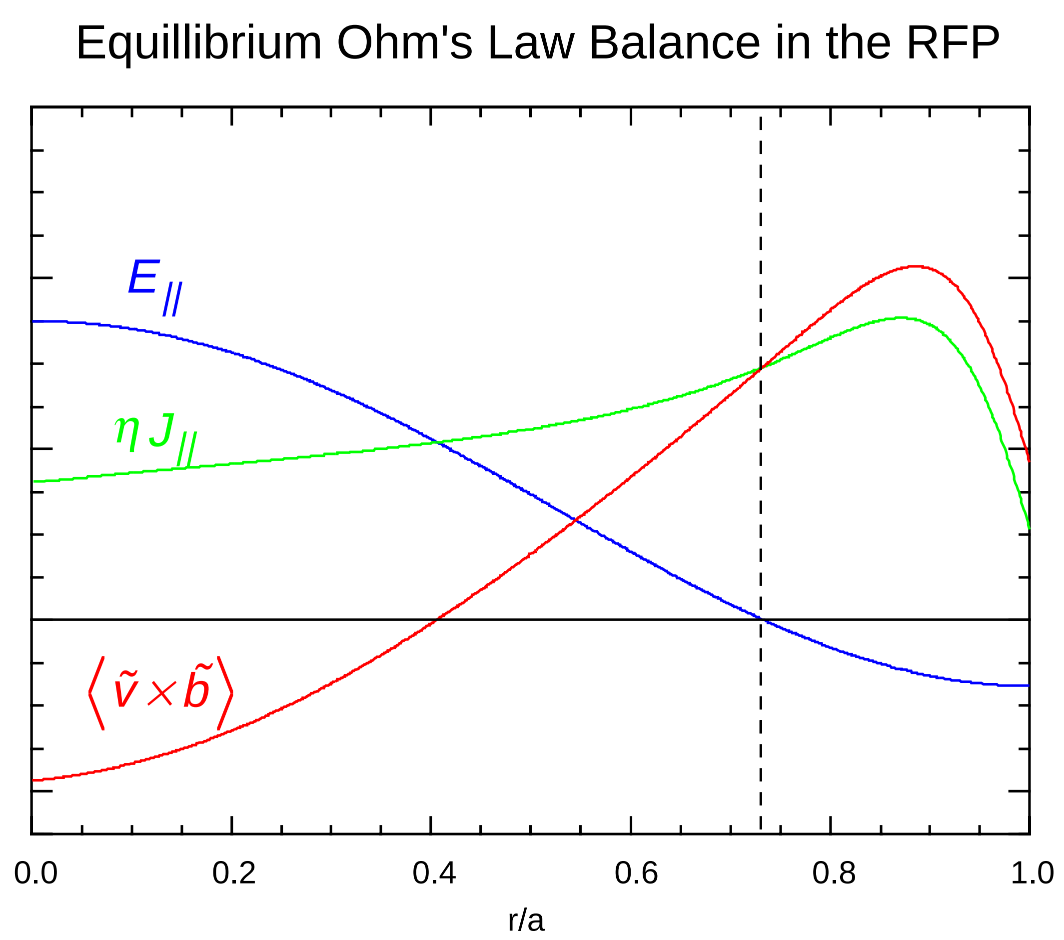
Abstract

The MHD dynamo electric field, $E_d = \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} \right\rangle$, is predicted to scale in the RFP in the range of S^0 to $S^{-1/2}$. Simulations and recent measurements in the MST-RFP have produced experimental scalings of $\left|\tilde{\mathbf{v}}\right|$ and $\left|\tilde{\mathbf{b}}\right|$ in this range [M. R. Stoneking, to be submitted to *Phys.Plasma*]. We will report here on the simultaneous measurement of ion velocity and magnetic field fluctuations at *S* values of approximately 3×10^5, 1×10^6, and 2×10^6 performed over a large ensemble of discrete dynamo or RFP-sawtooth events. Correlation analysis should yield the quasi-linear dynamo product over the sawtooth cycle at each value of *S* providing a three point scaling of both the *continuous* and *discrete* MHD dynamo. In addtion analysis of the equilibrium evolution over a sawtooth cycle should facillitate a clearer picture of the sawtooth relaxation cycle for different values of *S*. Finally, the measured dynamo field will be compared to that inferred from the balance of Ohm's Law modeled in the core of MST.

Ohm's Law Indicates Dynamo Scales Inversely with S



- toroidal field reversal in the RFP necessitates a strong source of noninductive current drive to balance Ohm's law

- one solution is the addition of the nonlinear product of ion velocity and magnetic field fluctuations which, properly phased, could produce a steady state dynamo field

- non-dimensional, parallel Ohm's law at the reversal surface indicates this product should scale inversely with Lundquist number

$$\left\langle \tilde{v} \times \tilde{b} \right\rangle_{\parallel} = -\frac{J_{\parallel}}{S}$$

- experimental measurements have show a weak scaling of magnetic fluctuations suggesting that velocity fluctuations should scale strongly

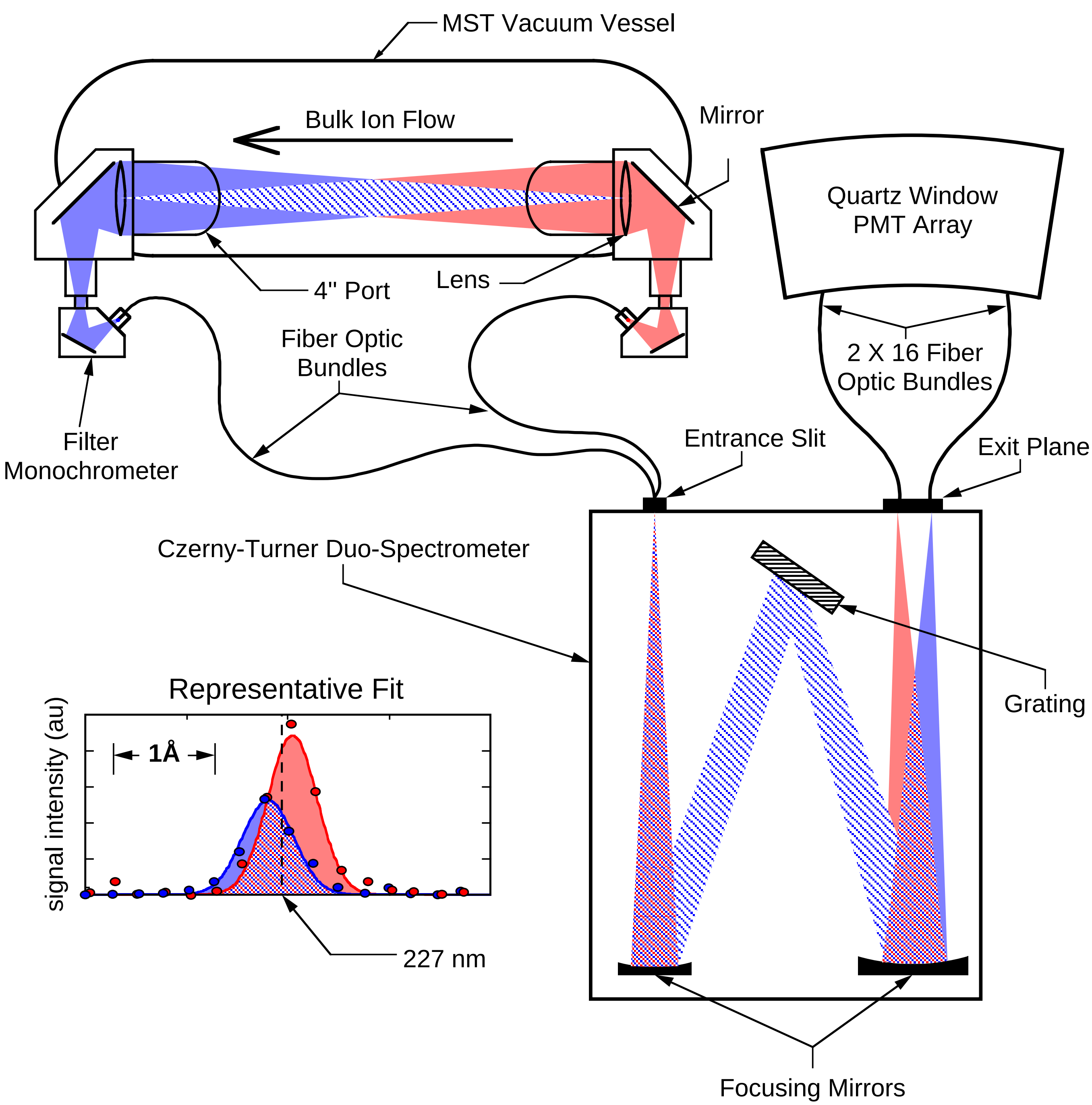
- strong scaling of magnetic fluctuation with S would provide optimistic transport scalings for an Ohmic RFP reactor

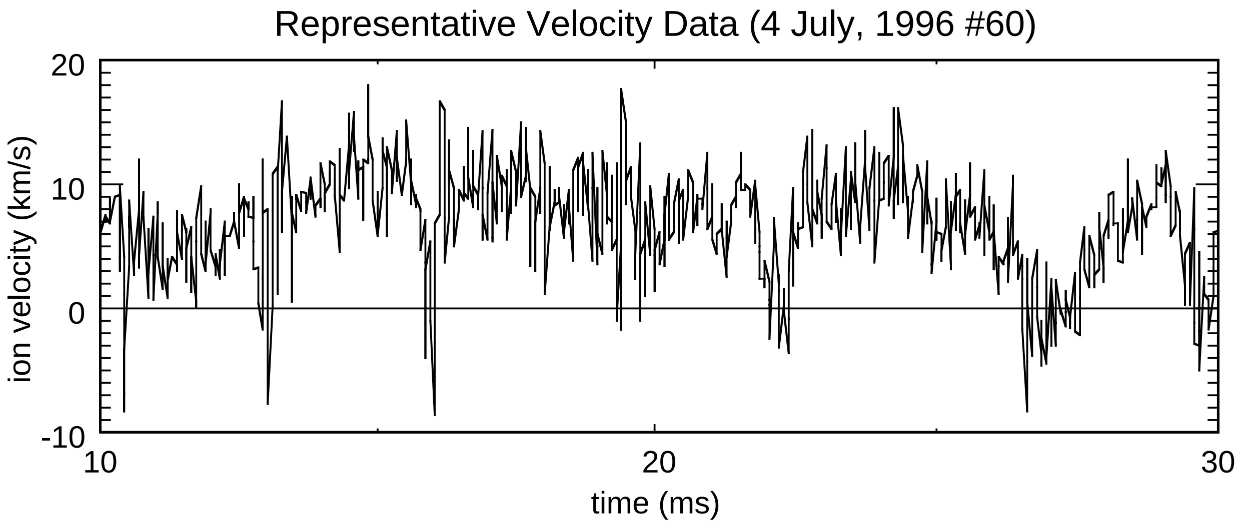
- spectroscopic measurements of the MHD dynamo in the MST core allows direct scaling of the dynamo product with S

Full MST Diagnostic Array Employed

ION DYNAMICS SPECTROMETER

• Ion Dynamics Spectrometer (IDS) provides passive velocity and temperature measurements of intrinsic impurities (CV)



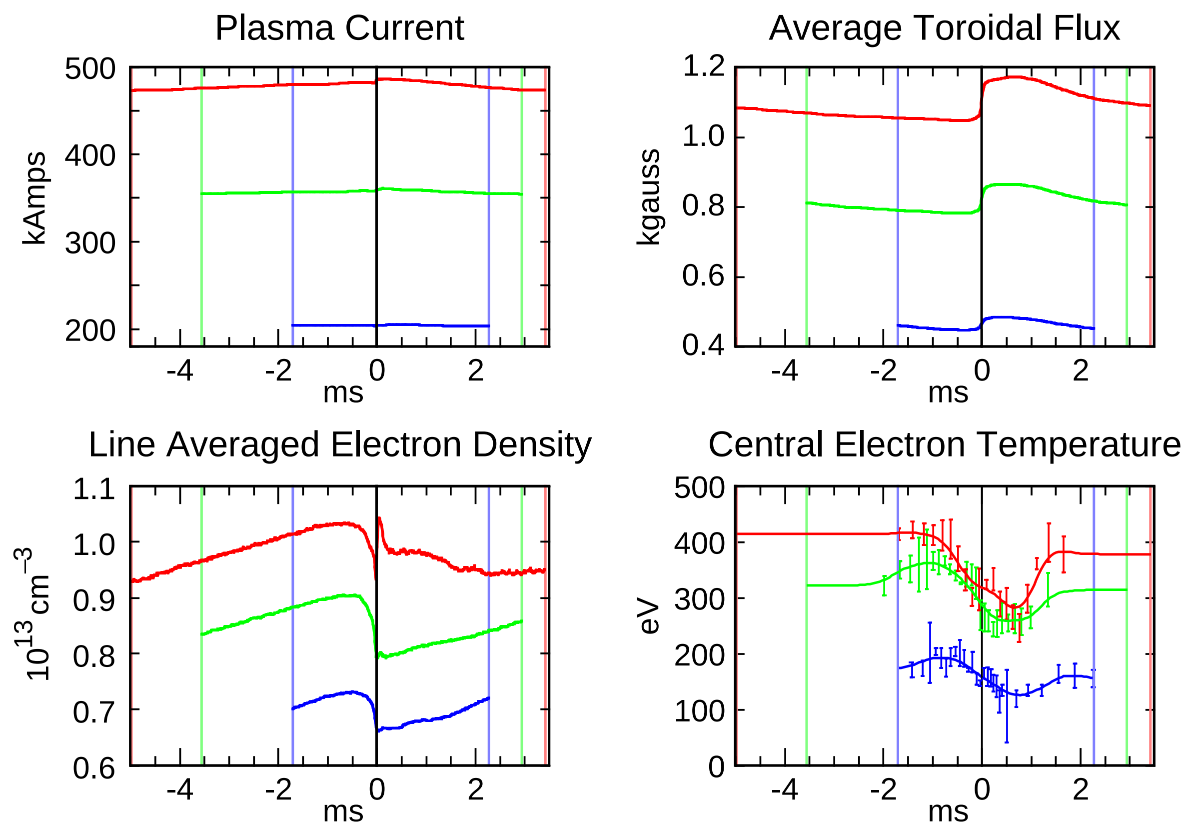


- IDS temporal resolution excellent - resolves phenomena on < 10μs time scale
- spatial resolution adequate to resolve low k fluctuations

ADDITIONAL DIAGNOSTICS

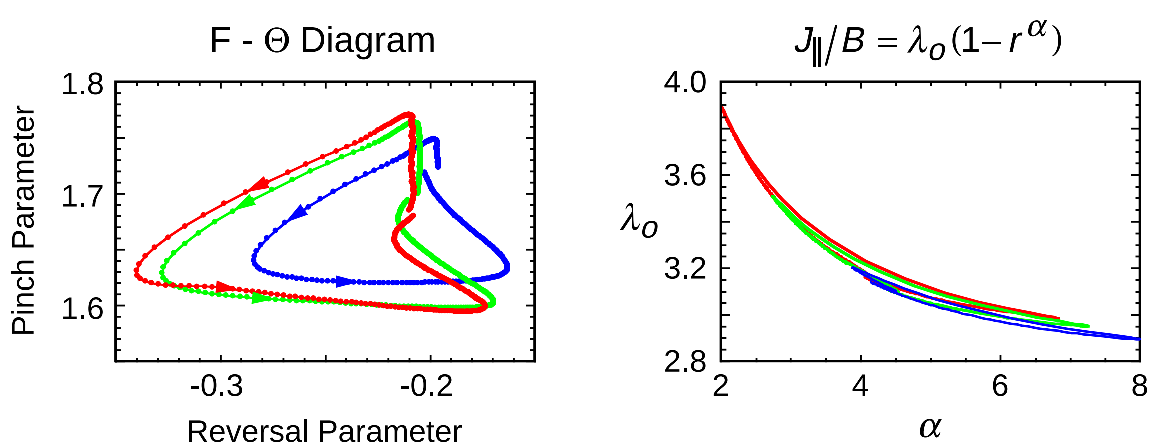
- 64-coil toroidal magnetic array recovers toroidal mode amplitude
- 11 chord FIR interferometer measures density profile density fluctuations (P3.07 N. Lanier et. al.)
- central electron density measured with CO_2 interferometer
- electron temperature profile measured with Thompson scattering (P3.10 T. Biewer et. al.)
- majority ion temperature measured with Charge Exchange Analyzer (P3.11 Paul Fontana et. al.)
- relative Z_{eff} measured with Bremstrahlung detectors

S-scaling explored 3 operational regimes



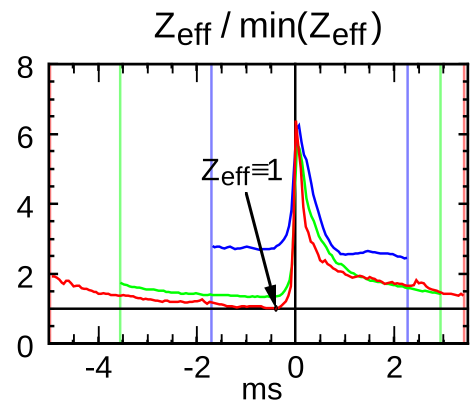
• scaled from low to high current at high I/N

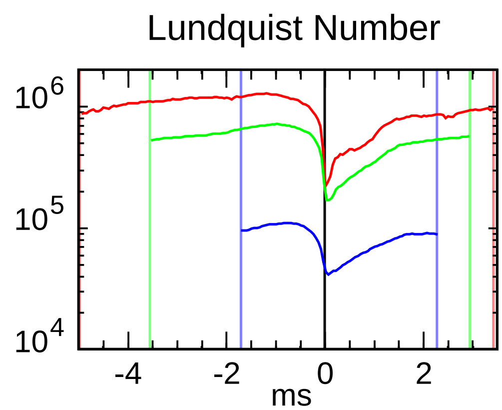
• approximately 300 shots taken in each regime



• profile shape held constant prior to crash for each regime

- F - Θ sawtooth excursion larger at medium and high S





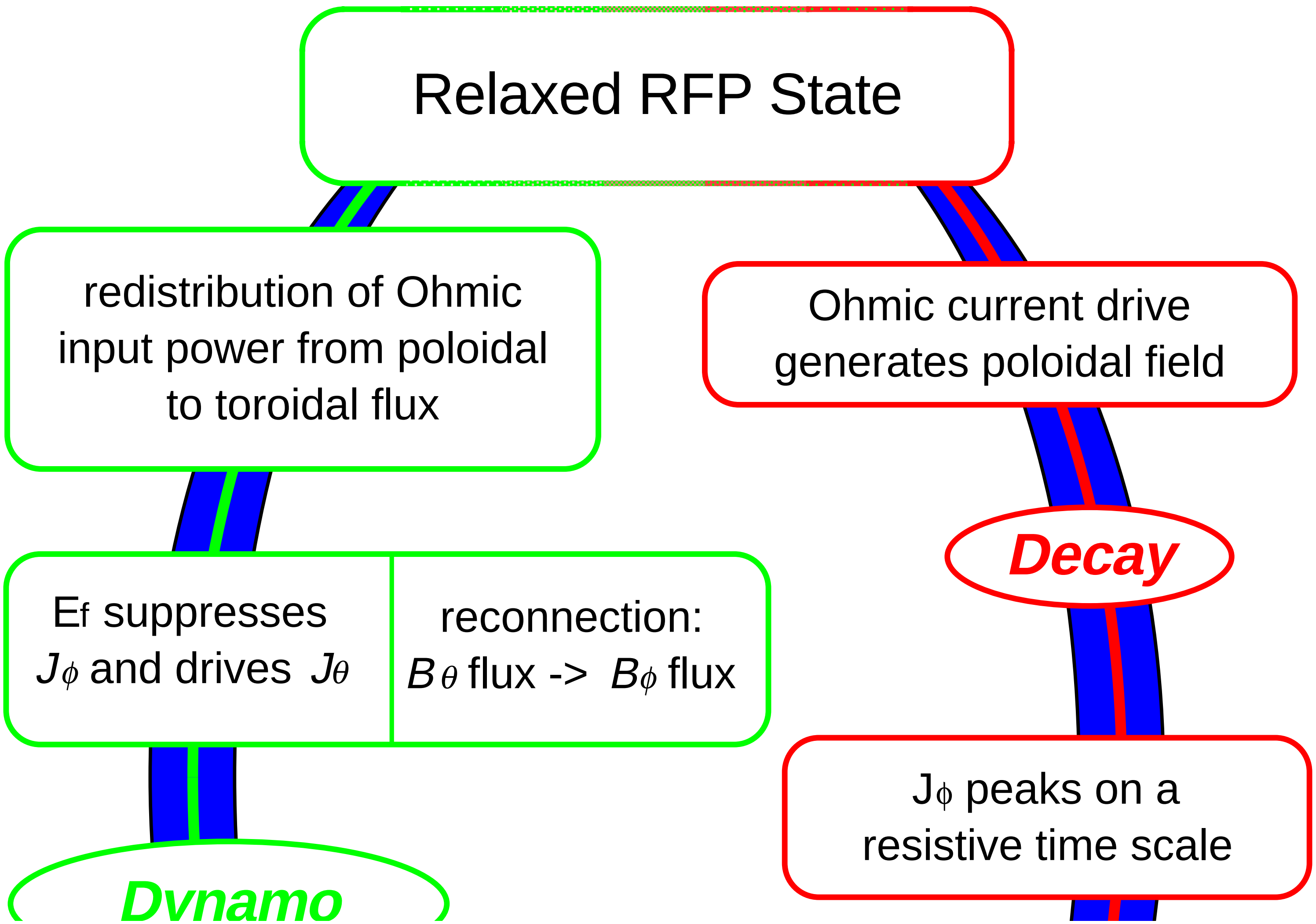
- order of magnitude in S achieved over three regimes
- Lundquist number scales roughly with plasma current
- large impurity spike at crash responsible for drop in S

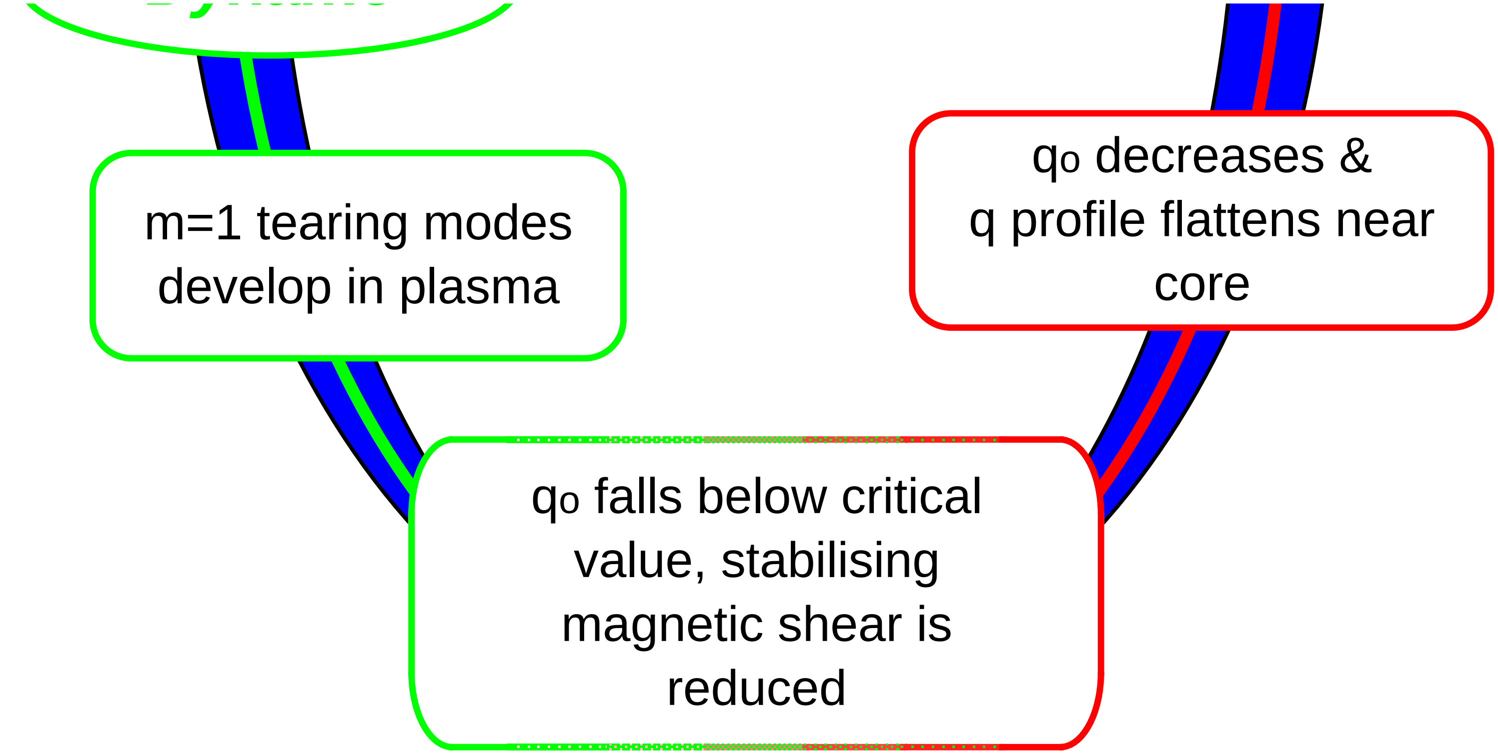
	Low	Med	Hi
N_{st}	728	457	127
I_p (kAmp)	204	357	481
F	-0.201	-0.205	-0.208
θ	1.74	1.75	1.77
n_e (10^{13} cm^{-3})	0.72	0.90	1.03
$f_{n\ 6}$ (kHz)	17.5	20.2	9.6
T_e (eV)	160	315	380
Z_{eff}	3.0	1.9	1.6
τ_{st} (ms)	4.0	6.5	8.4
τ_r (s)	0.36	1.44	2.08
τ_a (μs)	4.4	2.8	2.2
S (10^5)	0.82	5.21	9.41

- all values averaged over characteristic sawtooth period

Sawtooth Period Extends with S

• MST equillibrium characterized by dynamic oscillation about critical current, gradient, cycle of oscilation described as 'sawtooth'



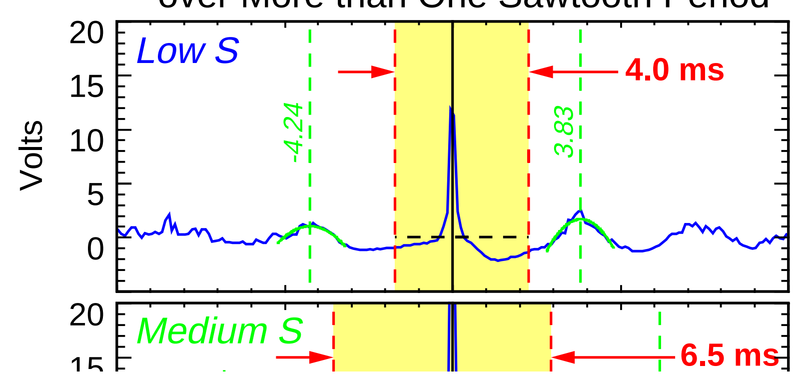


• sawtooth crash time defined by peak in toroidal gap voltage, or time of maximum toroidal flux generation

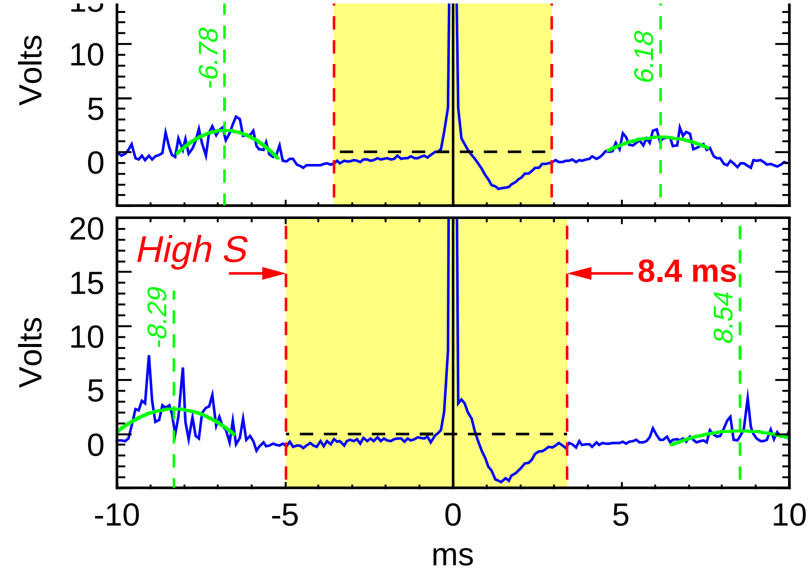
• all ensembles are referenced to this crash time

• sawtooth period quantified by examining

Average Toroidal Gap Voltage over More than One Sawtooth Period

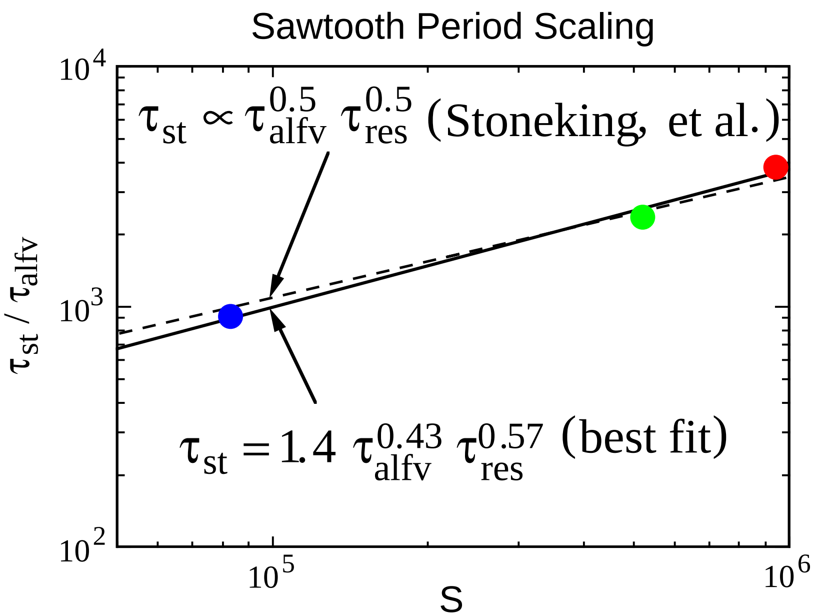


average location of neighboring sawteeth



- equillibrium characterized by averaging quantities over sawtooth cycle

- decay phase of sawtooth cycle scales roughly with resistive time - extending with S



- crash phase scales more closely to alfvén time - becoming more abrupt as S increases

- scaling factor indicates hybrid timescale for the sawtooth period in agreement with previous results

Magnetic Fluctuations Scale Weakly with S

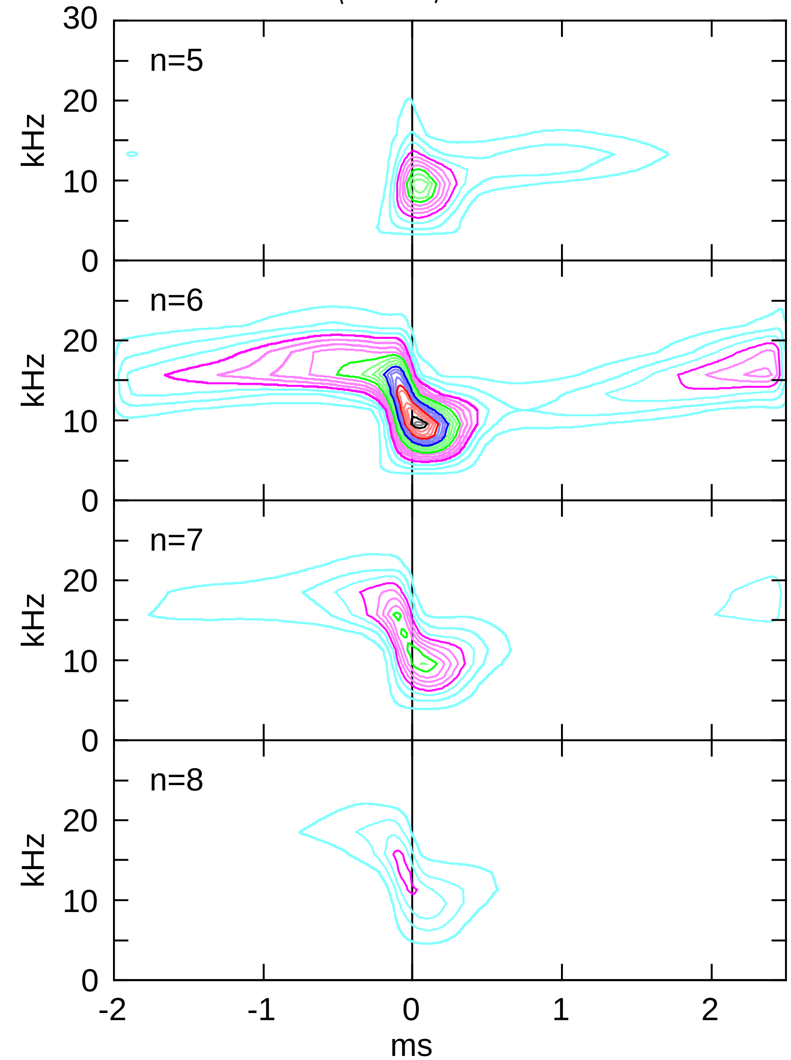
- magnetic fluctuations in MST dominated by m=1 internally resonant tearing modes

- modes fluctuate at Doppler shifted frequencies of 10 - 30 kHz, and decelerate at the sawtooth crash

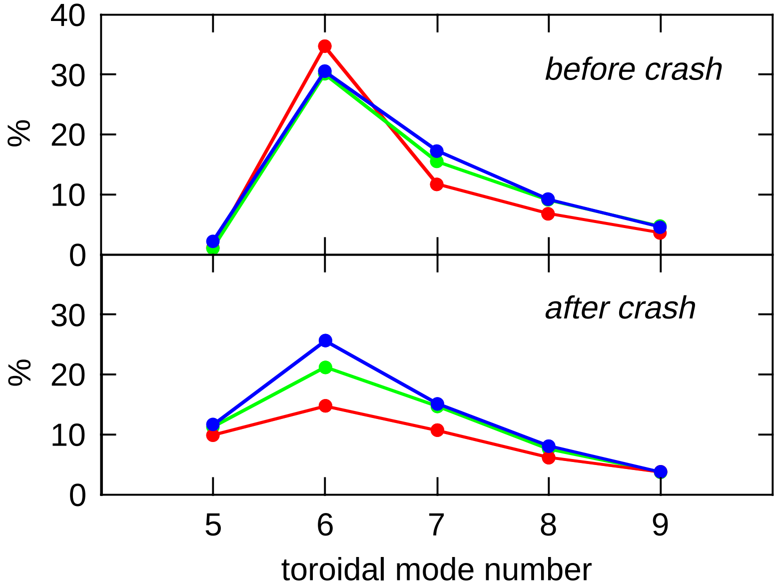
- the m=1, n=6 mode dominates fluctuation

- all mode amplitudes peak at crash

$\left\langle \tilde{b}_{\theta,n}^2 \right\rangle$ / kHz

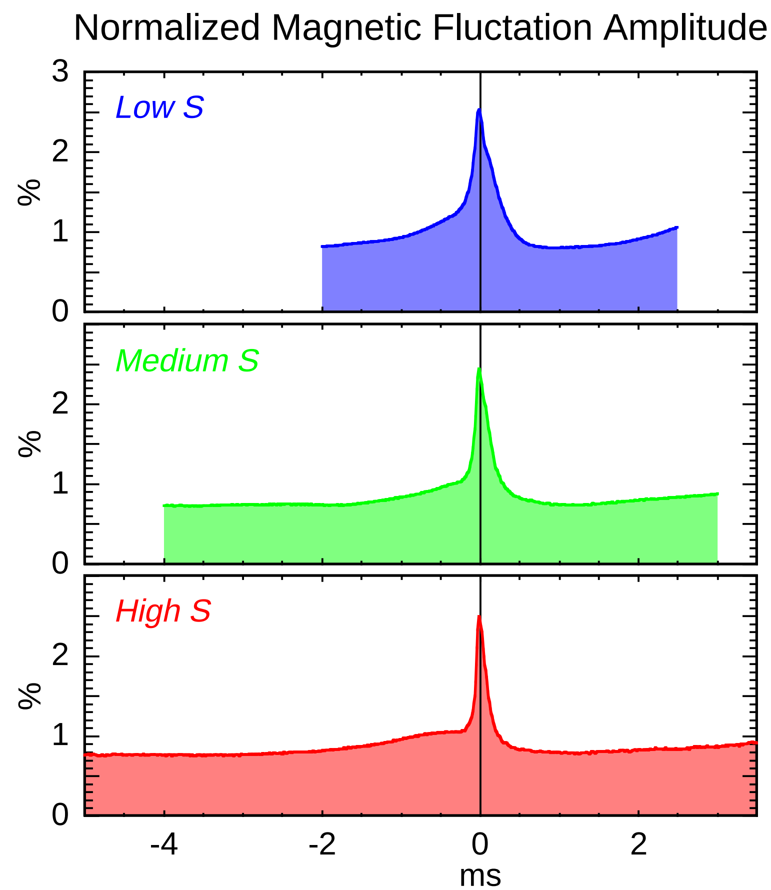


$$\left\langle \tilde{b}_{\theta,n}^2 \middle/ \tilde{b}_{\theta}^2 \right\rangle$$

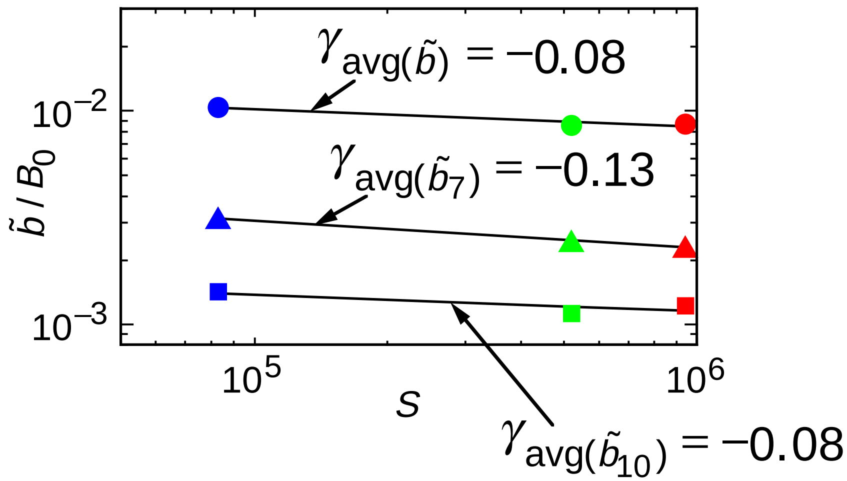


- mode dispersion peaks at n=6 prior to the sawtooth crash
- dispersion flattens after crash with power flowing from n=6 to n=5
- dispersion flattens more at high S

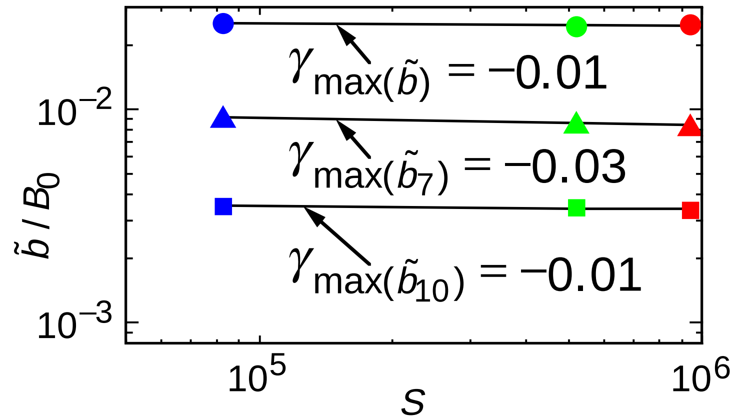
- between crash fluctuation level changes little with S
- fluctuation spike narrows with S
- scaling of average fluctuation level could reflect lower duty cycle at high S
- scalings reflect total m=1 fluctuation level
- Stoneking, et. al. found scaling of -0.22



Average Fluctation Amplitude Scaling

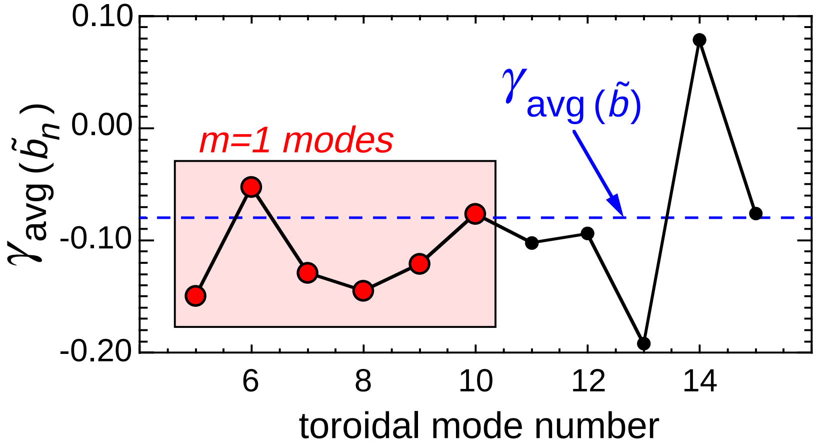


Peak Fluctuation Amplitude Scaling



• average and peak fluctuation levels consistent with exponents from 0.00 to -0.13

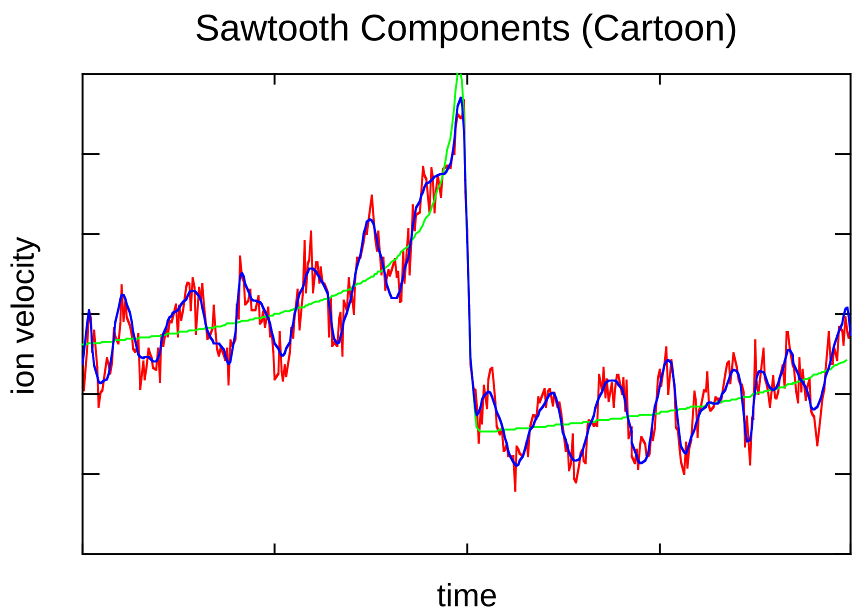
Scaling of Magnetic Fluctation
vs. Toroidal Mode Number



• n=6 scales less strongly than adjacent modes

• indicates tendency toward single helicity state at high S

Velocity Fluctuations Scale Weakly with S



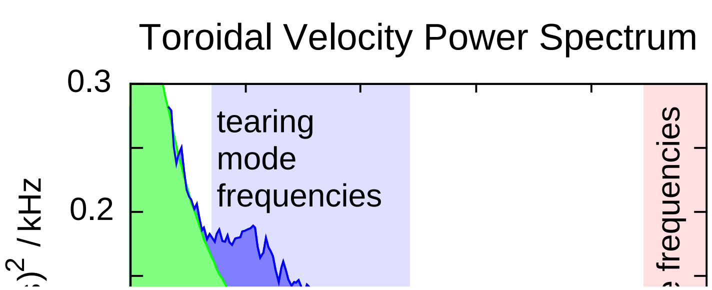
- velocity signal composed of secular, fluctuating, and noise components

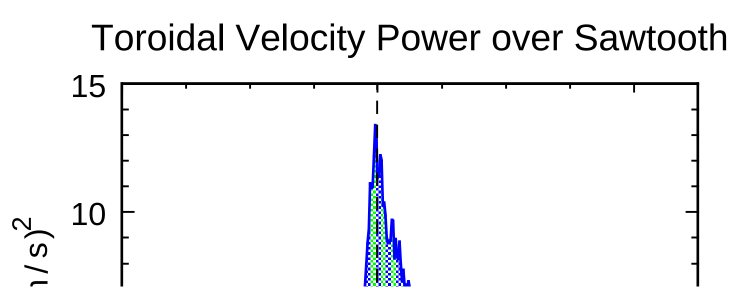
$$v(t) = v_o(t) + \tilde{v}(t)\cos(n\phi + m\theta + \omega t + \delta_v) + N(t)$$

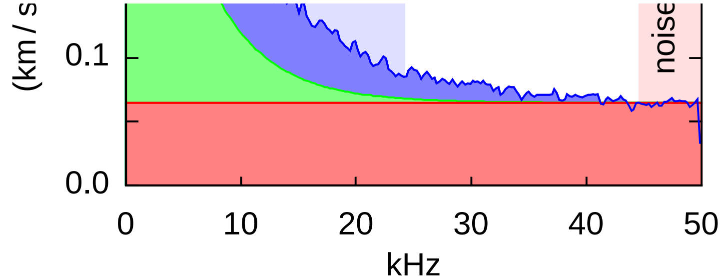
- ensembled power sum of components

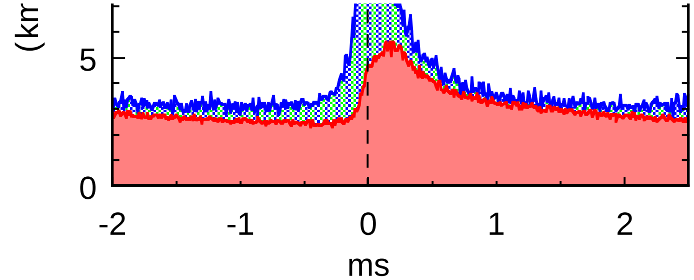
$$\langle v^2 \rangle - \langle v_o \rangle^2 = \langle v_o^2 \rangle - \langle v_o \rangle^2 + \langle \tilde{v}^2 \rangle + \langle N^2 \rangle \approx \langle \varepsilon^2 v_o^2 \rangle + \langle \tilde{v}^2 \rangle + \langle N^2 \rangle$$

- noise floor may be estimated assuming no fluctuations above 45 kHz
- secular component approximated by decaying exponential
- velocity fluctuation power apparent at tearing mode frequencies







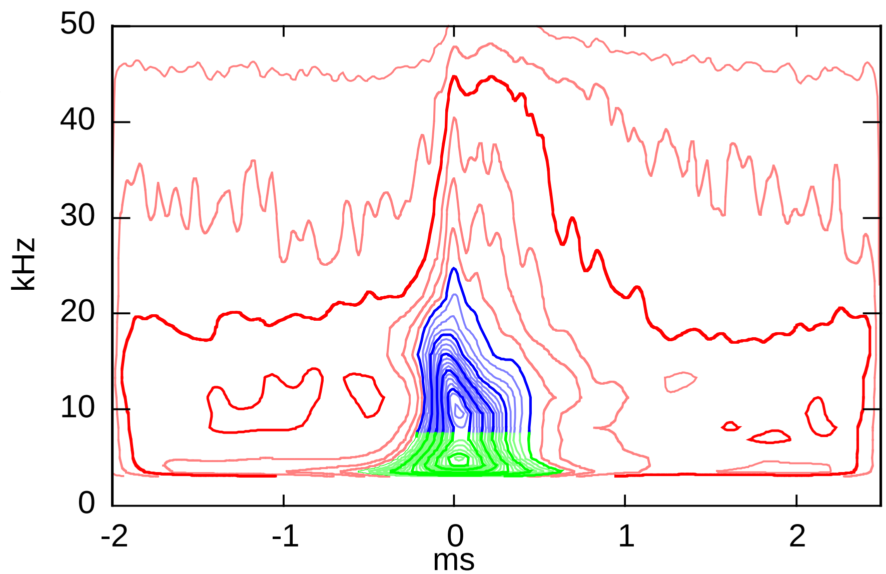


- fluctuations peak rapidly at crash, magnitude consistent with MHD simulations
- <1 km/s velocity fluctuation amplitude resolved away from crash

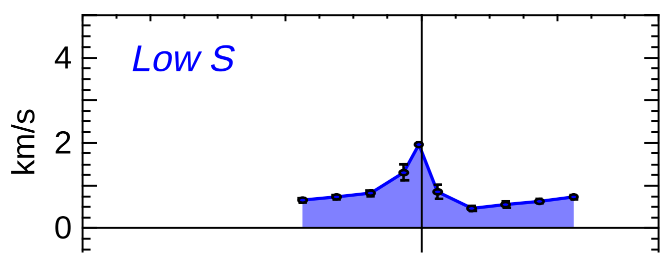
- wavelet analysis yields simultaneous resolution of fluctuations in time and frequency

- distinct peak observed near the sawtooth crash in the tearing mode frequencies

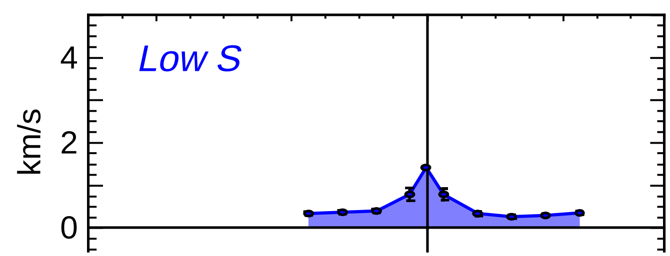
Wavelet Power Spectrum of Toroidal Veocity

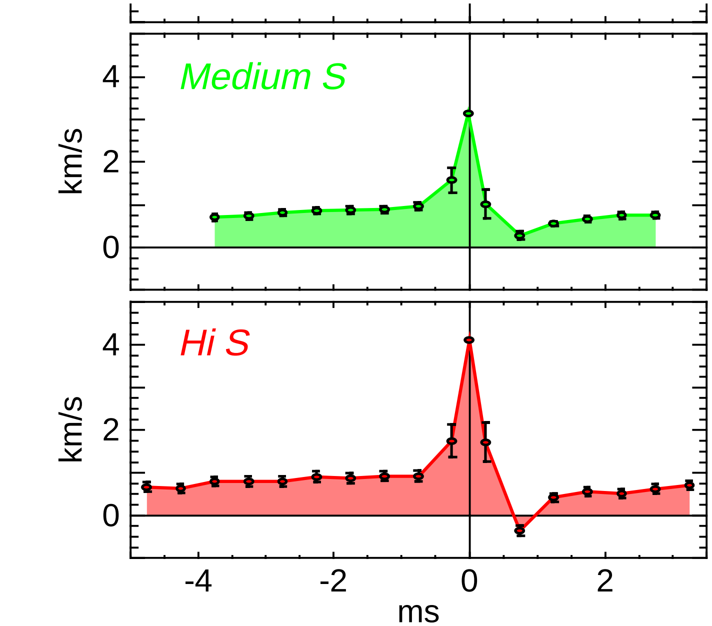


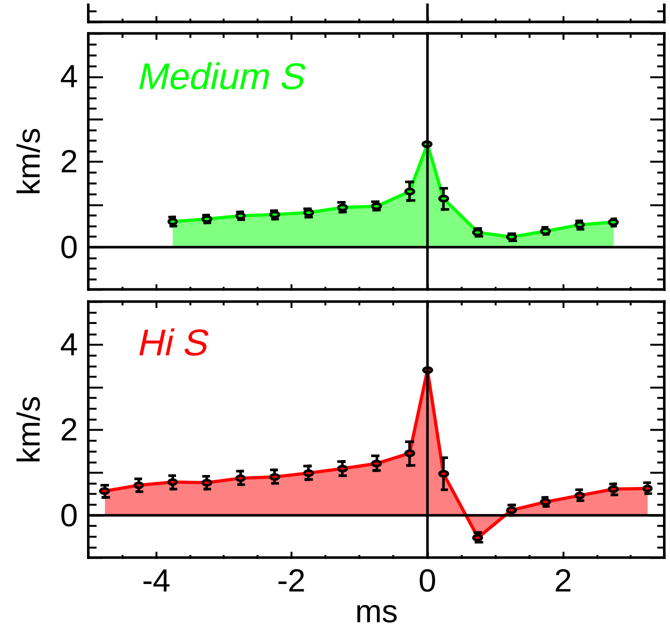
Poloidal Velocity Fluctuations



Toroidal Velocity Fluctuations

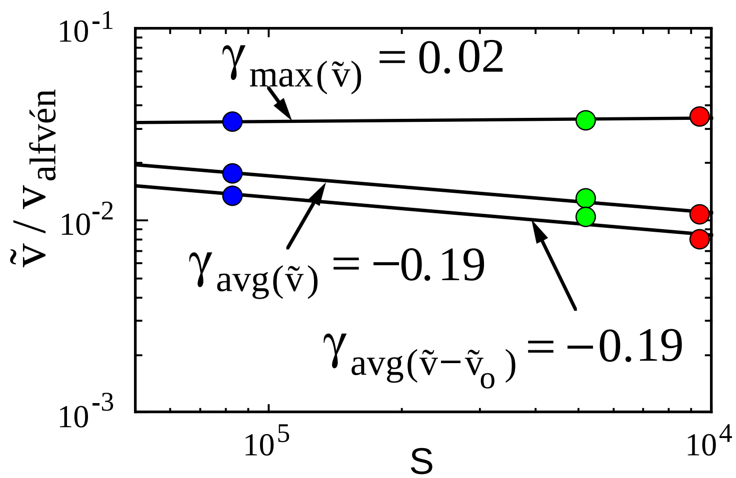




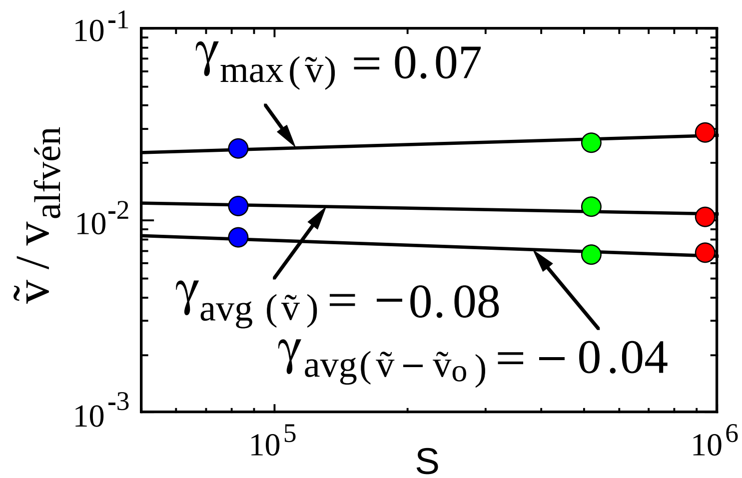


• measured velocity fluctuation represents instrumentally weighted sum over n

Poloidal Velocity Fluctuation Scaling



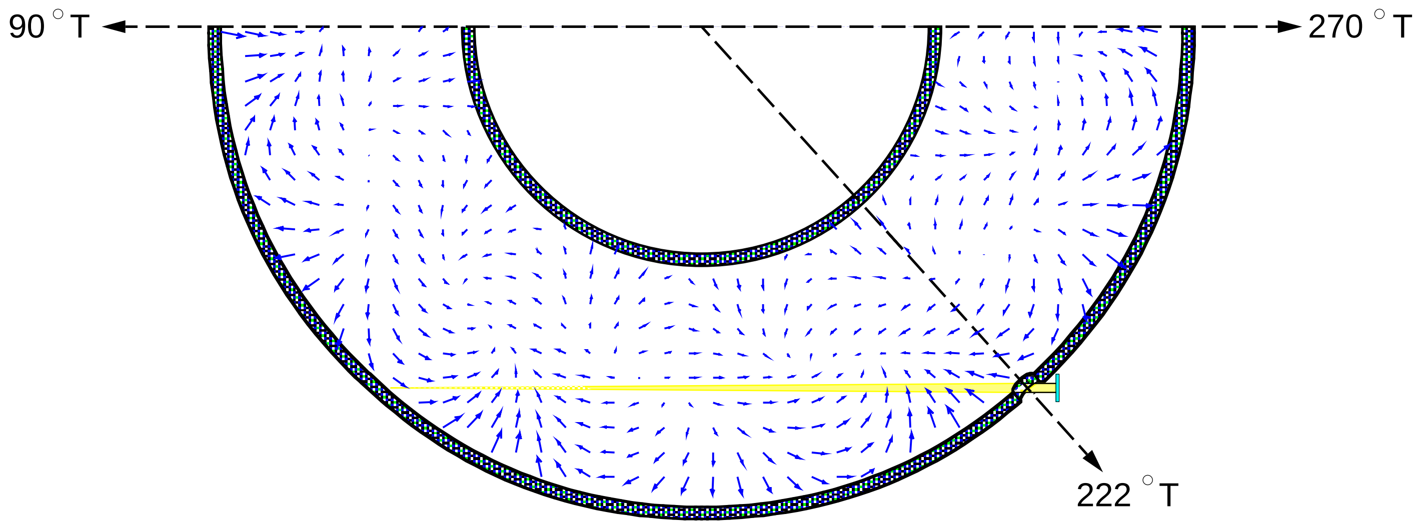
Toroidal Velocity Fluctuation Scaling

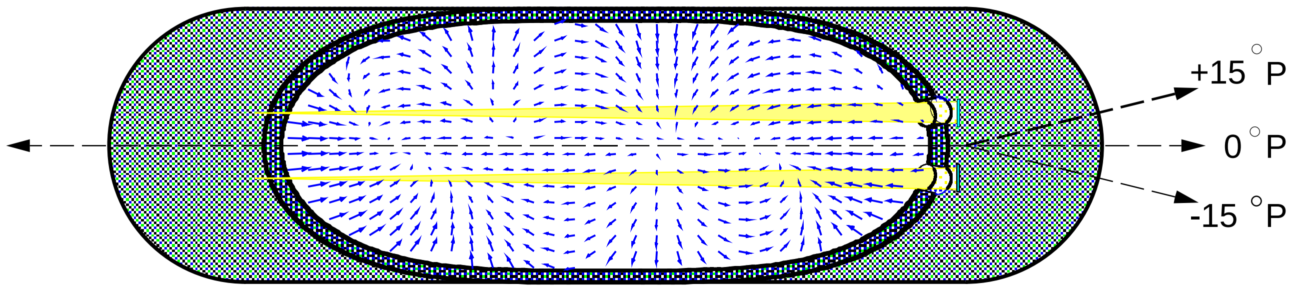


• both toroidal and poloidal, peak and average amplitudes scale weakly with S

IDS Optimally Resolves m=1, n=7 Velocity Fluctuations

- velocity fluctuations passively measured over up-down symmetric toroidal chords





- chordal geometry attenuates single helicity velocity fluctuations

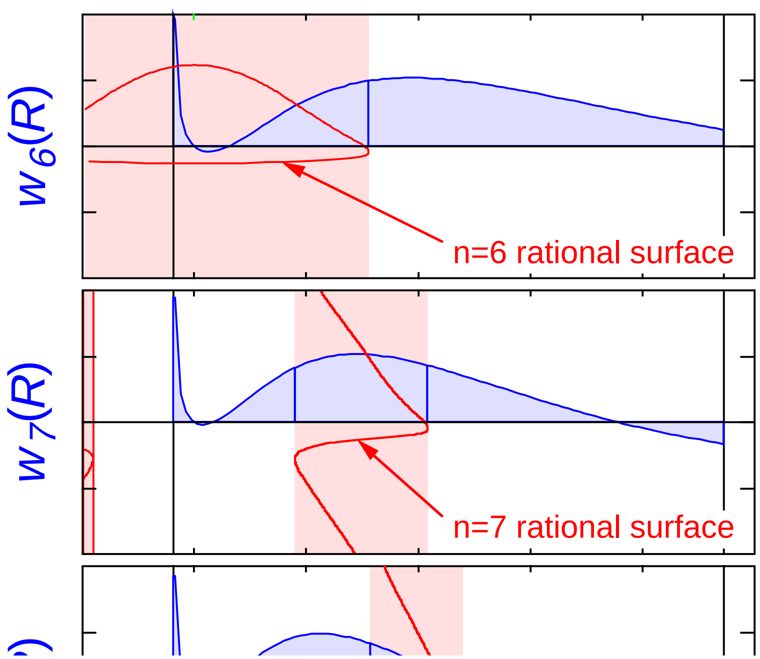
$$\left\langle \tilde{v}_\phi(t) \right\rangle_{path} = \frac{1}{2L} \int_{-L}^{L} dl \; \tilde{v}_\phi \cos(m\theta + n\phi + \omega t + \delta_v) \; (\hat{\phi} \cdot \hat{l})$$

$$= \left[\frac{1}{L} \int_0^L dl \; \tilde{v}_\phi \; \cos(n(\phi - \phi_0)) \; \cos(m\theta) \; \cos(\phi - \phi_0) \right] \cos(n\phi_0 + \omega t + \delta_v)$$

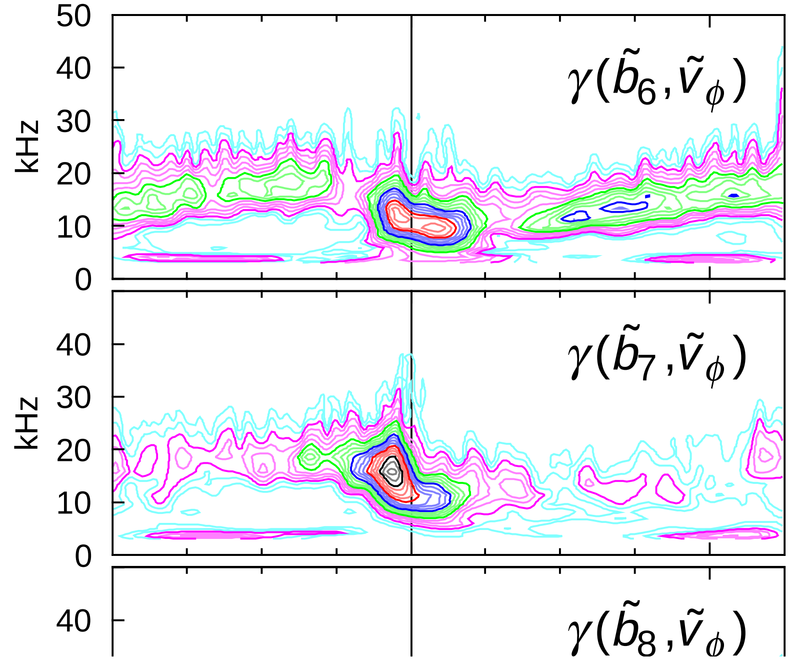
$$= \left[\frac{1}{L} \int_{R_0}^{R_L} dR \; \tilde{v}_\phi \left(\frac{dl}{dR} \right) w_n(R) \right] \cos(n\phi_0 + \omega t + \delta_v)$$

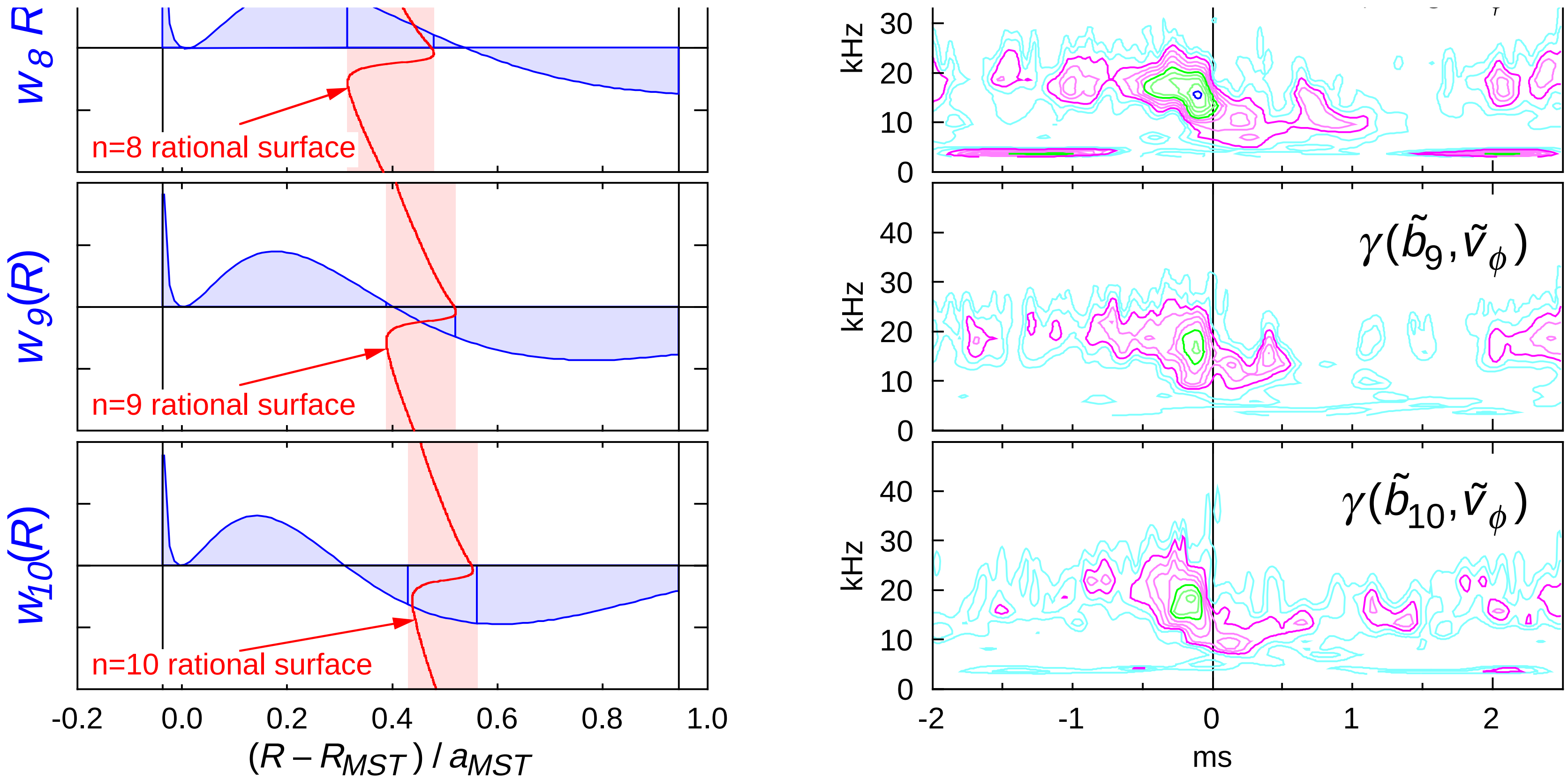
$$= \left\langle \tilde{v}_\phi \right\rangle_{path} \cos(n\phi_0 + \omega t + \delta_v)$$

IDS Geometric Instrument Function
for Different Toroidal Mode Numbers



Coherence of Toroidal Velocity Fluctuations
and Magnetic Modes





- coherence of velocity fluctuations and magnetic mode numbers understood by comparing IDS geometric instrument function and rational surface location

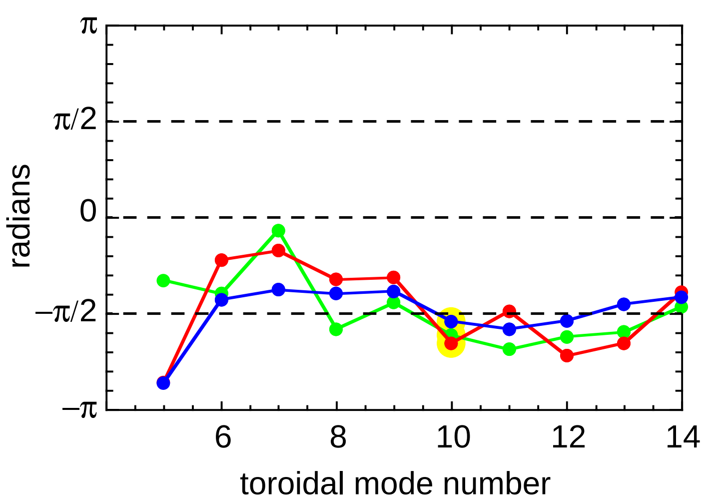
- n=7 toroidal mode maximally resolved over sawtooth cycle with greater than 50% peak coherence

MHD Dynamo Scales Strongly with S

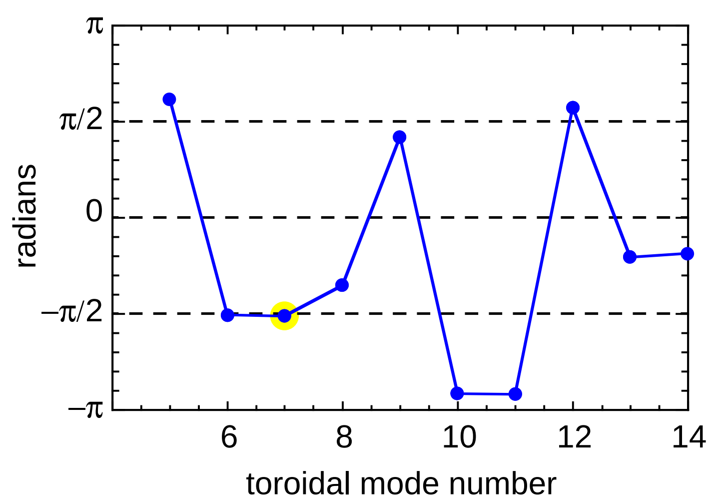
- local phase of dynamo product recovered from edge magnetic and chord averaged velocity measurements using the known helical geometry of the m=1 islands and the measured radial profile of the magnetic fluctuations

- phase of 90 degrees found between velocity and edge poloidal magnetics implying a local 0 degree phase shift between velocity and core radial magnetics

Phase of Poloidal Velocity Fluctuations
and Edge Poloidal Magnetic Field

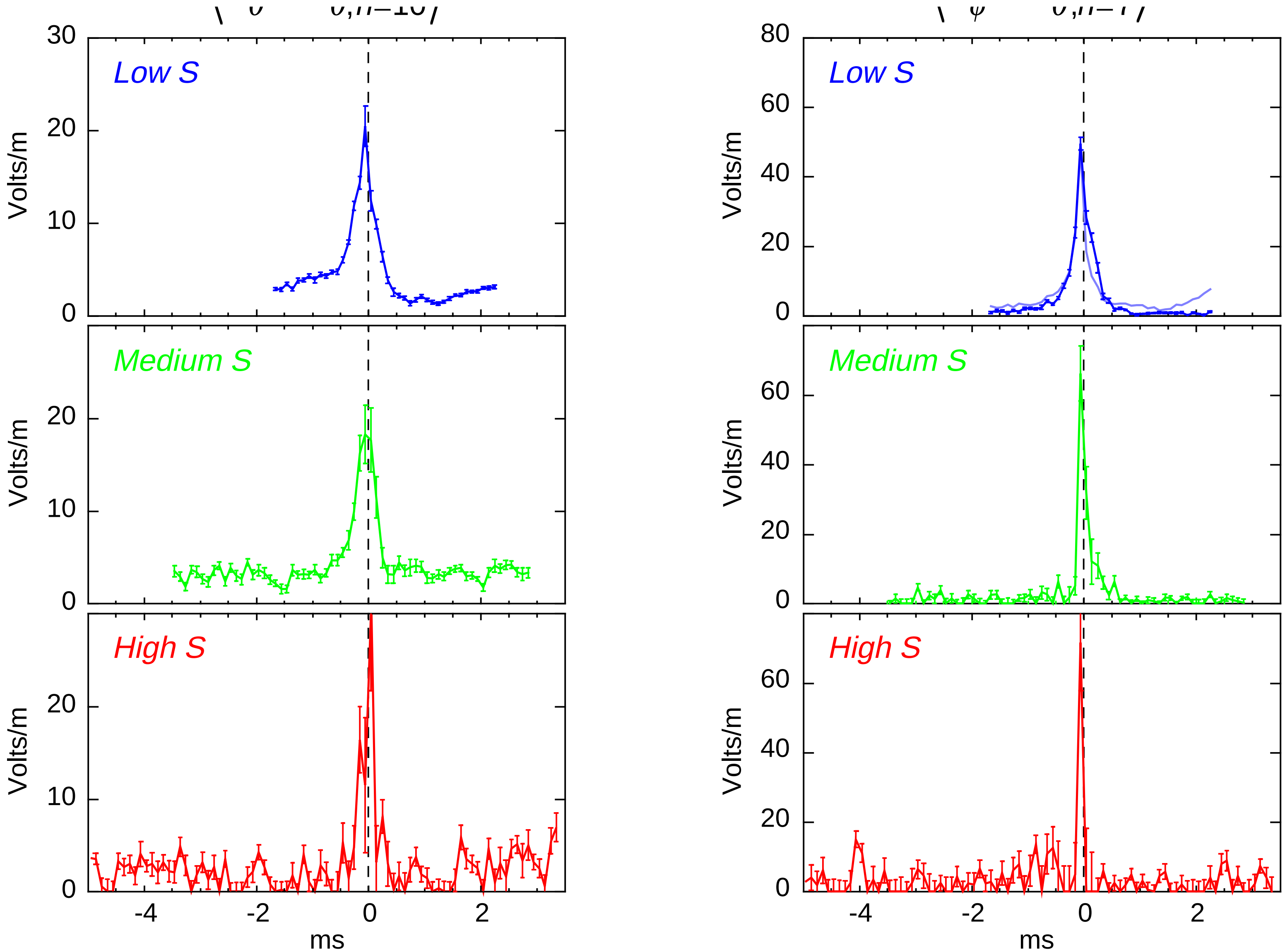


Phase of Toroidal Velocity Fluctuations
and Edge Poloidal Magnetic Field



- resoloution of dynamo product optimal at n=10 for the poloidal chord and n=7 for the toroidal chord

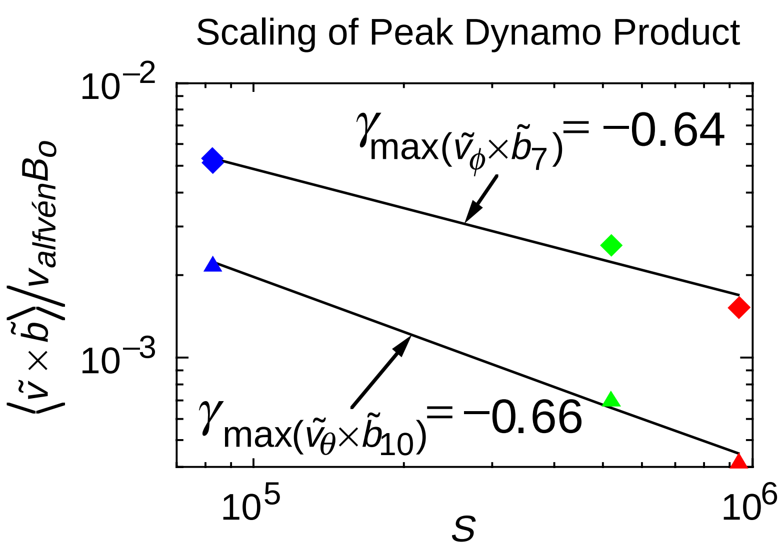
$$\langle \tilde{v}_\theta \times \tilde{b}_{\theta,n=10} \rangle \qquad \langle \tilde{v}_\phi \times \tilde{b}_{\theta,n=7} \rangle$$

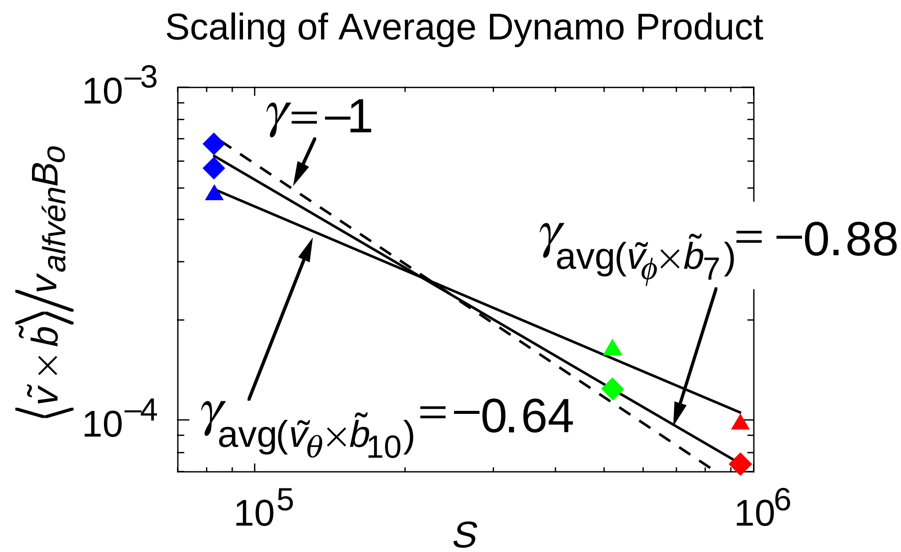


• better light levels and a larger number of sawtooth events at low S allow cleaner resolution of dynamo product

• dynamo resolved at and away from the sawtooth event indicating both continuous and discrete dynamo activity

- 'discreteness' increases with Lundquist number leading to fewer larger sawteeth





- dynamo product scales more strongly than either component individually

- results from loss of coherence between velocity and magnetic fluctuations at higher Lundquist number

- may indicate strong non-dynamo components to the velocity fluctuation which decrease scaling

Primary Conclusions

- as S increases the sawtooth cycle extends with a long decay phase followed by a violent discrete dynamo phase

- magnetic fluctations scale weakly with S in agreement with previous scalings

- ion velocity fluctuations also scale weakly with S

- preliminary measurements show phasing of ion velocity fluctuations and magnetic fluctuations consistent with a dynamo in the core of MST

- the measured dynamo exhibits strong scaling with S in rough agreement with Ohm's Law