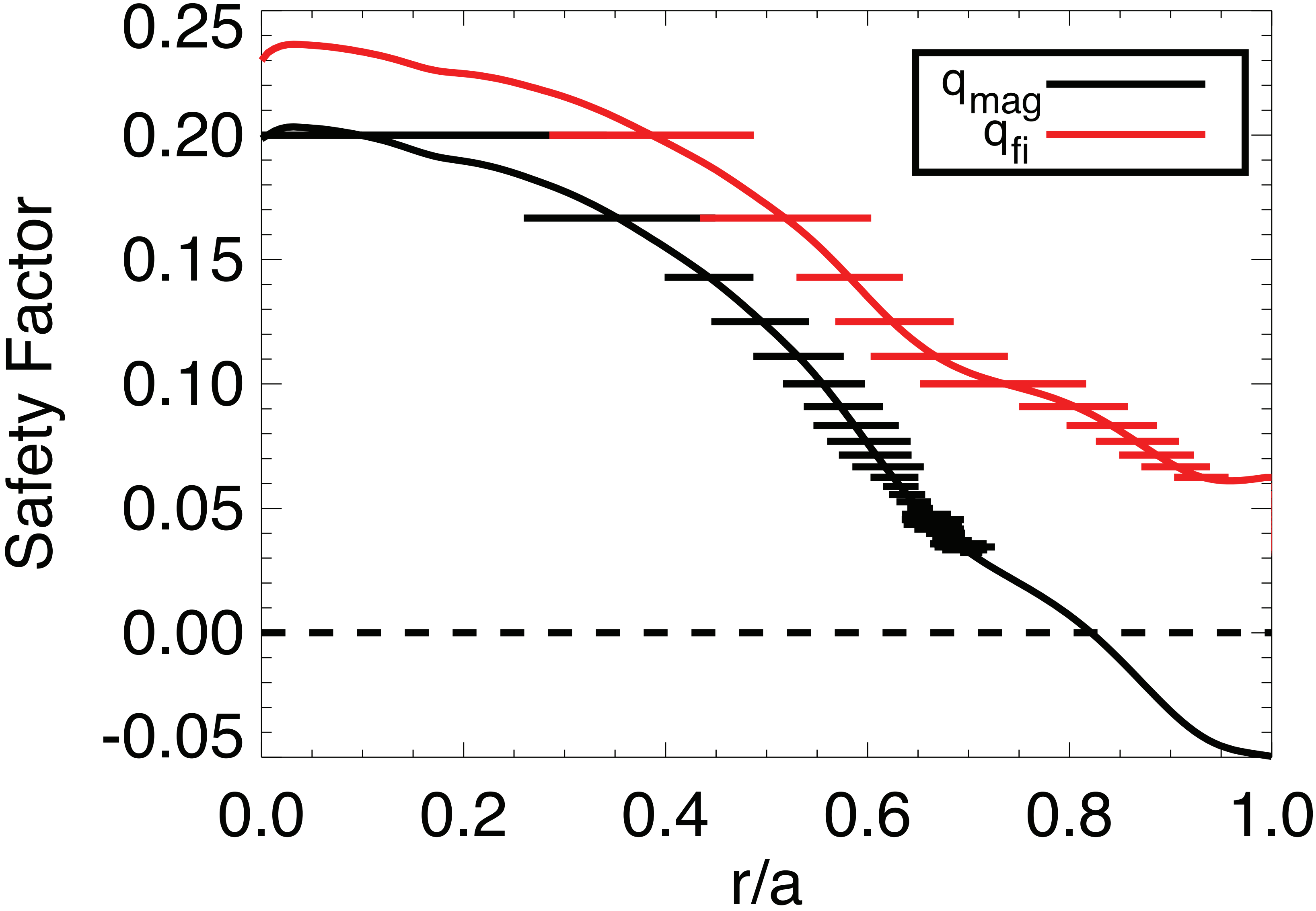
- Neglecting **ExB**, taking the cylindrical approximation, rearranging and Taylor expanding in V/ω_{ci} we get:

$$q_{fi}^{gc} \cong q_m + \frac{1}{B_\theta^2}\frac{|V|}{\omega_{ci}}\left[\frac{\lambda B_\theta^2}{R} - \frac{r}{2\lambda R}\left(1-\lambda^2\right)|B|B'\right]$$

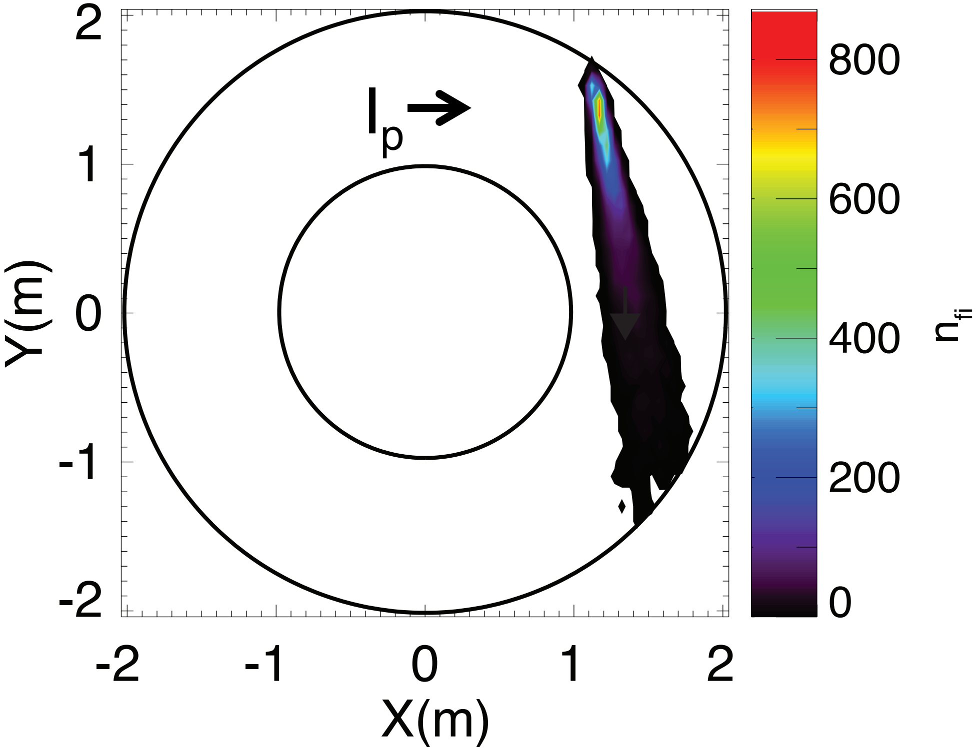
A. I. Morozov and L. S. Solov'ev, *Reviews of Plasma Physics* 2, Consultants Bureau, 1966

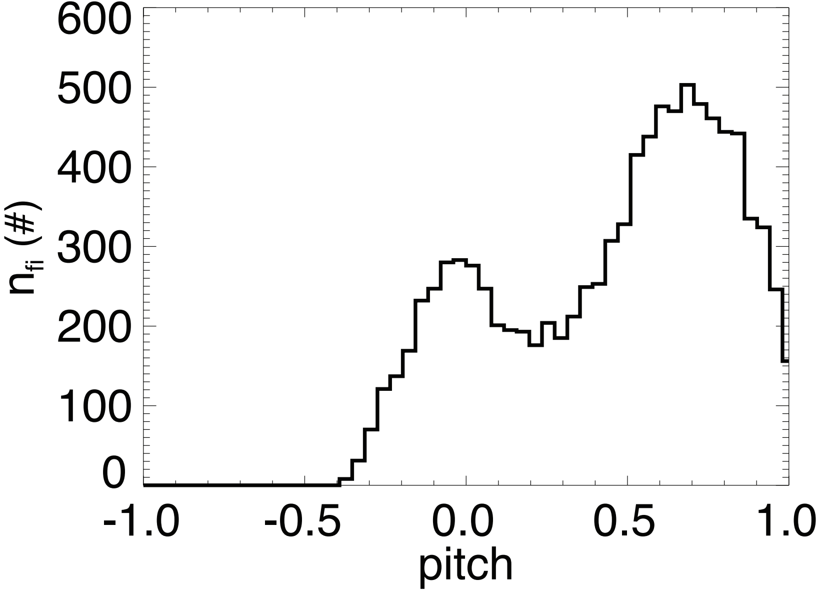
B. Hudson II Ph.D. Thesis, University of Wisconsin – Madison, 2006

Curvature and Grad-B drifts cause the fast ions to have an effective q different from magnetic q in the RFP

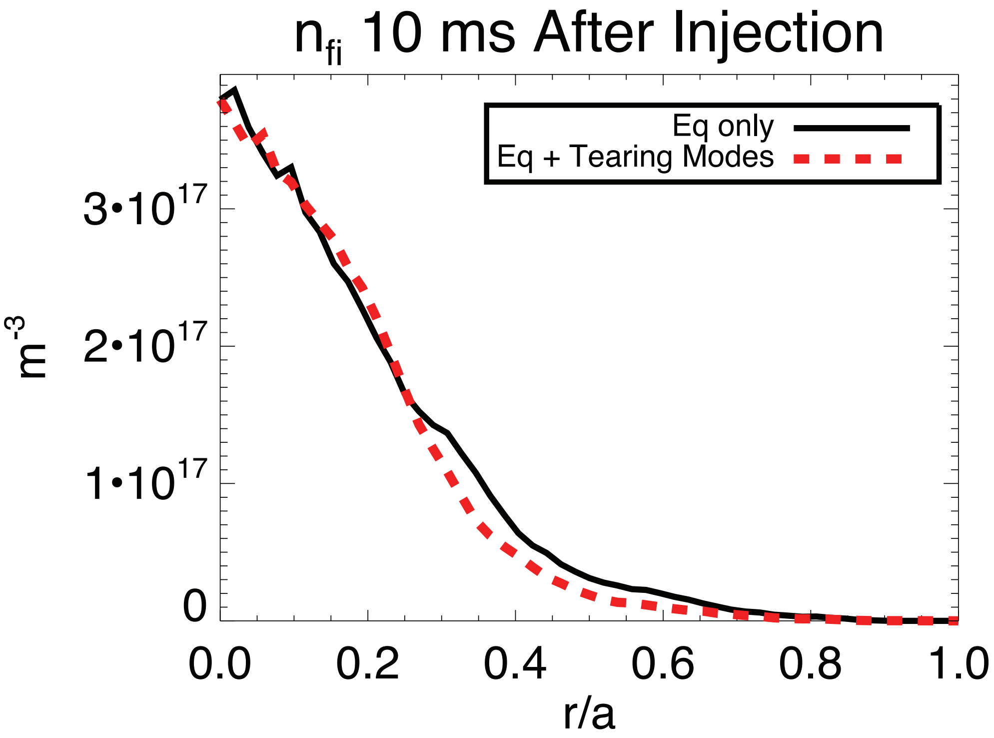


RIO models the neutral beam deposition through charge exchange in toroidal geometry

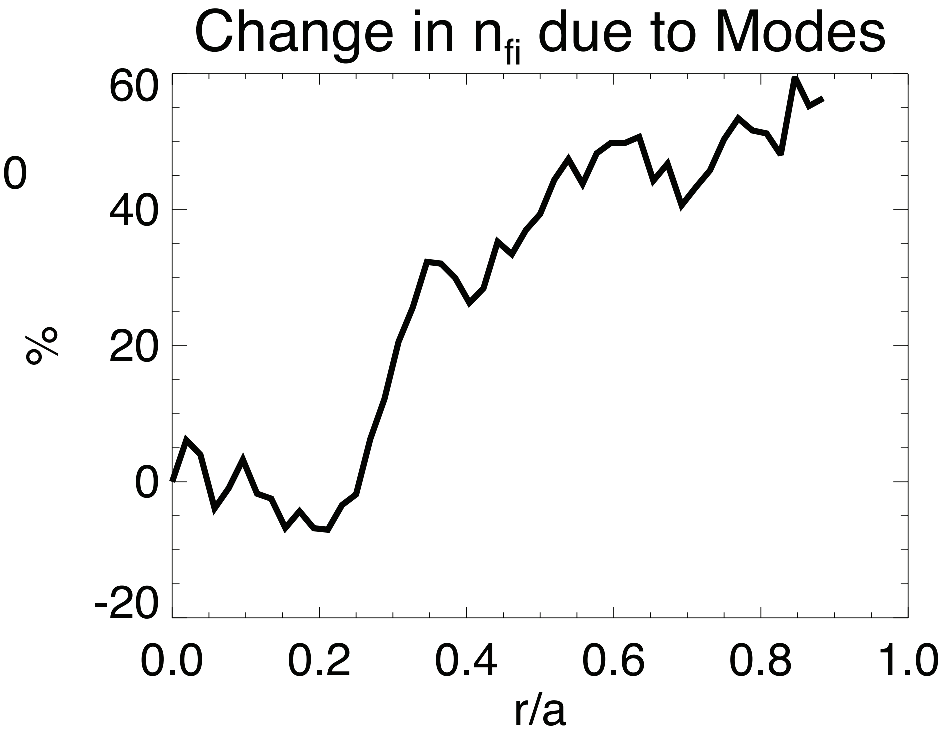

Deposition: Top view


n_{fi} vs pitch

Co-current beam injected ion density is predicted to be core peaked and largely unaffected by tearing modes



- A 1ms beam blip is modeled with 10^4 particles
- After 10ms in stochastic field tearing modes have done little to the core ions



- Ions in the mid radius do see the MHD activity and enhanced fast ion loss

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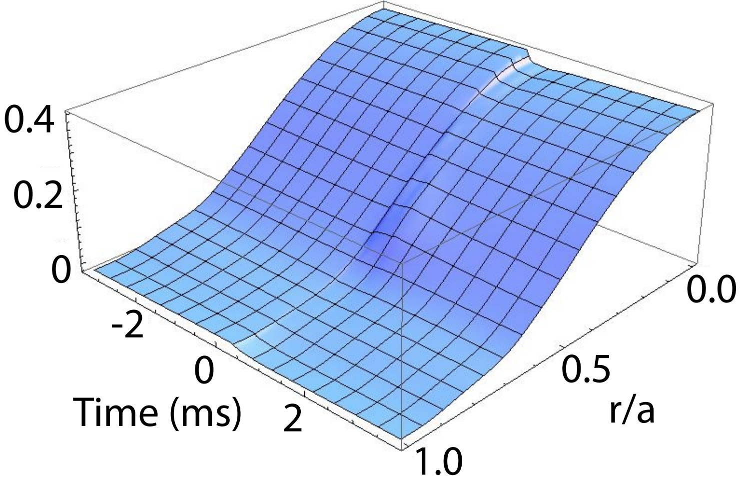
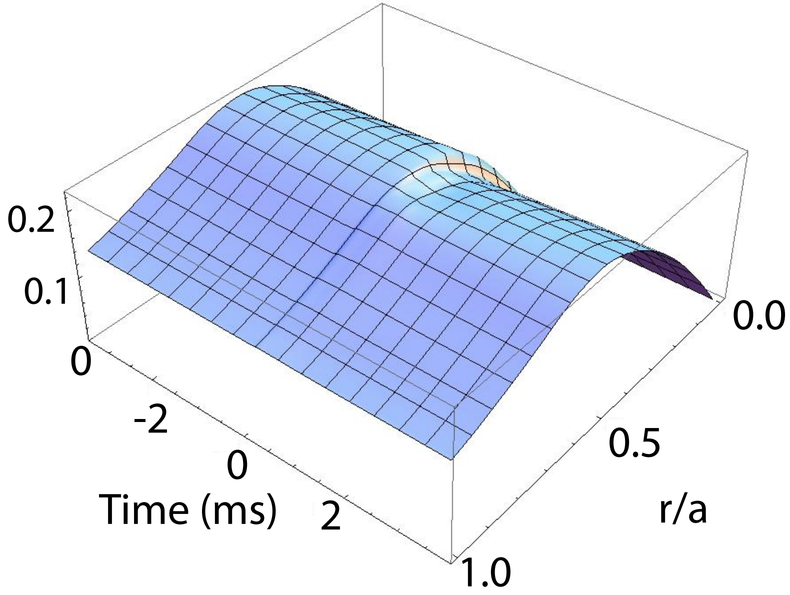
RIO can use the time evolving electric and magnetic fields from MHD simulations of sawteeth in MST

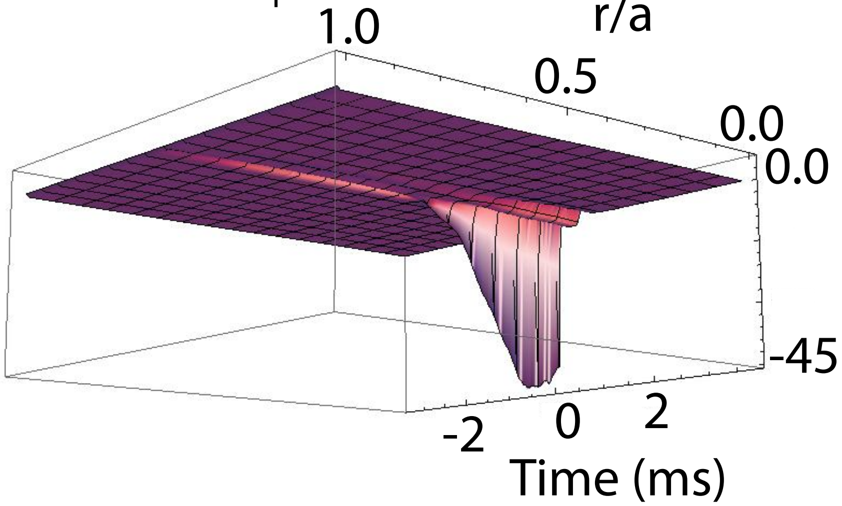
B_ϕ (T)



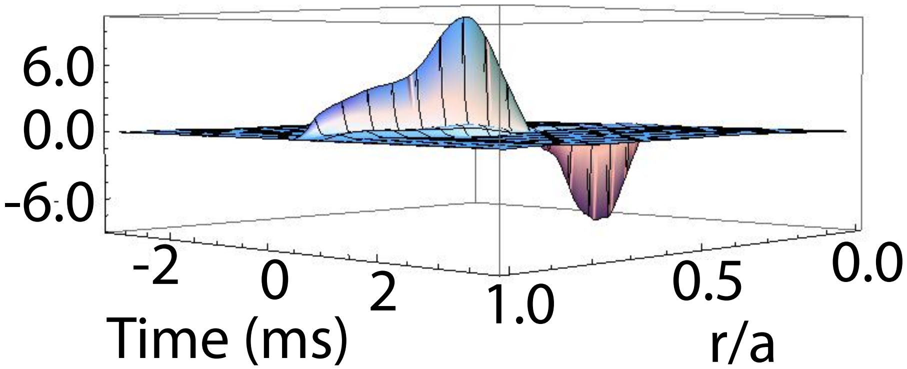
B_θ (T)



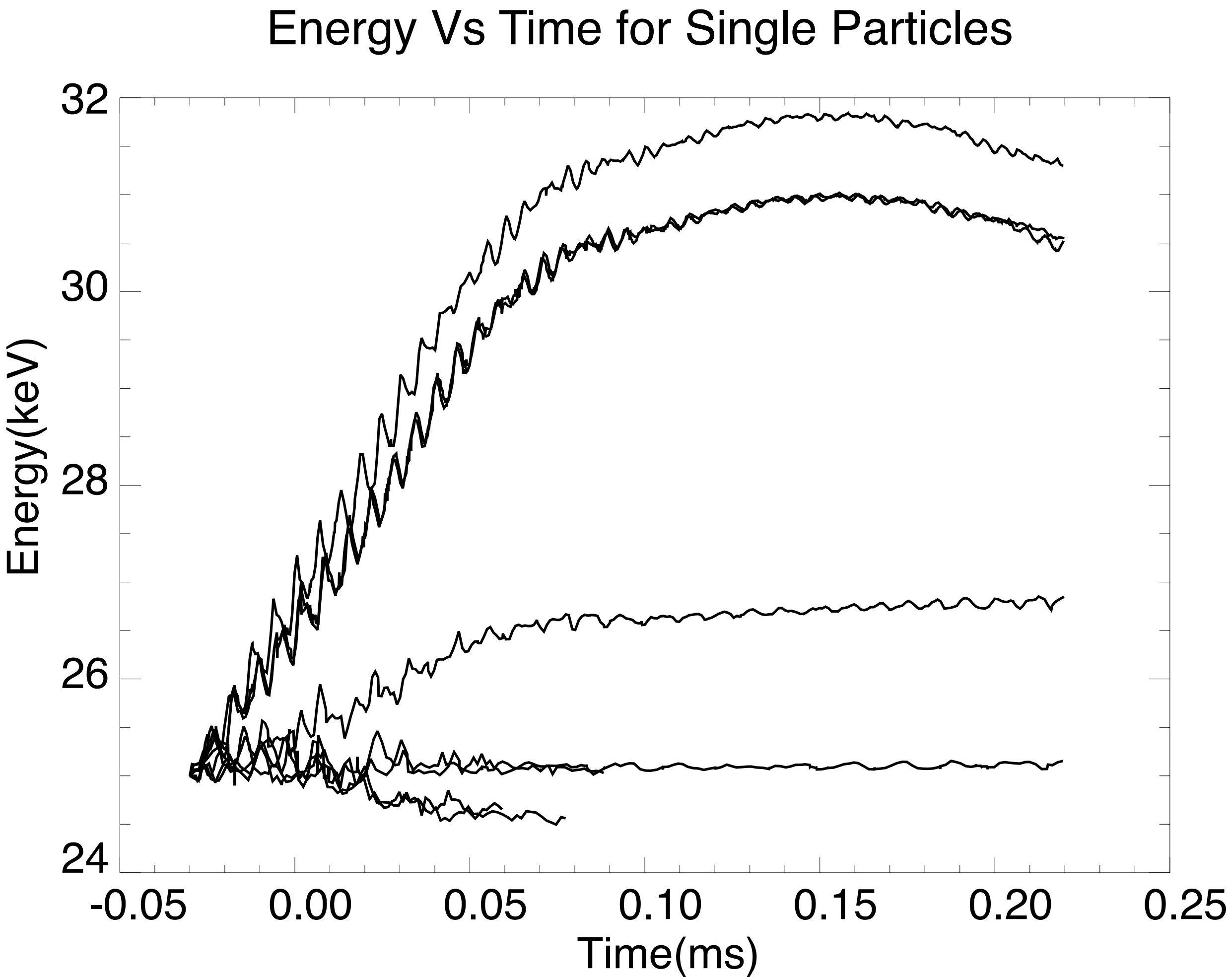
E_ϕ (V/m)



E_θ (V/m)



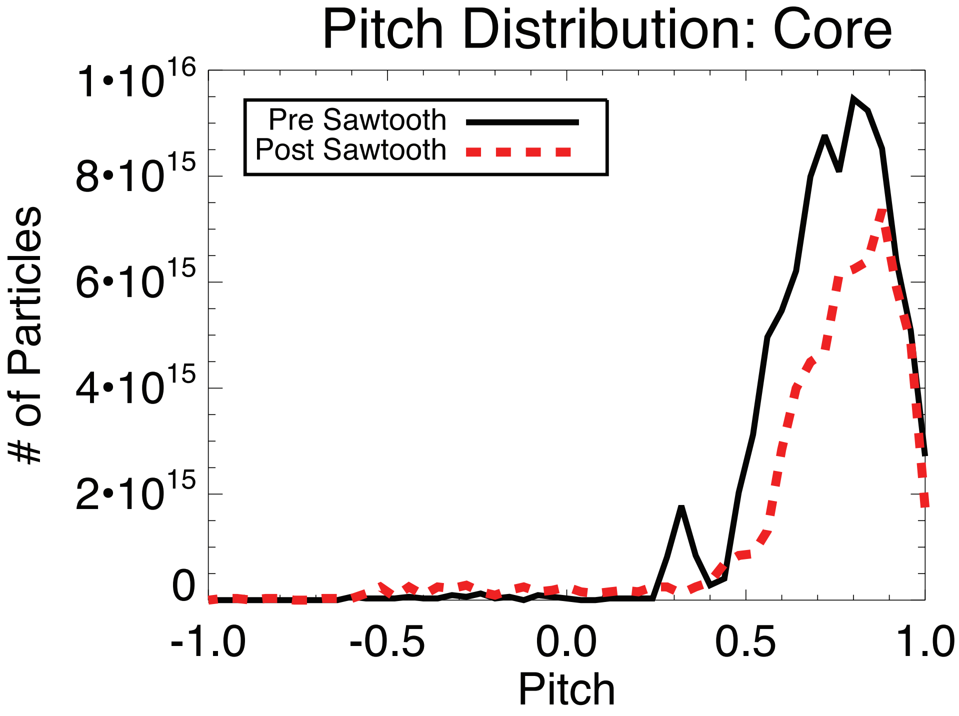
Fast ion acceleration is observed in RIO using the simulated fields, similar to ANPA measurements



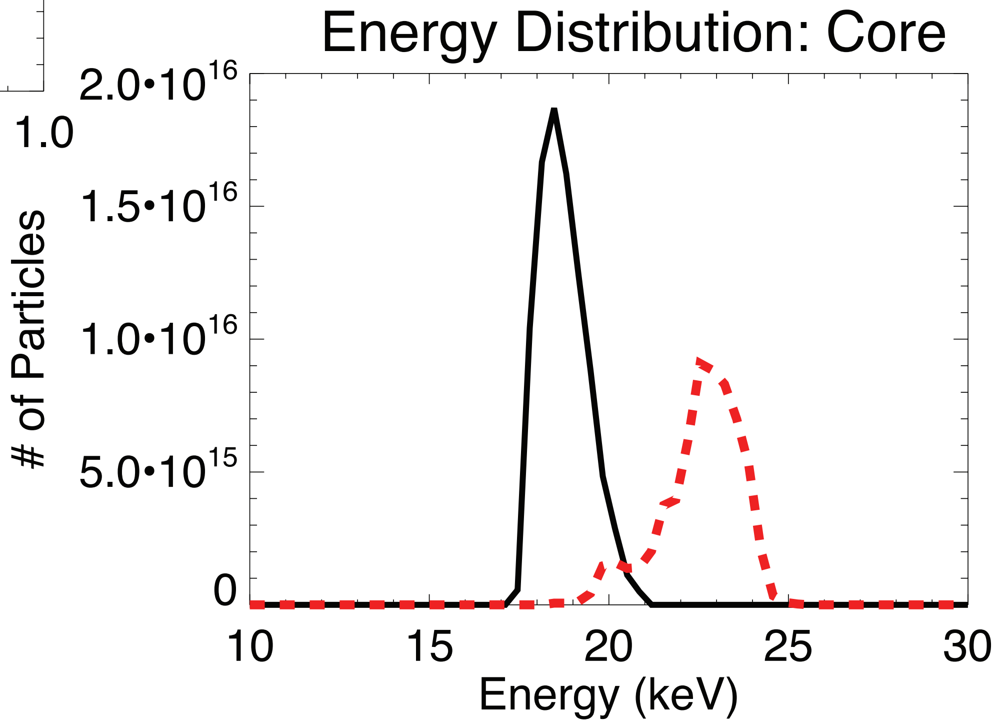
- Ion acceleration of over 20% of the initial ion energy is observed for single particles

- Acceleration is consistent with ion runaway due to large, transient parallel electric field at crash

Acceleration at sawtooth pushes fast ion distribution to towards higher pitch and higher energy

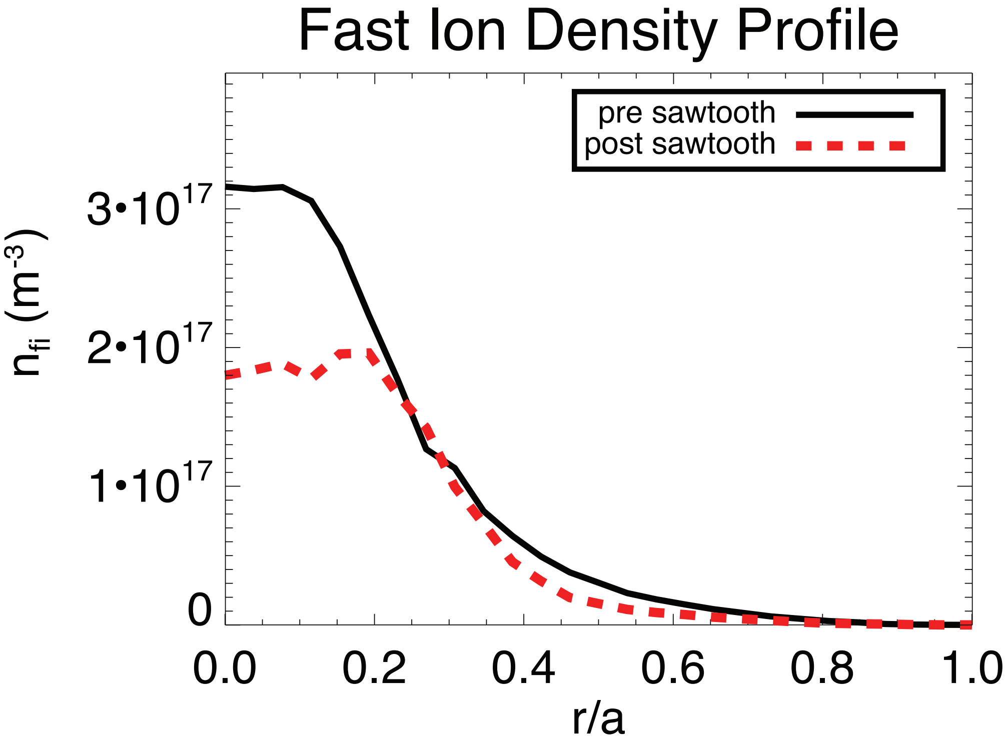


- 10^4 H neutrals injected over 1ms as with a beam blip, slow for 4ms
- Sawtooth crash causes dominantly parallel acceleration



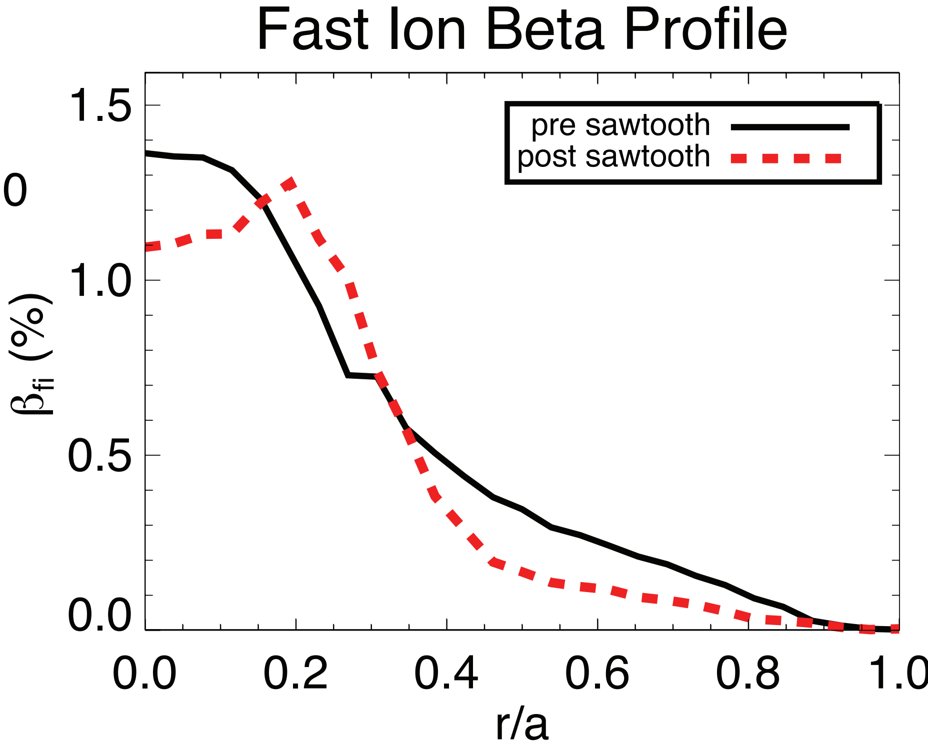
- Average energy increase of core high pitch beam ions is ~ 5keV

The fast ion density is significantly reduced at the sawtooth crash, the fast ion beta is less so.

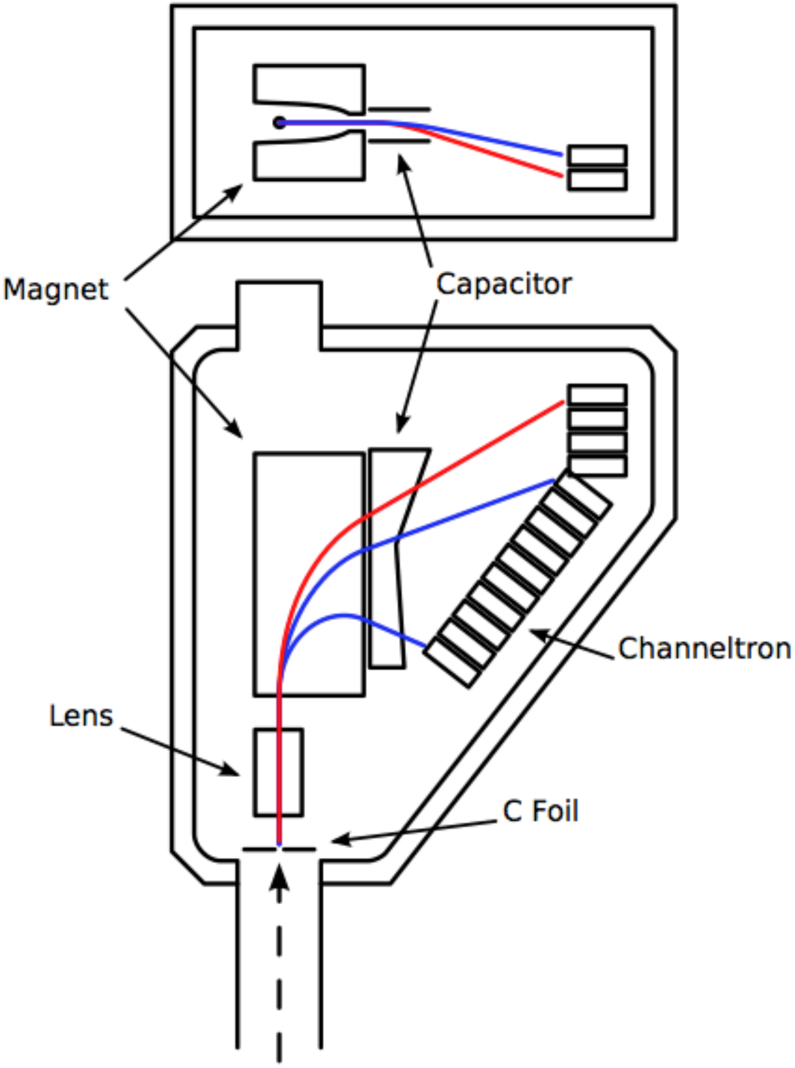


- At crash, ~40% of total fast ion population is lost

- Confined ions are accelerated and magnetic field is redistributed causing a much more muted drop in β_{fi}



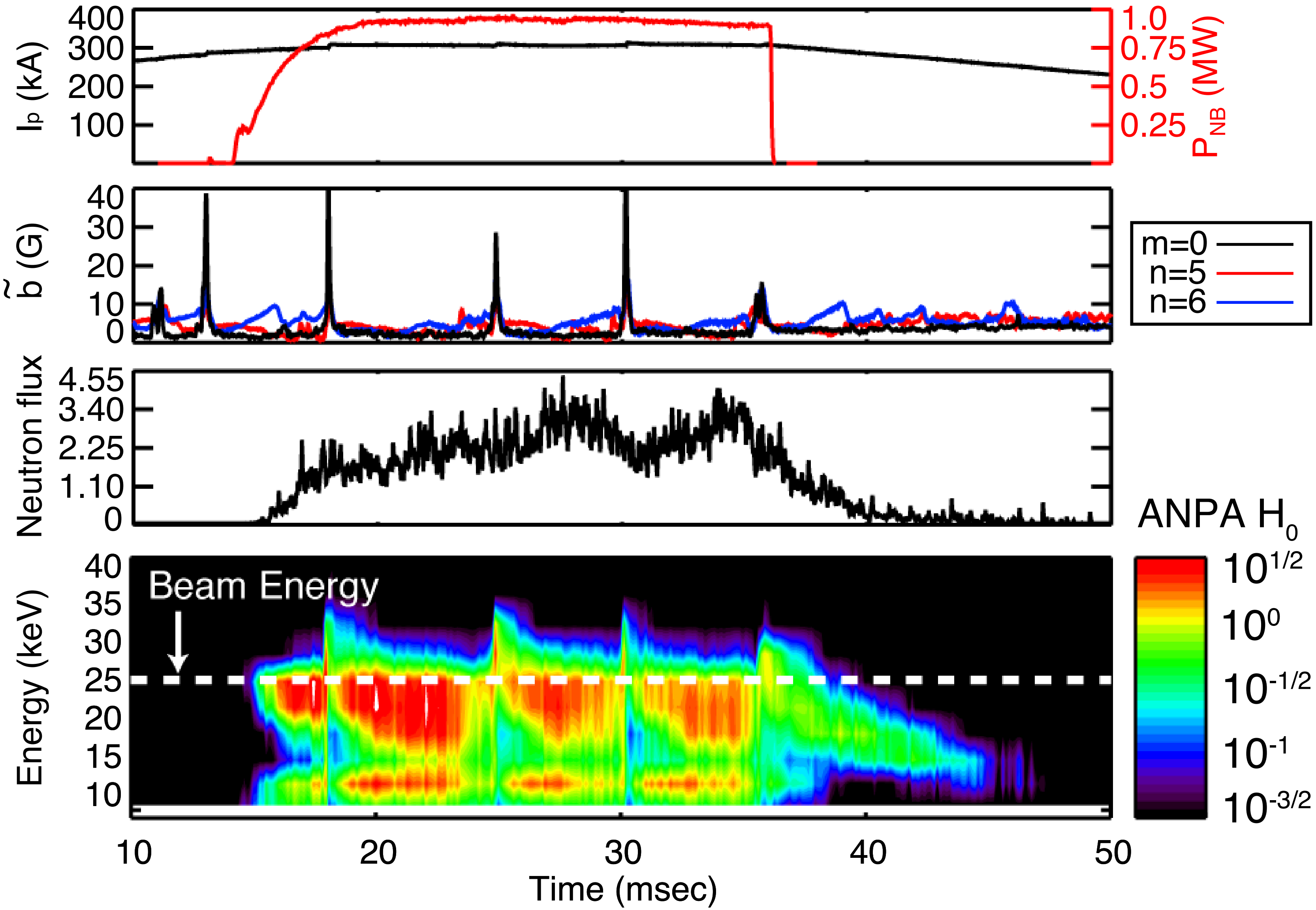
The sawtooth evolution of the fast ions distribution can be measured with the ANPA



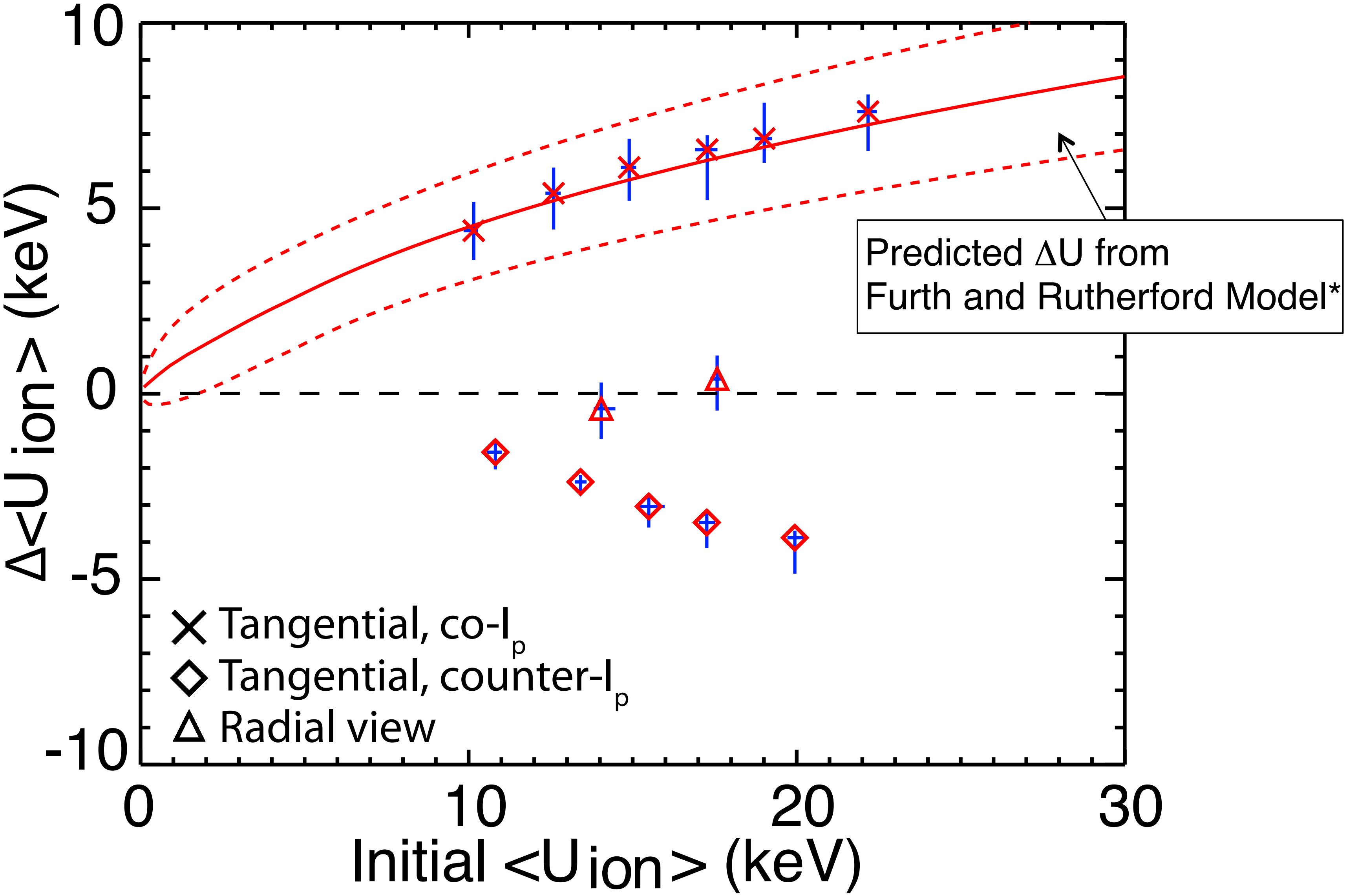
MST

- E ll B Neutral particle analyzer
- 10 Hydrogen + 10 Deuterium channels
  - 10-45 keV range
- 250kHz time resolution allows sawtooth and fluctuation analysis
- Small form factor allows tangential to radial views to be used

In MST, acceleration of high pitch, core localized fast ions is observed at the sawtooth crash



Recent ANPA measurements show fast ions acceleration consistent with ion runaway



Ion energization measured with ANPA
S. Eilerman et. al. PRL (in preparation)

*H. Furth and P. Rutherford, PRL **28** (1972)

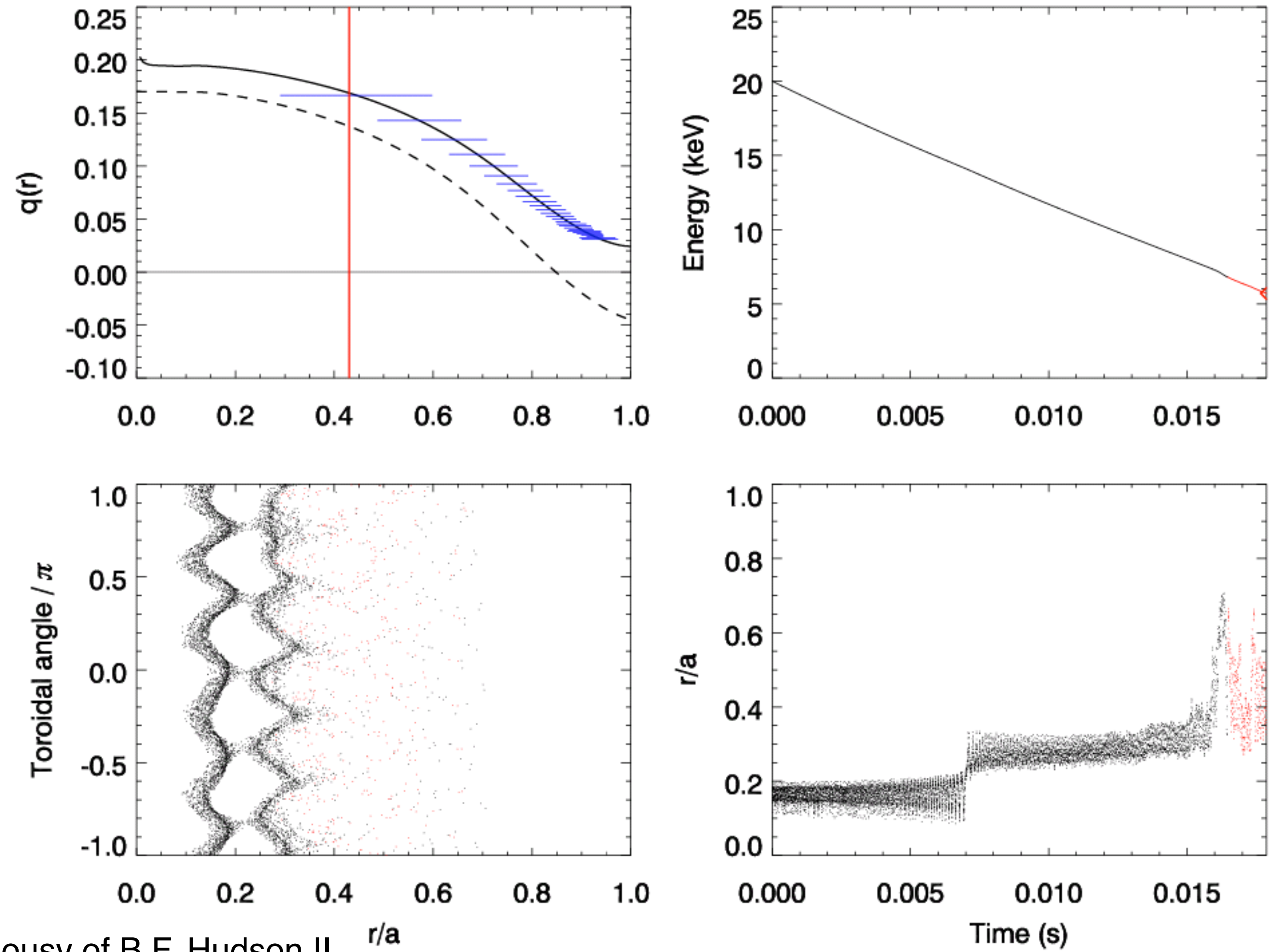
Summary and Conclusions

- Upgraded TS system enabled the determination of sawtooth evolution of χ_e at 20 kHz
- χ_e varies by orders of magnitude in the core region and the mid radius throughout the sawtooth cycle.
- High S nonlinear single fluid resistive MHD simulates MST well, even reproducing the duration of the sawtooth crash
- Trapped particles do not carry heat along diffusing magnetic field lines and must be taken into account for the predicted χ_e to match the measured χ_e.
- χ_e in the mid-radius is stochastic, other transport mechanisms are important in the core before the sawtooth crash.

Summary and Conclusions (cont'd)

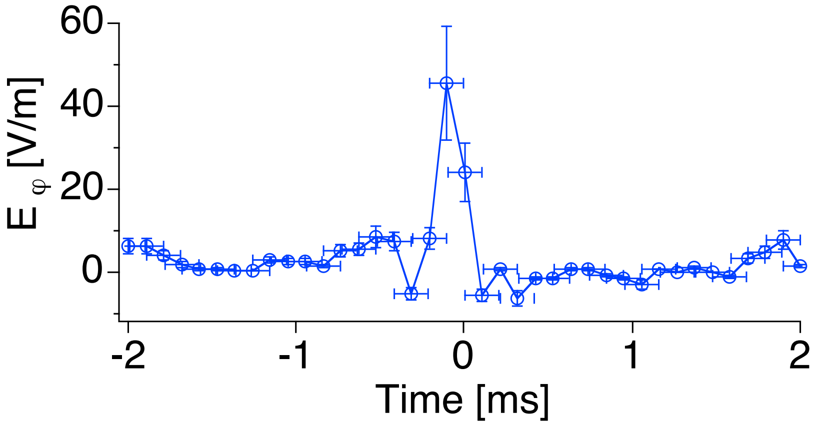
- Modeling the fast ion trajectories in MST is challenging due to the large number of tearing modes and strongly evolving electric and magnetic fields but can now be done with RIO
- Broad spectrum tearing mode activity cause some direct loss in the mid-radius, while the core is largely unaffected
- High energy beam injected ions are accelerated at the sawtooth crash due to transient parallel electric field
- Large fluctuations amplitudes at sawtooth crash deplete fast ion density but ion acceleration mutes the effect on β_{fi}
- Measured parallel fast ion acceleration is likely from ion runaway, this does not explain perpendicular heating of thermal ions

Well confined fast ions slow down, eventually interacting with the stochastic field and are lost



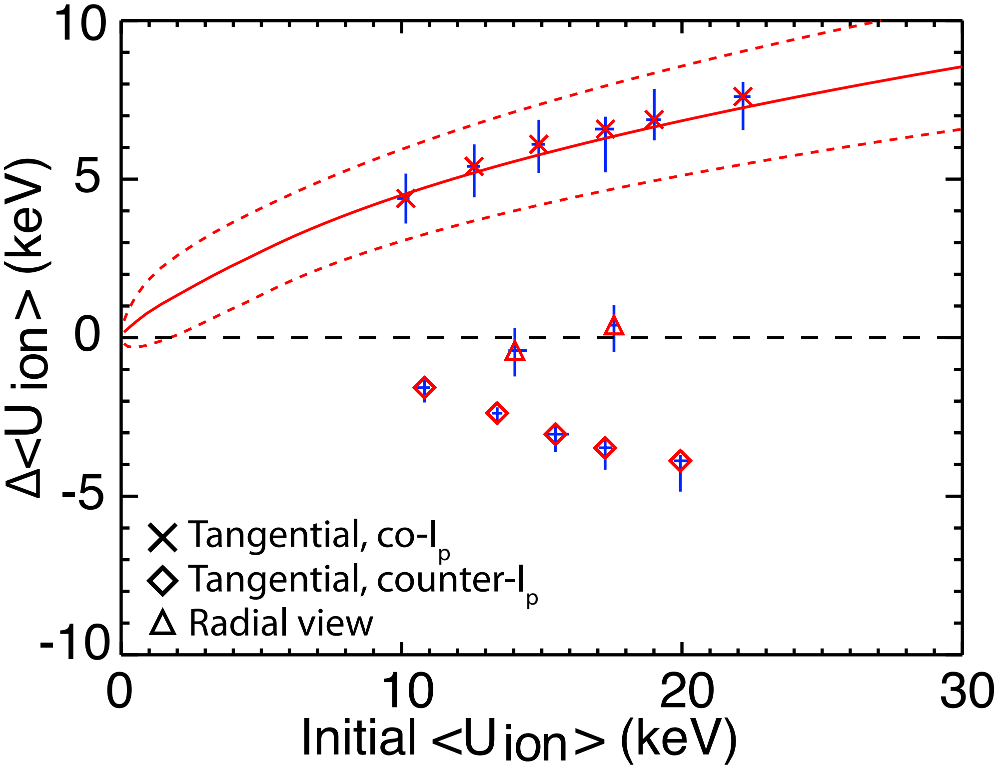
*Curteousy of B.F. Hudson II

Recent ANPA measurements show fast ions acceleration consistent with ion runaway



- Toroidal electric field in MST measured with polarimeter
- Measured acceleration again consistent with ion runaway

- Average energy gain is 4-8kV for high pitch beam injected ions, ~0kV for low pitch ions
- Does not explain preferential perpendicular heating of thermal ions

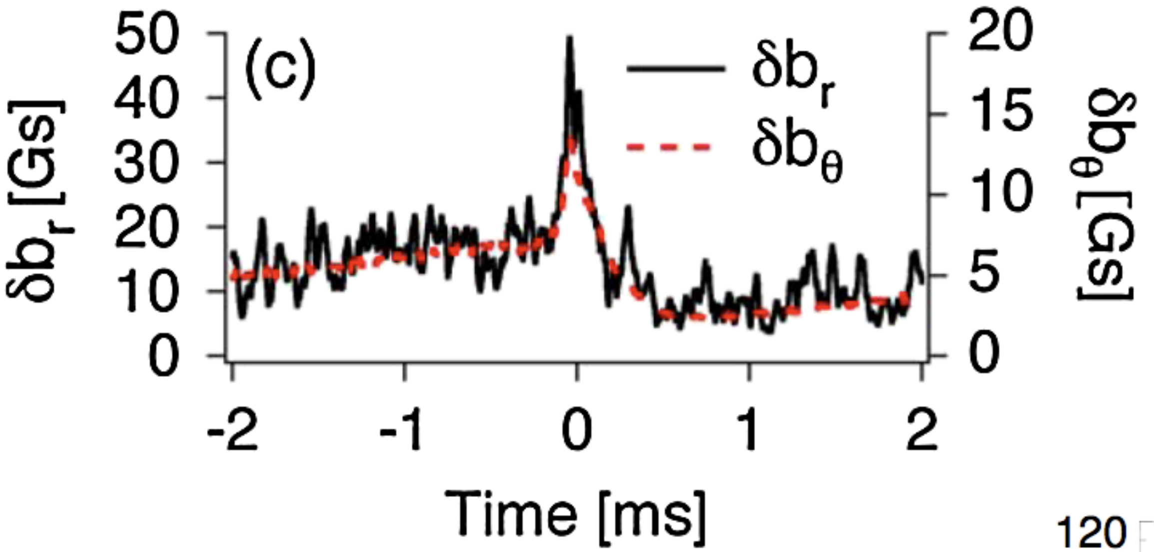


Electric field measured using FIR polarimetry
W.X. Ding et. al. PRL 2004

Ion energization measured with ANPA
S. Eilerman et. al. PRL (in preparation)

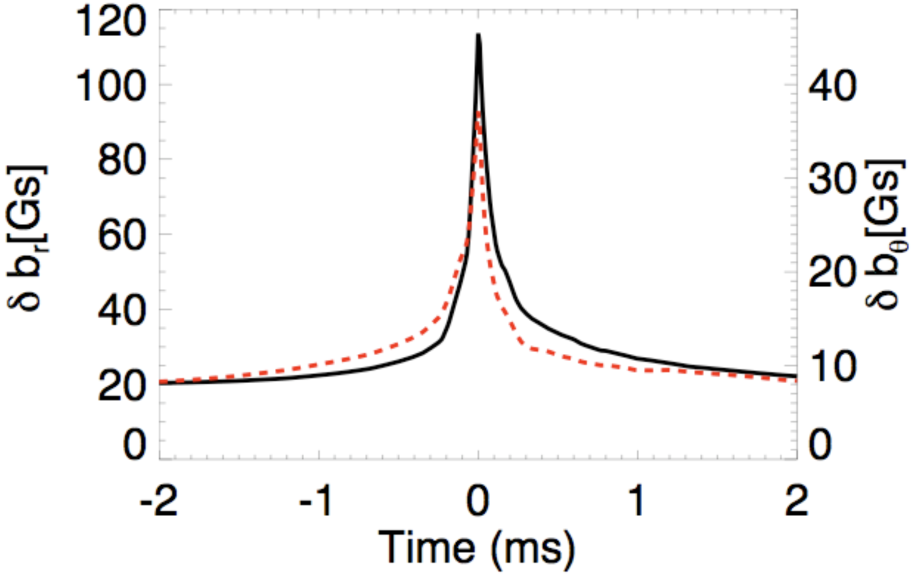
The ratio of the edge poloidal fluctuation to the core radial fluctuation matches that seen in experiment.

m=1, n=6: Experiment*



- In MST the core B_r is about 2.5 times the edge B_θ

Simulation



- This ratio is also seen in the simulated fluctuations

*W.X. Ding, *et al.*, PRL, **103**, 025001, 2009