Measurement and simulation of electron thermal transport in the MST Reversed-Field Pinch[a]

D. J. Den Hartog[1,2], J. A. Reusch[1], J. K. Anderson[1], F. Ebrahimi[1,2,*], C. B. Forest[1,2], D. D. Schnack[1], and H. D. Stephens[1,2,†]

[1] *Department of Physics, University of Wisconsin–Madison, Madison, Wisconsin, 53706 U.S.A.*
[2] *The Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, University of Wisconsin–Madison, Madison, Wisconsin, 53706 U.S.A.*

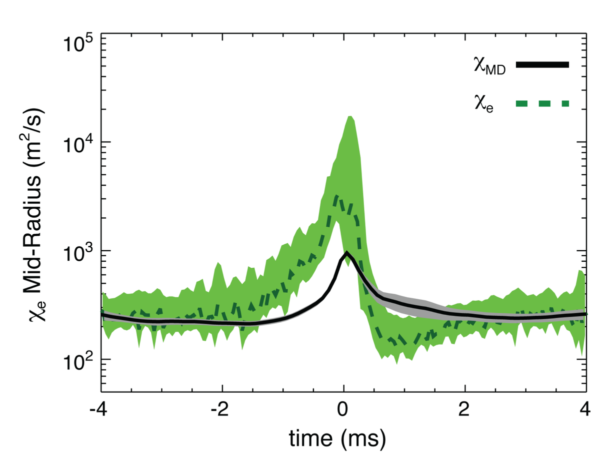
E-mail contact of main author: djdenhar@wisc.edu

Comparison of measurements made in the MST Reversed-Field Pinch (RFP) to the results from extensive single-fluid nonlinear resistive MHD simulations provides two key observations. First, thermal diffusion from parallel streaming in a stochastic magnetic field is reduced by particle trapping in the magnetic mirror associated with the toroidal equilibrium. Second, the structure and evolution of long-wavelength temperature fluctuations measured in MST shows remarkable qualitative similarity to fluctuations appearing in a finite-pressure nonlinear MHD simulation. New high-time-resolution measurements of the evolution of the electron temperature profile [$T_e(r,t)$] through a sawtooth event in high-current RFP discharges have been made using the recently enhanced capabilities of the multi-point, multi-pulse Thomson scattering diagnostic on MST. Thermal diffusion is calculated by performing a low resolution fit of the χ_e profile to the electron temperature data via the energy conservation equation, assuming Fourier's law $q_e = -n_e \chi_e \nabla T_e$. These measurements are then compared directly to simulations using the nonlinear, single-fluid MHD code DEBS, run at parameters matching the RFP discharges in MST. These simulations display MHD activity and sawtooth behavior similar to that seen in MST. In a zero β simulation, the measured χ_e is compared to the thermal diffusion due to parallel losses along diffusing magnetic field lines, $v_{||}D_{mag}$, where D_{mag} is determined from the simulation by tracing magnetic field lines. Agreement within uncertainties is only found if the reduction in thermal diffusion due to electron trapping is taken into account. In a second simulation, the pressure field was evolved self consistently assuming Ohmic heating and anisotropic thermal conduction. Although these pressure-evolved simulation results need further confirmation, the fluctuations in the simulated temperature are very similar in character and time evolution to temperature fluctuations measured in MST.

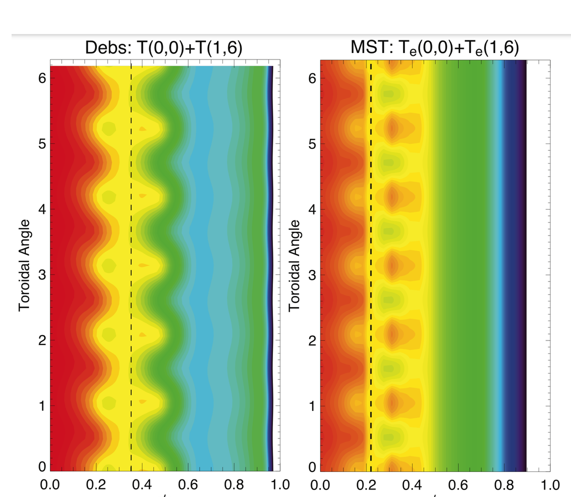
[a] This work is supported by the U. S. Department of Energy and the National Science Foundation.
* Currently at University of New Hampshire, Durham, New Hampshire, 03824 U.S.A.
† Currently at Pierce College, Lakewood, Washington, 98498 U.S.A.

Comparison of measurements to single-fluid nonlinear resistive MHD simulations provides two key observations.

- Thermal diffusion from parallel streaming in a stochastic magnetic field is reduced by particle trapping in the magnetic mirror associated with the toroidal equilibrium.



- The structure and evolution of long-wavelength temperature fluctuations measured in MST shows remarkable qualitative similarity to fluctuations appearing in a finite-pressure nonlinear MHD simulation



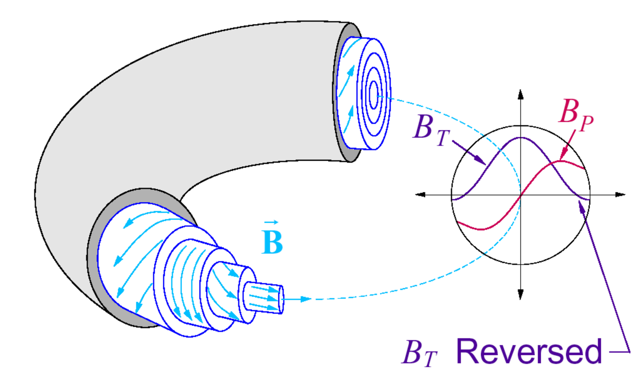
OUTLINE

- Introduction to RFP
  - Fusion advantages
  - MST
  - Tearing modes and sawteeth
- Transport measurements
  - RFP confinement
  - High-rep-rate Thomson scattering
    - T_e through a sawtooth
  - Themal diffusion
- Simulations
  - Nonlinear, single-fluid MHD code DEBS
  - Zero β
  - Finite β

The Reversed-Field Pinch (RFP)

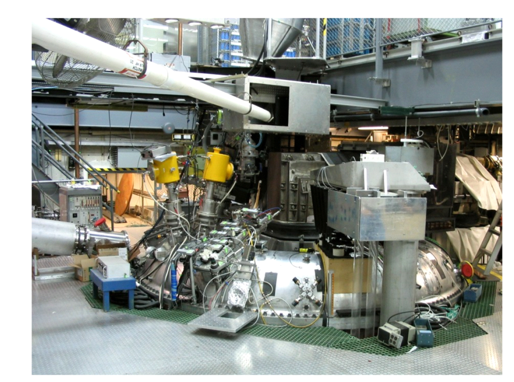
In the RFP, the magnetic field is produced primarily by the toroidal plasma current.

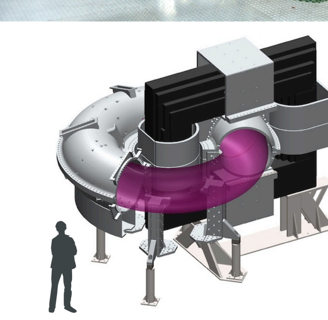
- Only a small externally applied toroidal field is required:
  - Specific advantage for fusion application
  - Large magnetic shear and weaker toroidal (neoclassical) effects
    - explores complementary/overlapping parameter space with respect to the tokamak and stellarator
  - Basic science: magnetic self-organization and nonlinear plasma physics



The MST device is a moderate current RFP with some unique features.

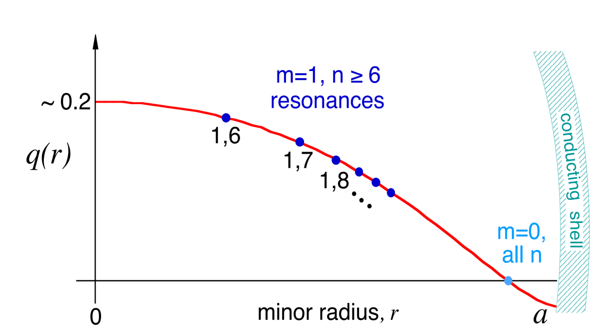
- Thick aluminum shell serves as:
  - Vacuum vessel
  - Single-turn TF coil
  - PF shaping boundary
  - Stabilizing shell
- Typical parameters:
  - R = 1.5 m, a = 0.5 m
  - I_p < 0.6 MA (B < 0.6 T)
  - $n_e \leq 5 \times 10^{19}$ m^{-3}
  - 200 eV < T_e, T_i < 2 keV
  - τ_{pulse} < 0.1 s

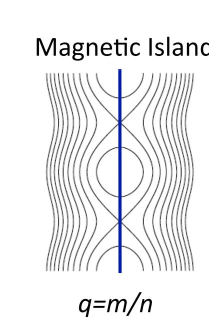




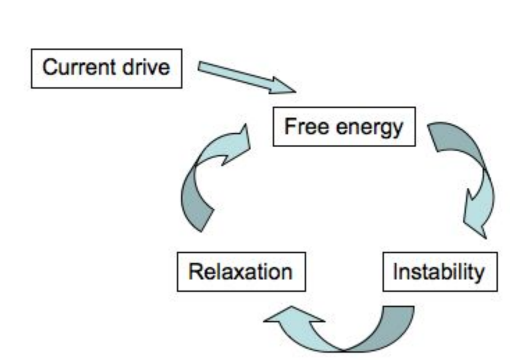
The magnetic tearing instability underlies the nonlinear dynamics of the RFP.

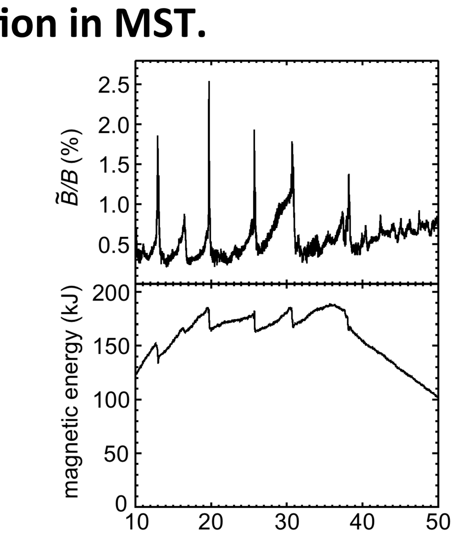
- Stability depends on $J_{||}(r)$ profile, and therefore the current drive method





The tearing modes associated with sawteeth produce impulsive magnetic reconnection in MST.



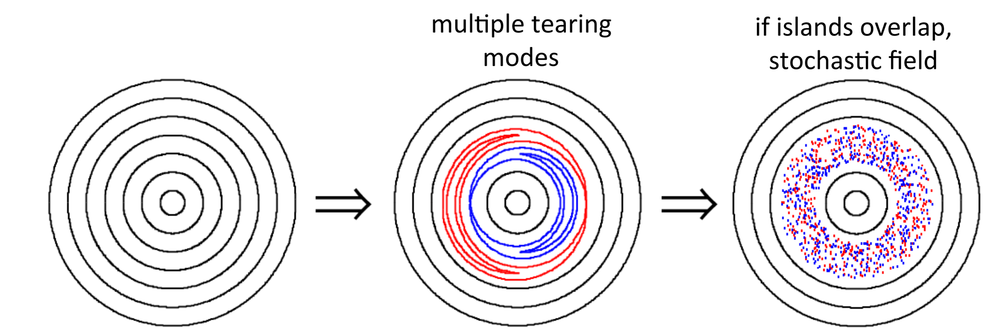


- Plasma parameters change dramatically during fast reconnection events
  - fluctuations increase, stochasticity increases, confinement drops, ….

Transport measurements

Multiple tearing modes can cause the magnetic field to become stochastic.

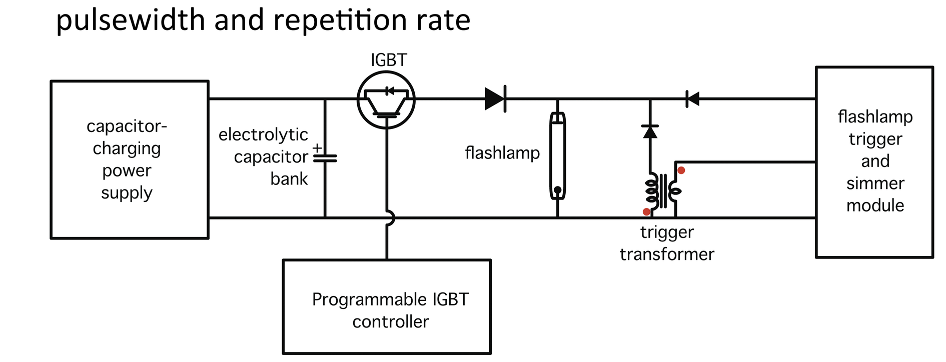
- Stochastic instability occurs when magnetic islands overlap
  - field lines wander randomly throughout the plasma volume
- Heat conduction out of the plasma is greatly enhanced



- Stochasticity in the RFP can be dramatically decreased by current profile control or initiation of a quasi-single-helicity state

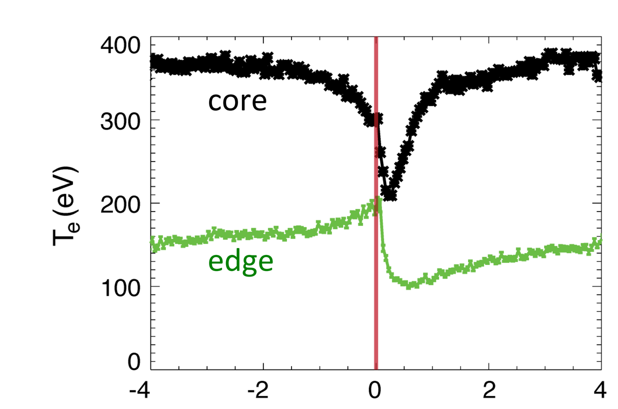
The Thomson scattering diagnostic on MST uses two upgraded Nd:YAG lasers.

- First upgrade was to take direct control of Pockels cell Q-switching
- Second and more involved upgrade was to take control of flashlamp pulsewidth and repetition rate



- Collect thirty T_e profiles during a single MST discharge
  - at rates from 1–25 kHz (with two interleaved lasers)
  - each T_e profile consists of twenty spatial points
  - detailed measurements in an *overdense* plasma

Sawtooth ensembling enables measurement of Te evolution at high time resolution.

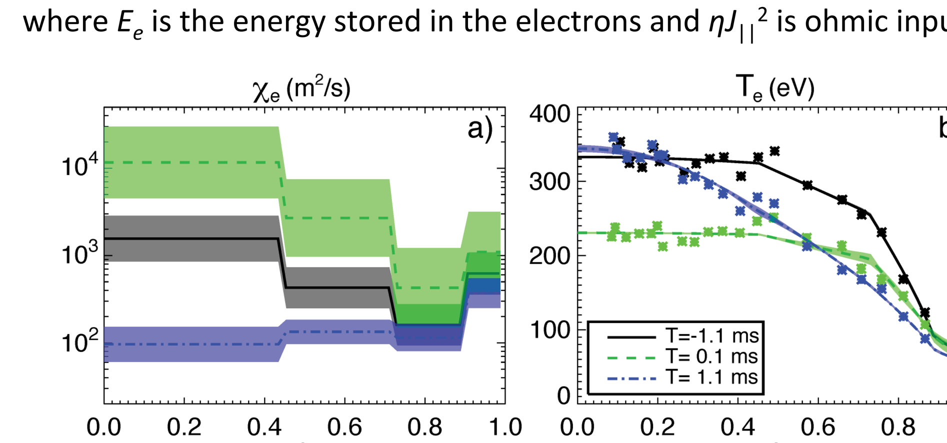


Thermal diffusion is calculated by performing a low resolution fit of the χ_e profile to $T_e(r,t)$ via the energy conservation equation.

- Assuming Fourier's law $q_e = -n_e \chi_e \nabla T_e$, the energy conservation equation can be written as

$$\partial E_e/\partial t = \mathrm{div}(q_e) + \eta J_{||}^2 - \mathrm{sinks}$$

where E_e is the energy stored in the electrons and $\eta J_{||}^2$ is ohmic input power

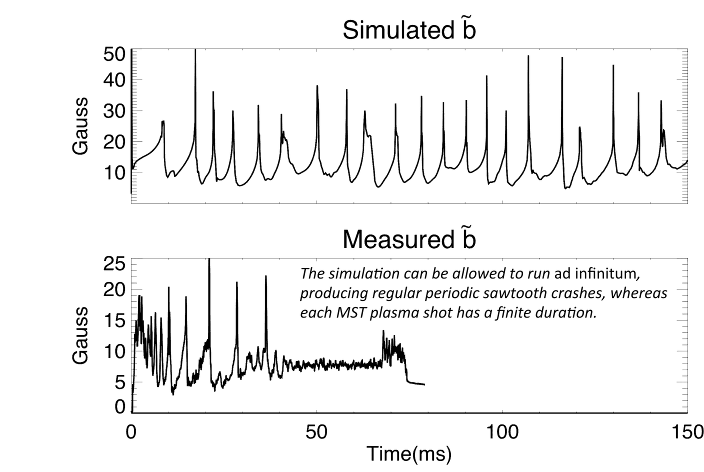


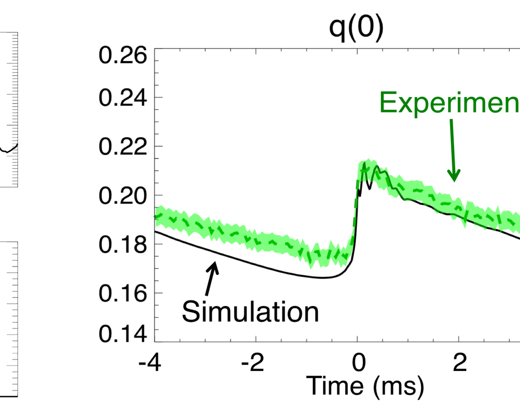
- Plasma is divided into four regions: core, midradius, reversal surface, and edge
  - χ_e is calculated for each of these regions at each of the three times
  - χ_e varies by over two orders of magnitude over a sawtooth cycle

Transport simulation

Single fluid, 3D, nonlinear, resistive MHD simulations at zero β reproduce many observed RFP dynamics.

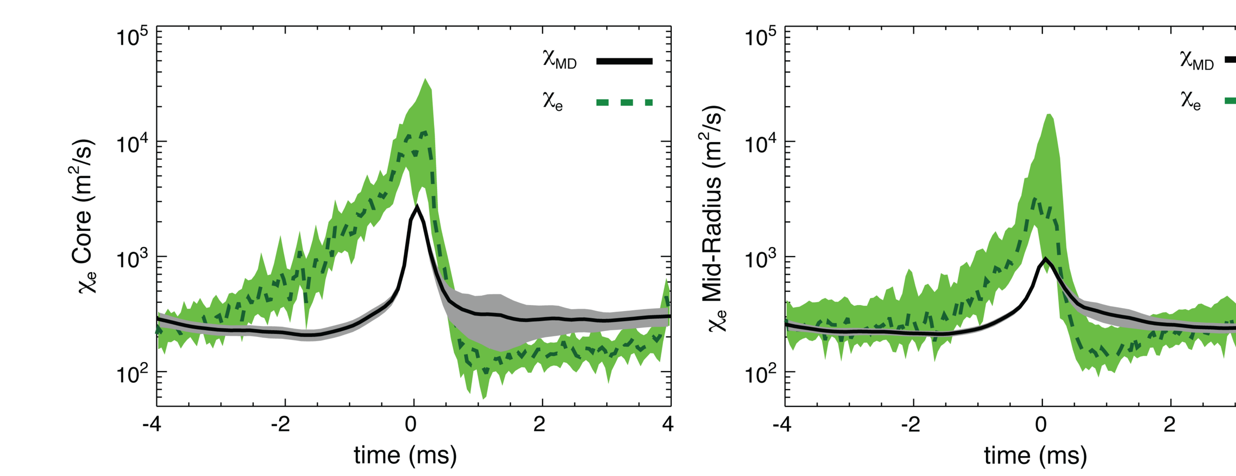
- DEBS is a single-fluid MHD simulation code run in cylindrical geometry
  - simulation Lundquist number $S = \tau_R/\tau_A$ matches the ~4×10^6 in experiment
  - measured $T_e(r)$ is used for calculation of the simulation resistivity profile
- Simulations reproduce sawtooth period and duration, and equilibrium evolution of MST





The reduction in χ_e due to electron trapping must be taken into account in order for simulation and measurement to agree.

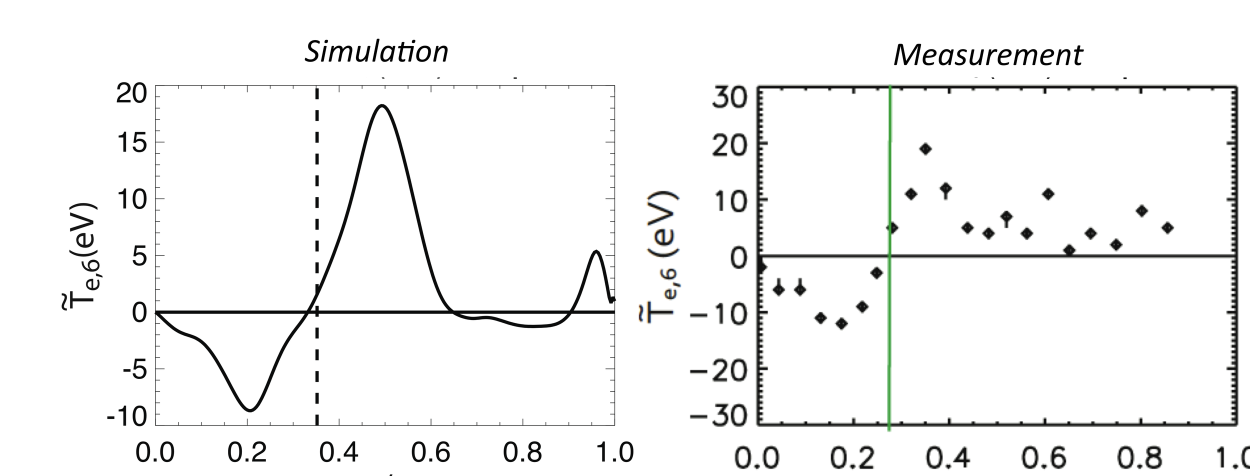
- Resulting effective electron thermal diffusion is $\chi_{MD} = f_c v_{||} D_{mag} \approx f_c v_{th,e} D_{mag}$
  - D_{mag} is calculated using simulation mode eigenfunctions and field line tracing
  - f_c is the circulating fraction of the electron population



- In the core, the measured χ_e is greater than χ_{MD} prior to and during the sawtooth crash
  - other transport mechanisms such as temperature profile flattening due to magnetic islands may be important at these times

DEBS simulations at finite β exhibit pressure fluctuations which allow temperture structures to be investigated.

- Pressure can be self-consistently evolved assuming Ohmic heating and anisotropic thermal conduction
- Pressure-evolved simulation results need further confirmation, but the fluctuations in the simulated temperature are very similar to temperature fluctuations measured in MST



SUMMARY

- Particle trapping reduces thermal diffusion in the RFP
- DEBS simulation reproduces detailed measurements of RFP dynamics