Measurement of Current Fluctuations and Charge Transport During Reconnection

by N. A. Crocker, G. Fiksel, S.C Prager, J. S. Sarff

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Dept. of Physics, Univ. of Wisconsin - Madison

Abstract (Revised)

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The current perturbation associated with magnetic reconnection has been measured in the Madison Symmetric Torus (MST). A reversed field pinch plasma configuration such as MST normally exhibits strong magnetic field fluctuations due to resistive tearing modes. Large amplitude, highly spatially localized perturbations in the parallel current density are expected to occur in the region of the reconnection. One such region, the reversal surface, is in the plasma edge. This region was accessed using a pair of insertable probes, each with Rogowskii coils and magnetic coils. The current perturbation's radial structure is broad, comparable to the expected island width, rather than highly localized. The magnetic fluctuation driven radial charge flux due to these perturbations was also measured. This charge flux is proportional to the flux surface average of the product of the parallel current density perturbation and the radial magnetic field perturbation. The measured charge flux is small between sawtooth crashes. This is partly in agreement with theoretical expectation.

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Introduction

- **Reconnection associated with tearing mode activity is frequent in edge plasma of MST – diagnostically accessible.**

- **What is spatial structure of current and magnetic perturbation? Interesting spatial scales important to resistive and collisionless reconnection:**

  - **resistive layer width, δ_R**
    $<$ electron skin depth, c/ω_{pe}
    $<$ ion acoustic gyroradius, ρ_s
    $\ll$ ion skin depth, c/ω_{pi}, and island width, W

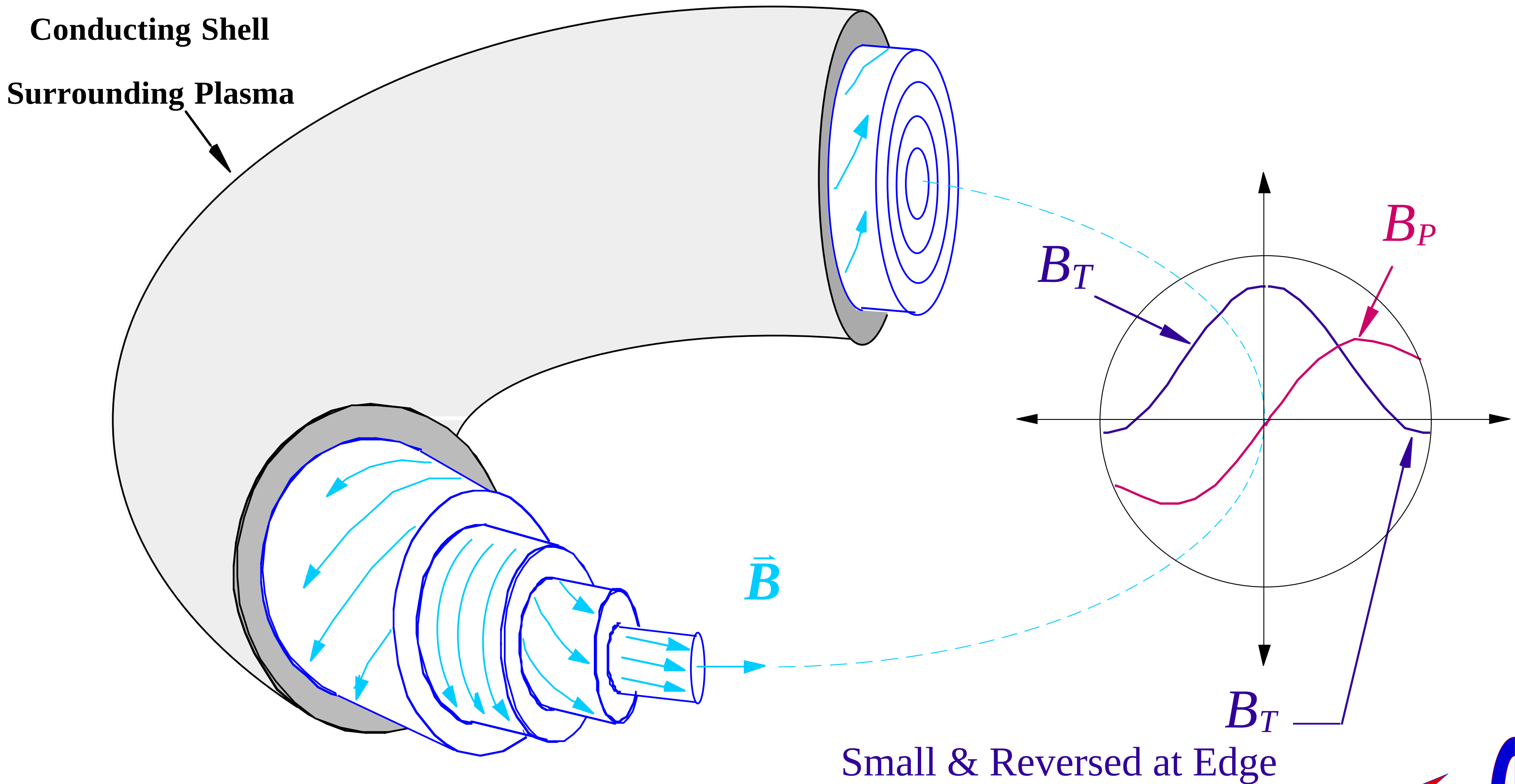
- **Is particle transport from reconnection ambipolar?**

  - **Theoretical expectation for tearing modes:**
    Current and magnetic perturbation out of phase -
    no charge transport.

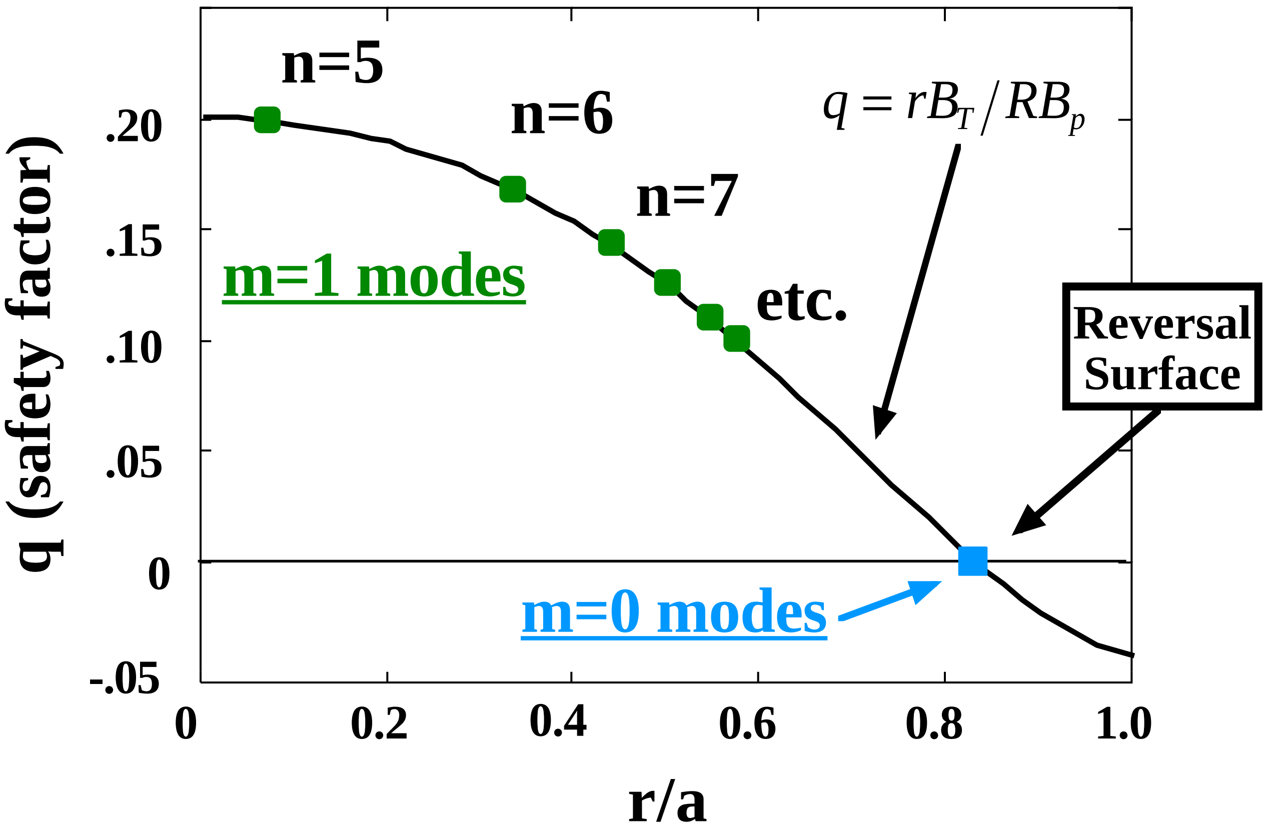
MST is a Toroidal Magnetic Plasma Confinement Device with Large Field Shear and Comparable Toroidal and Poloidal Magnetic Field

toroidal field $B_T \approx$ poloidal field B_P

large “magnetic shear”
(field line twists >90° from center to edge)



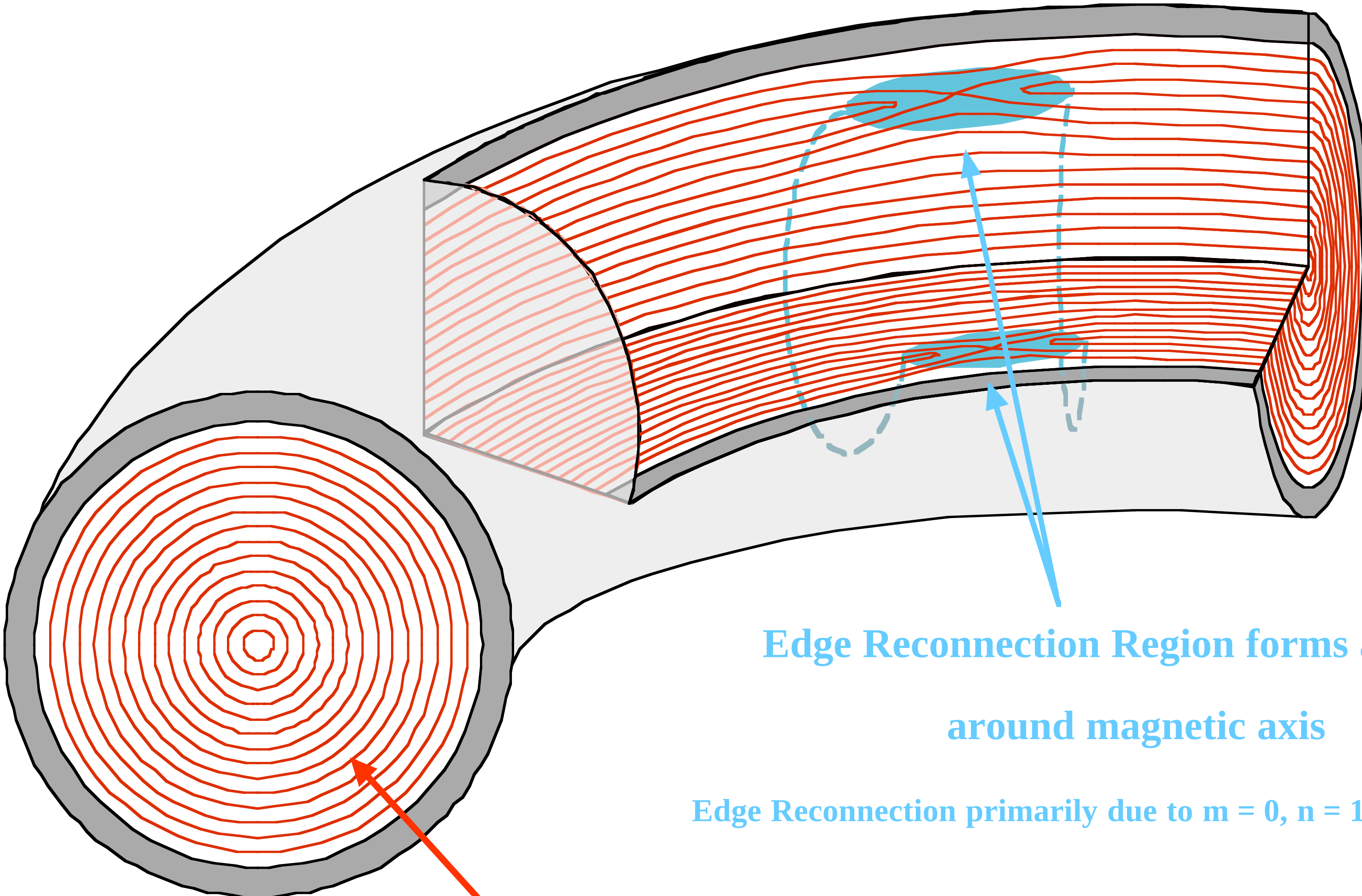
Tearing Modes Produce Large Magnetic Fluctuations in MST



- Tearing modes alter field line topology (i.e. "tear" field lines) at rational surfaces where they are resonant.

- MST has two classes of active tearing modes:
  - core resonant: poloidal mode number m = 1. magnetic perturbations are global in scale.
  - edge resonant: poloidal mode number m = 0

Edge Reconnection Region is Poloidally Distributed and Toroidally Localized



Edge Reconnection Region forms annulus around magnetic axis

Edge Reconnection primarily due to m = 0, n = 1 tearing modes

Nested Flux Surfaces of Equilibrium Magetic Field

Reconnection Allowed in MHD by Non-Ideal Effects in Ohm's Law

Ohm's Law for MHD

$$\vec{E} + \vec{v} \times \vec{B} = (\textbf{non-ideal terms})$$

non-ideal term	physical meaning	scale length
$\eta \vec{J}$	resistivity	$\delta_R = a/S^{2/5}$
$\left(\omega_{pe}^2 \varepsilon_0\right)^{-1} \partial \vec{J} / \partial t$	electron inertia	c/ω_{pe}
$\vec{J} \times \vec{B} / en$	Hall term/ion inertia	c/ω_{pi}
$-\vec{\nabla} p_e / en$	electron pressure	ρ_s

Current and Magnetic Spatial Spectra Estimated

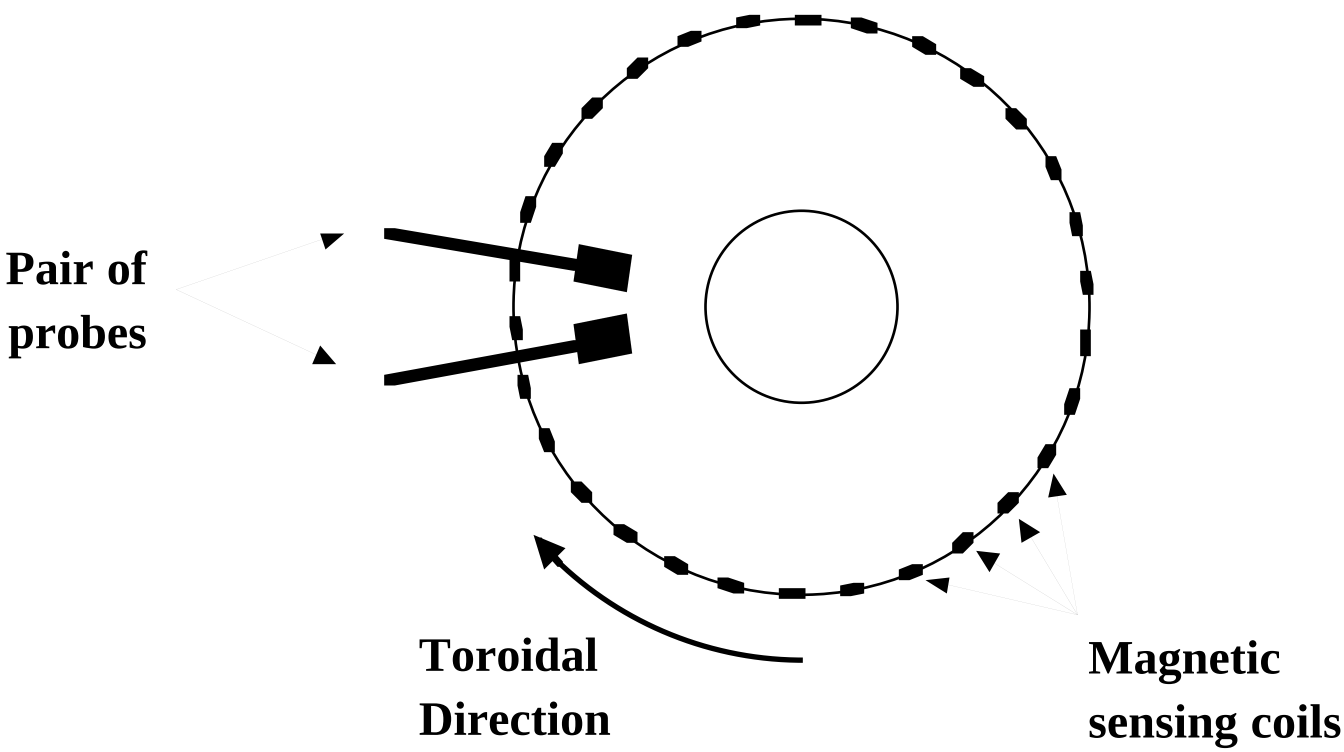
- **Using a pair of insertable probes, measure simultaneously at same location:**
  - **parallel current density (Rogowskii coil)**
  - **various components of magnetic field (multiple magnetic field sensing coils)**

- **Separation of probe pair gives estimate of poloidal or toroidal wave number spectra.**

- **Correlation with magnetic toroidal spectrum from surface coil array estimates toroidal spectrum inside plasma.**

Experimental Setup

Top View of MST



Pseudo-spectra are Estimates of Spatial Spectra for Fluctuations Measured at Single Point

- **Toroidal magnetic mode number spectrum at plasma surface is measured.**
  - **uses wall-mounted toroidal array of 32 or 64 magnetic sensing coils**

- **Fluctuation is measured at single point inside plasma.**

- **Pseudo-spectrum obtained from correlation of fluctuation with toroidal magnetic modes:**

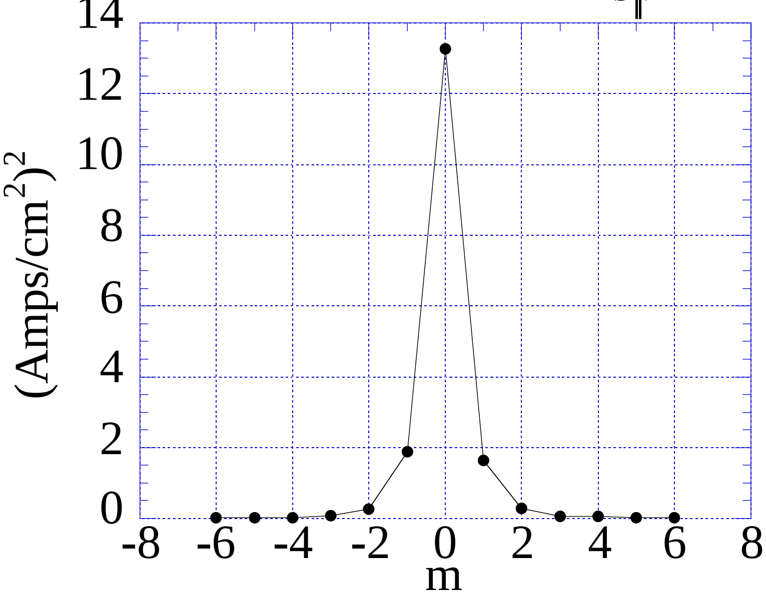
$$\tilde{a}_n = \left\langle \tilde{a}\tilde{b}_n^{\,*} \right\rangle \Big/ \left\langle \left|\tilde{b}_n\right|^2 \right\rangle^{1/2}$$

- **where:**

  $\langle\ \rangle$ denotes an ensemble average
  $\tilde{a}$ is a fluctuation
  $\tilde{b}_n$ is the complex toroidal magnetic mode amplitude for mode number n
  $\tilde{a}_n$ is the pseudo-spectral mode amplitude of $\tilde{a}$ for mode number n

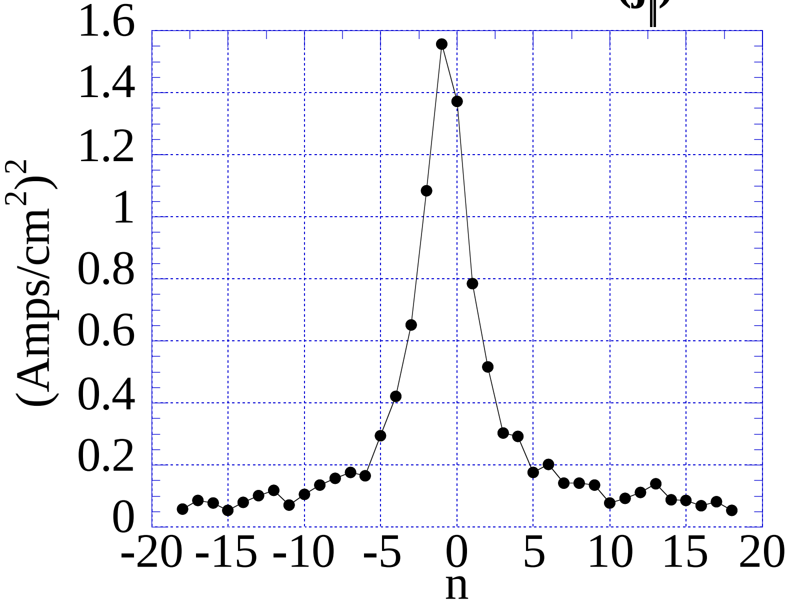
Edge Current Fluctuations are Dominated by Modes Resonant at Reversal Surface

Poloidal Spectrum of Current Fluctuations ($j_\parallel$)



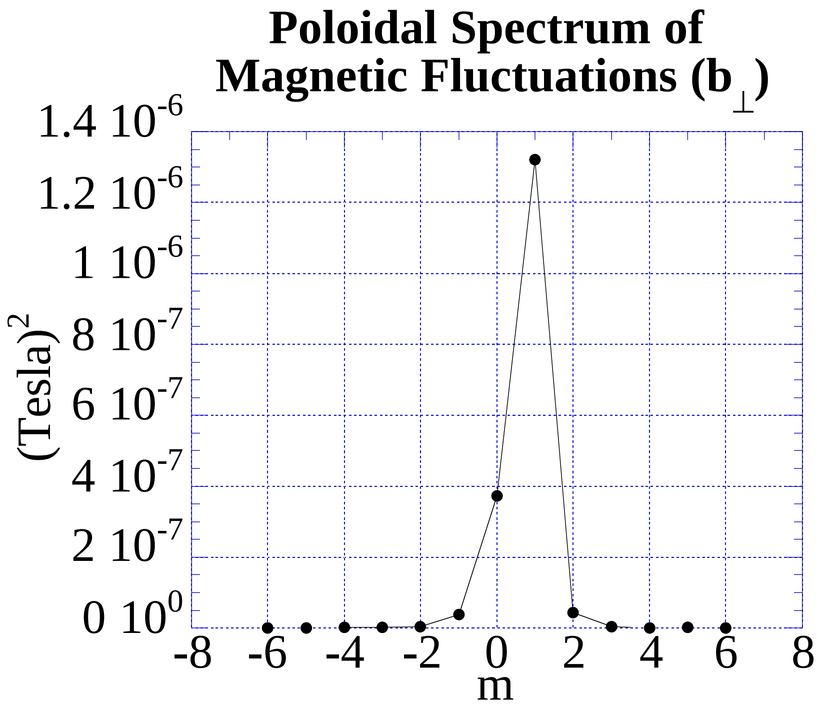
- **Measured at Reversal Surface by two-point method.**

Toroidal Spectrum of Current Fluctuations ($j_\parallel$)



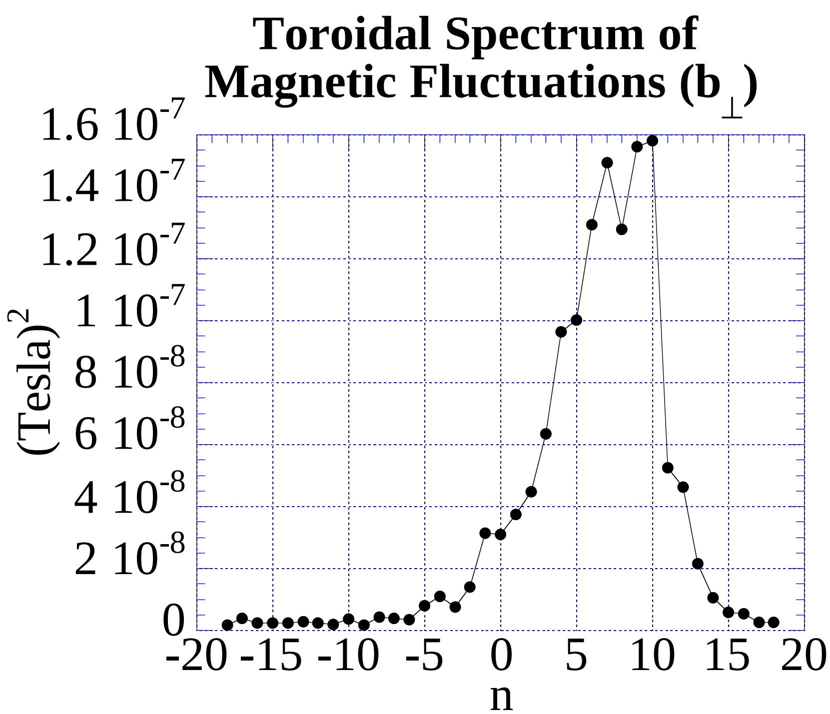
- **Edge resonant current perturbation is reconnection current "sheet".**

Edge Magnetic Fluctuations are Dominated by Modes Resonant in Core

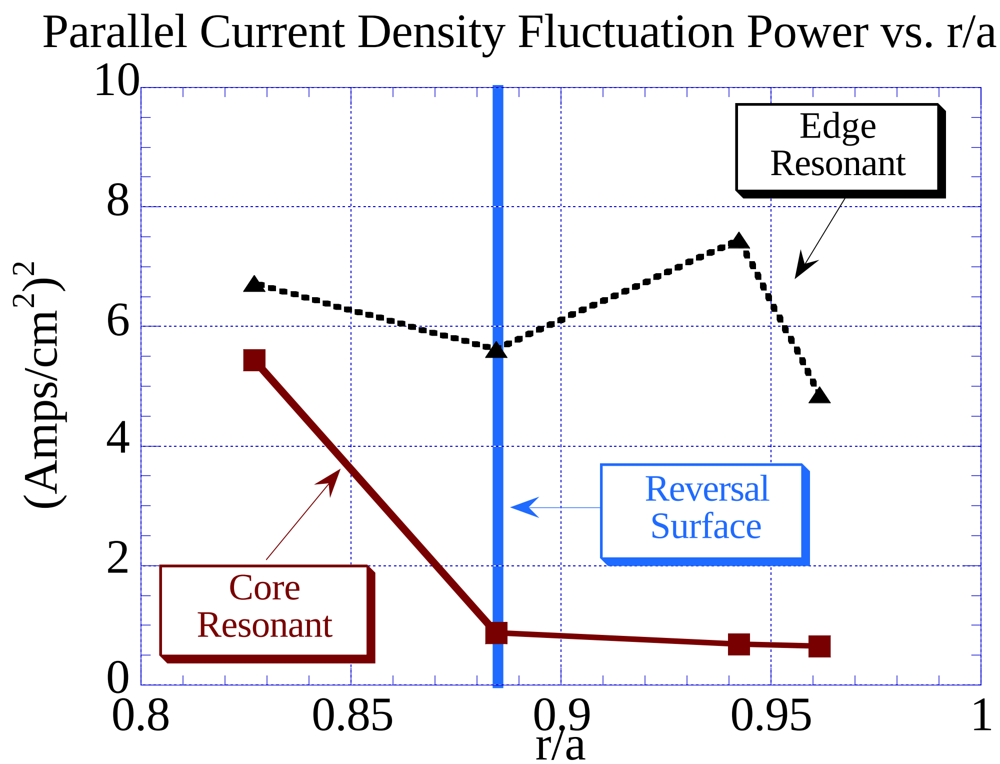


- **In-surface perpendicular magnetic fluctuations measured at Reversal Surface by two-point method.**

- **Edge resonant $\tilde{b}_\perp$ is small while $\tilde{j}_{||}$ is large: consistent with $\tilde{j}_{||}$ more localized than $\tilde{b}_\perp$.**

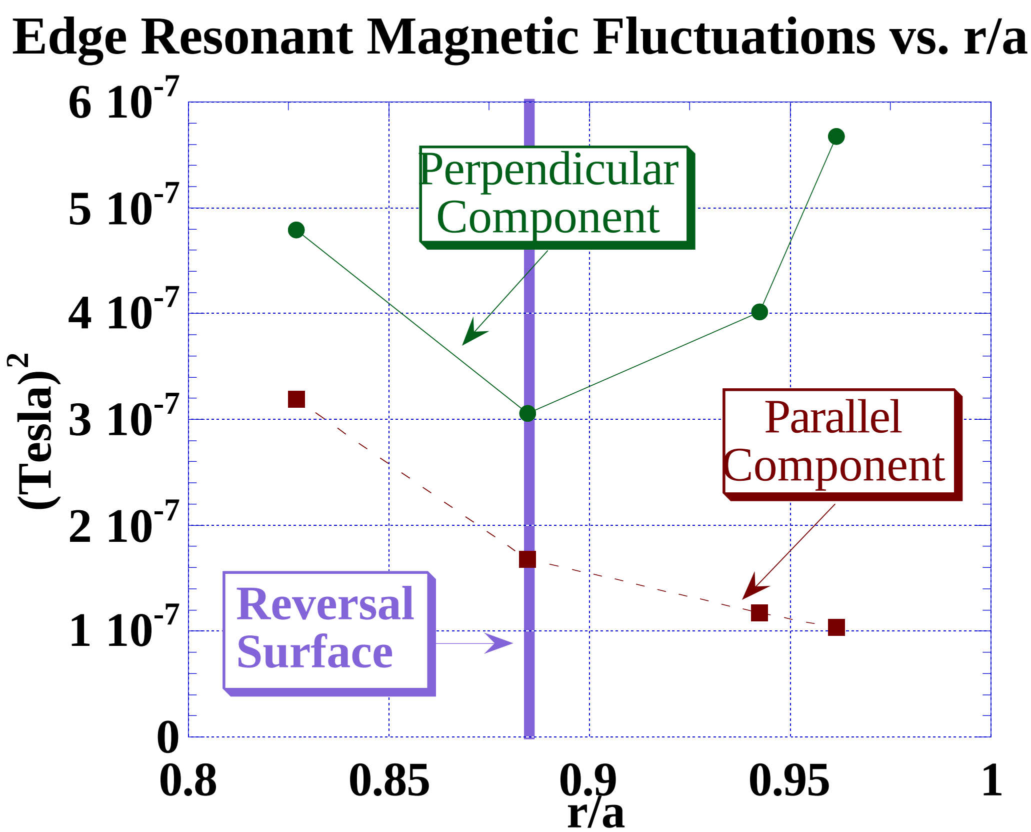


Current "Sheet" of Edge Reconnection is Broad



- **Current layer width may provide insight into physics of edge reconnection:**
  - **Cannot be determined by much smaller reconnection scale lengths such as**
    - **ion gyroradius, ρ_s (~ 1.5 cm)**
    - **electron skin depth, c/ω_{pe} ($\lesssim$ 0.5 cm)**
    - **resistive layer width from resistive tearing mode theory, δ_R (~ 0.2 cm)**
  - **May be determined by comparable scale lengths such as**
    - **ion skin depth, c/ω_{pi} ($\gtrsim$ 16 cm), a reconnection scale**
    - **reversal surface island width, W ($\lesssim$ 10 cm), a possible transport scale.**

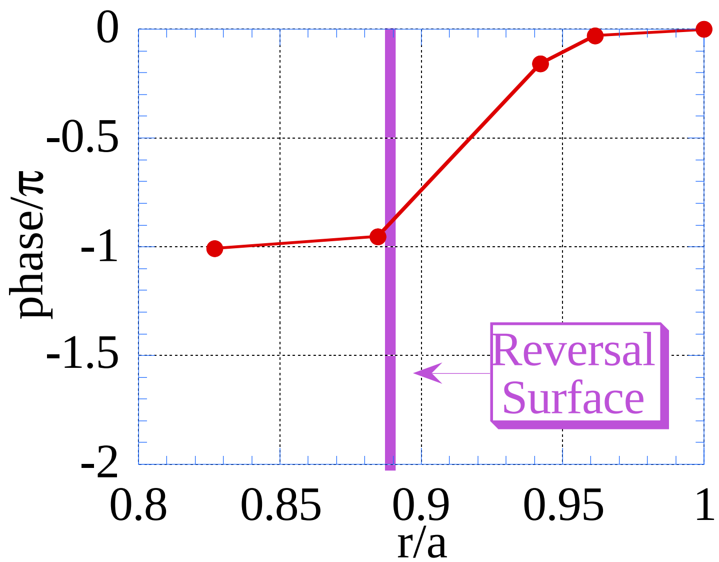
Edge Resonant Magnetic Fluctuations Are Preferentially Perpendicular to Magnetic Field



- **Dominance of perpendicular magnetic fluctuations consistent with dominance of parallel current density fluctuations.**

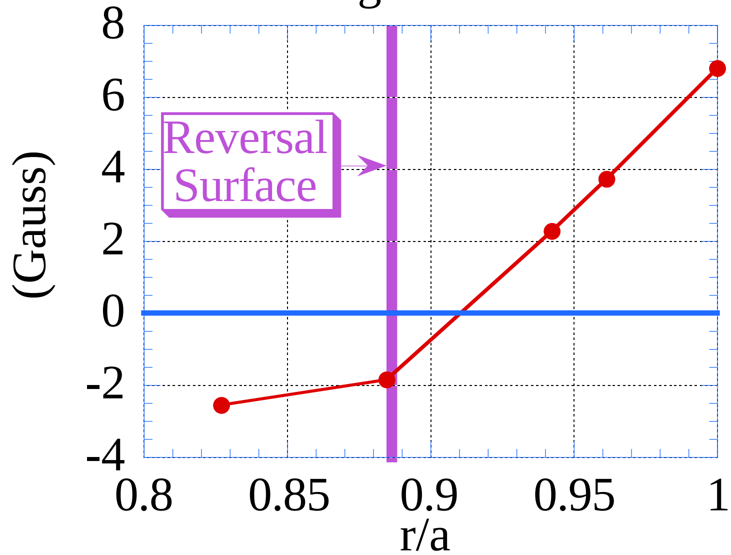
$\tilde{b}_\perp$ (n = 1) Shows Tearing Mode Structure

n = 1 $\tilde{b}_\perp$ Phase Relative to n = 1 $\tilde{b}_\perp$ at Wall During Sawtooth Crash



- **Edge resonant (n = 1, m = 0), in-surface $\tilde{b}_\perp$ reverses sign inside reversal surface.**

Real part of n = 1 $\tilde{b}_\perp$ Eigenfunction Measured During Sawtooth Crash



- **Measured real part of edge resonant (n = 1, m = 0), in-surface $\tilde{b}_\perp$ eigenfunction crosses zero near reversal surface.**

Magnetic Fluctuation Driven Radial Charge Flux Measured in Plasma Edge

- **Magnetic fluctuation driven radial charge flux is the flux surface average of parallel current density and radial magnetic field fluctuations:**

$$\Gamma_{\mathbf{q}} = \left\langle \tilde{j}_{\|} \tilde{b}_r \right\rangle / B_0$$

- **Plasmas are rotating: correlation of current and radial magnetic field fluctuation gives flux surface average.**

Magnetic Fluctuation Driven Radial Charge Flux is Small Between Sawteeth

Total particle transport:

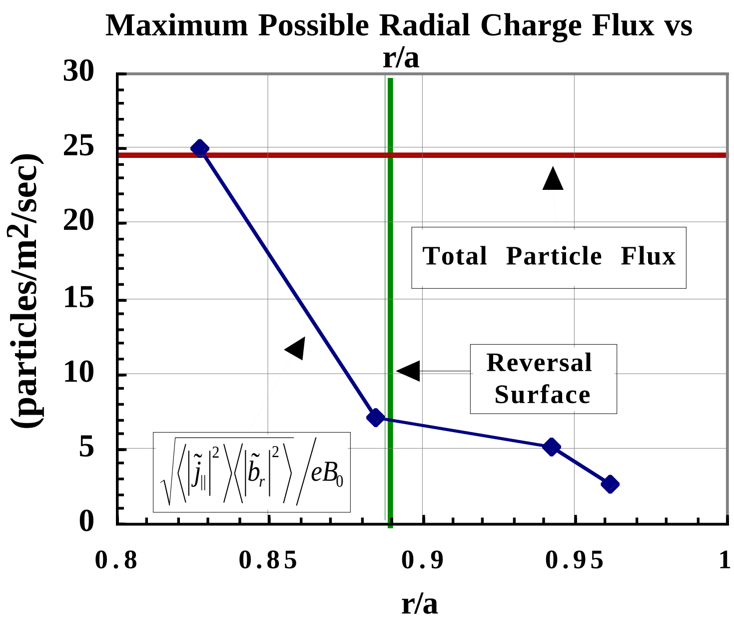
$$\Gamma_{\mathbf{total}} \sim \mathbf{25x10^{20}\ (m^2 sec)^{-1}}$$

Magnetic Fluctuation Driven Radial Charge Flux Between Sawteeth:

$$\left| \left\langle \tilde{j}_{||} \tilde{b}_r \right\rangle / e B_0 \right| < \mathbf{4x10^{20}\ (m^2 sec)^{-1}}$$

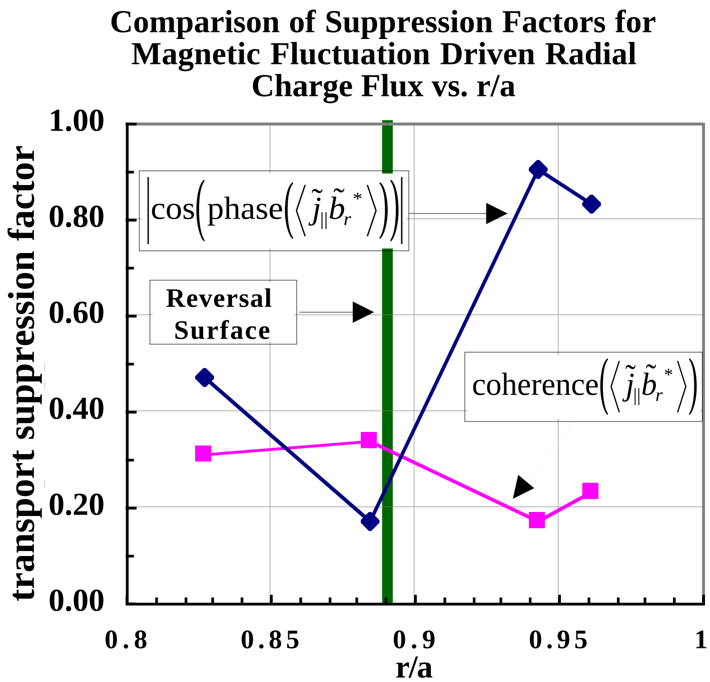
- **Relatively small $\Rightarrow$ corresponding particle transport ambipolar.**
- **Physical cause of ambipolarity varies with depth.**

Outside Reversal Surface: Small Fluctuations Causes Small Radial Charge Flux



- **Outside Reversal Surface, $\tilde{j}_{\parallel}$ and $\tilde{b}_r$ have small amplitude $\Rightarrow$ small magnetic fluctuation driven radial charge flux.**

Inside Reversal Surface: $\pi/2$ Phase and Moderate Coherence Cause Small Radial Charge Flux



- **Inside Reversal Surface $\tilde{j}_{\|}$ and $\tilde{b}_r$ are only moderately coherent and nearly out of phase.**
  - **Near-$\pi/2$ relative phase consistent with increased overlap of $\tilde{j}_{\|}$ and $\tilde{b}_r$ spectra plus theoretical expectation for $\pi/2$ relative phase of resistive tearing modes.**
  - **Core mode proportion of $\tilde{j}_{\|}$ spectrum greater than outside reversal surface, but *not* dominant $\Longrightarrow$ greater coherence with $\tilde{b}_r$, but still only *moderate*.**

Conclusions

- **Reconnection current perturbation is broad.**
  - **Current layer width cannot be determined solely by reconnection physics associated with c/ω_{pe}, δ_R and ρ_s scales.**
  - **Reconnection physics associated with c/ω_{pi} scale or current transport process over island width, W, may determine layer.**

- **Current perturbation of reconnection more localized than magnetic perturbation.**

- **Magnetic fluctuation driven radial charge flux associated with reconnection small between sawtooth crashes $\Rightarrow$ corresponding particle transport ambipolar.**
  - **Physical cause of ambipolarity varies with depth in plasma.**
  - **Inside reversal surface, near-$\pi/2$ relative phase between $\tilde{j}_{\parallel}$ and $\tilde{b}_r$, which is expected from resistive tearing mode theory, plays a role.**