Improved confinement in the RFP and the role of the magnetic turbulence spectrum.

J.S. Sarff, J.K. Anderson, T.M. Biewer, S. Castillo, B.E. Chapman, D. Craig, D.J. Den Hartog, G. Fiksel, C.B. Forest, R. O'Connell, S.C. Prager, J.C. Reardon—*University of Wisconsin-Madison*

D.L. Brower, W.X. Ding, S. Terry—*University of California-Los Angeles*

Introduction

Control of magnetic turbulent transport in the reversed field pinch yields increased energy confinement, plasma temperature, and beta. Relative to standard toroidal induction with incumbent dynamo relaxation, added poloidal current drive in MST increases the energy confinement time ten-fold to 10 ms, increases beta from 9% to 15%, and permits electrons to exceed 1 keV despite decreased Ohmic heating, a clear demonstration of reduced transport. The electron heat diffusivity drops to ~5 m²/s, comparable to typical tokamak plasma values. Central to these improvements is a broad spectral reduction of tearing fluctuations associated with magnetic relaxation and dynamo, implying reduced magnetic stochasticity. The role of particular spectral features in determining transport will be emphasized. For example, the reduction of poloidal number m=1 modes resonant in the middle to outer region of the plasma is crucial to realize the best improved confinement.

Summary

- Auxiliary poloidal current drive greatly improves RFP confinement and beta.
- Maximum temperature (and confinement) occurs in PPCD plasmas with long periods of low amplitude m=1, n=9-15 modes.
- The innermost core-resonant mode amplitudes (m=1, n=6 & 7) weakly correlate with core temperature.
- Increased temperature gradient in region of high-n modes fits physical picture of stochastic transport in the RFP.
- Very best PPCD plasmas have temperatures greater than shot-averaged Thomson profiles:

⇒ PPCD plasmas almost surely exist with higher energy confinement for known reasons (measurable with single-shot diagnosis).

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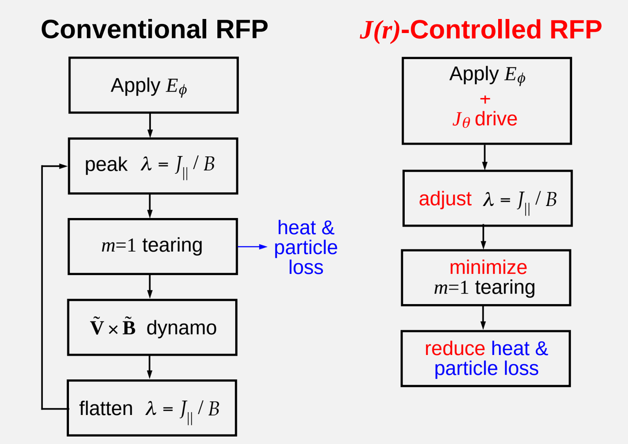
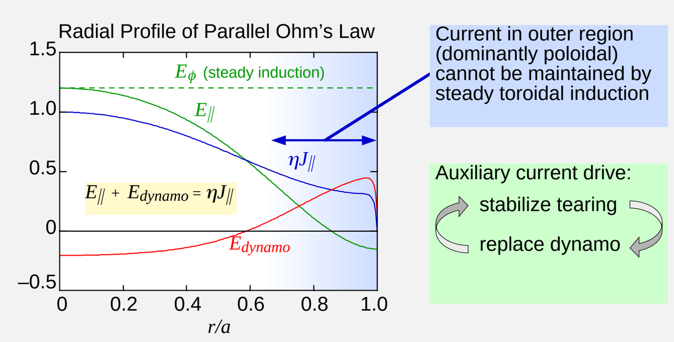
An RFP without Dynamo

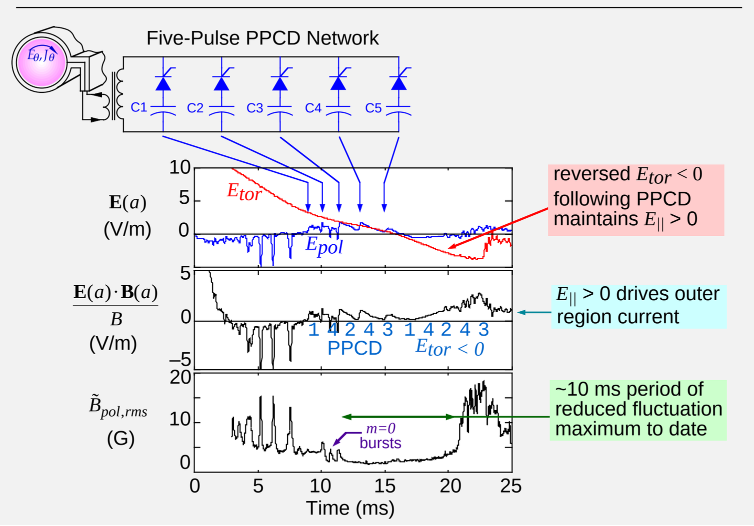


Auxiliary current drive replaces dynamo sustainment of poloidal current.



- Break "paradigm" : RFP = turbulent relaxation = stochastic transport
- First cut toward optimization of low-BT toroidal confinement

Pulsed poloidal current drive (PPCD) has evolved to produce ~10 ms periods of fluctuation suppression.



Future PPCD: "What's the optimum $\vec{E}(a,t)$ which minimizes transport for longest time period and why?"

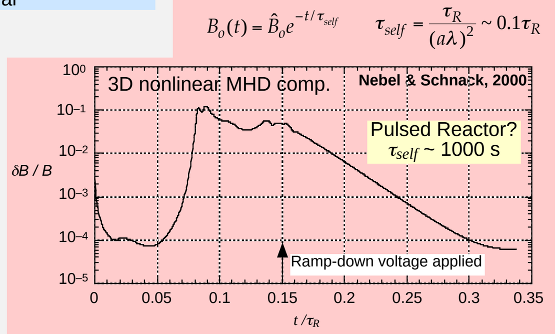
- $q(a) > 0$ at start of PPCD
  - minimize $m=0$ instability
  - ending $q(r)$ closer to standard
- "Oscillating" PPCD
  - time average improvement? (some gain observed in RFX)
  - BT-half of OFCD (sinusoidal)
  - non-sinusoidal

- "Self-similar decay" (or "Catching")
  > space-time separable solutions of magnetic diffusion, for example:

$$-\frac{\partial \mathbf{B}}{\partial t} = \frac{\eta}{\mu_o} \nabla \times (\nabla \times \mathbf{B}) = \frac{\eta \lambda^2}{\mu_o} \mathbf{B}$$

Separable solution $\mathbf{B}(r,t) = B_o(t)\, \mathbf{b}(r)$ has stationary $\mathbf{b}(r)$ and $q(r)$ with

$$B_o(t) = \hat{B}_o e^{-t/\tau_{self}} \qquad \tau_{self} = \frac{\tau_R}{(a\lambda)^2} \sim 0.1 \tau_R$$



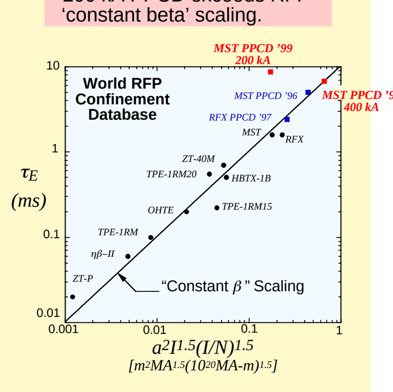
Record Confinement & Beta

9X improved energy confinement, T_e > 1 keV with PPCD.

	200 kA Standard		200 kA PPCD
n	$0.8 \times 10^{19}\ m^{-3}$		$0.7 \times 10^{19}\ m^{-3}$
T_{eo}	200 eV	× 3	600 eV
τ_E	1 ms	× 10	10 ms
β_{tot}	9%	× 1.7	15%
β_θ	9%	× 2	18%
τ_p	0.6 ms	× 8	4.7 ms

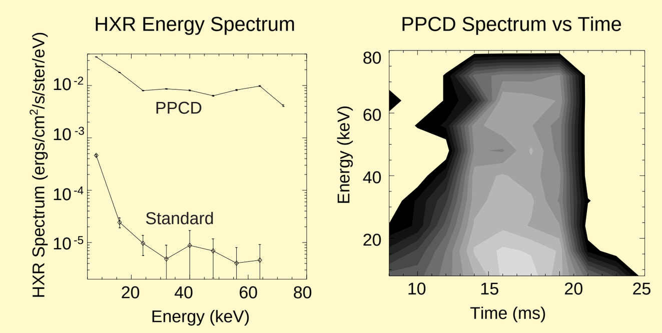
- 400 kA PPCD:
  T_{eo} = 800 eV (from 400 eV)
  β_{tot} = 11% (from 5%)
  τ_E = 9 ms (from 1 ms)
- 500 kA PPCD:
  $T_{eo} \approx$ 1.3 keV (MST max. to date)

- 200 kA PPCD exceeds RFP 'constant beta' scaling.



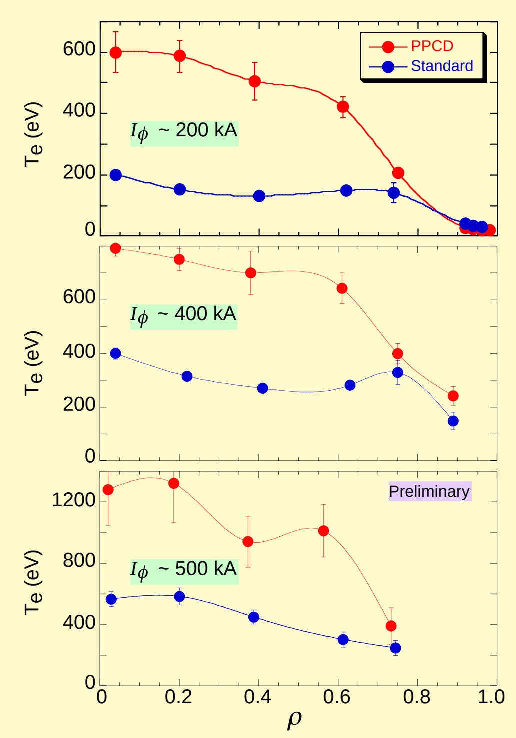
χ ~ 5 m²/s, only a few times larger than typical tokamaks

Three-order of magnitude increase in high energy HXR emission with PPCD.



- Toroidal loop voltage in core during PPCD ~5 V ⇒ >10⁴ toroidal transits to reach 80 keV
- Suggests partial restoration of closed flux surfaces.

Electron temperature doubles.



Magnetic Transport

Standard picture for parallel streaming transport depends on stochastic diffusivity from *locally resonant* modes.

- Quasi-linear heat diffusion (collisionless limit):

$$\chi = v_{th} D_m \text{ with } D_m = \int_0^\infty ds\, \langle \tilde{B}_r(0) \tilde{B}_r(s) \rangle / B_o^2 = L_\| \tilde{B}_r^2 / B_o^2 \text{ for } s \text{ along unperturbed field}$$

Rechester-Rosenbluth (for tokamak ordering)

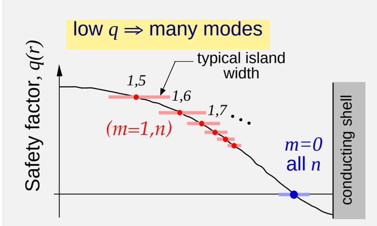
$$D_m(r) \sim \pi R \sum_{m,n} \frac{\tilde{B}_{r\,mn}^2}{B_o^2} \delta(m - nq(r))$$

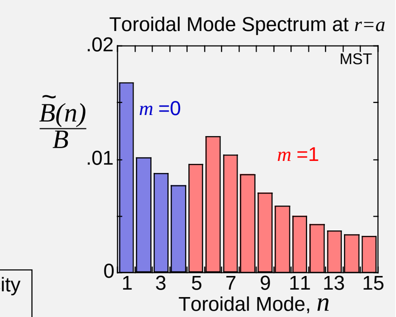
Terry, et al ("coherent" response in weak turbulence solution from DKE)

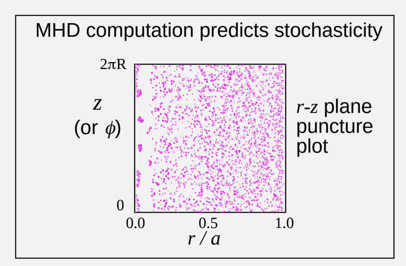
$$D_m(r) = \frac{1}{2\sqrt{\pi}} \sum_k \frac{\tilde{B}_{rk}^2}{B_o^2} \frac{1}{|k_\||} \left(\frac{\omega^2}{k_\|^2 v_{th}^2} \right) \exp\left(-\frac{\omega^2}{k_\|^2 v_{th}^2} \right)$$

additional ambipolar constrained "incoherent" response discussed in P.W. Terry et al., Phys. Plasmas **3**, 1999 (1996)

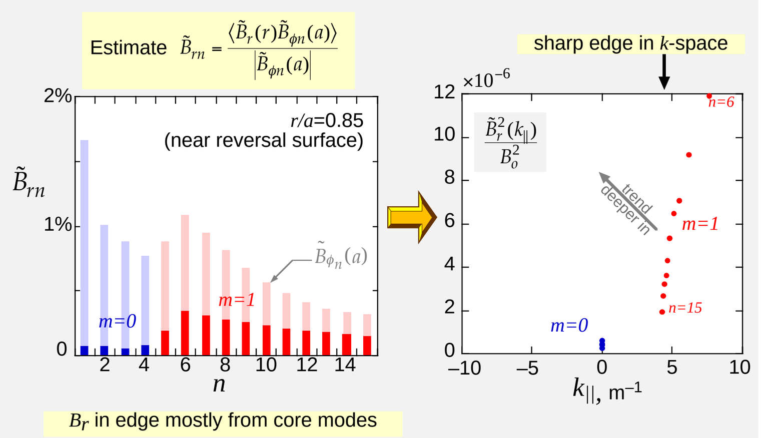
MHD tearing produces large magnetic fluctuations in RFP.



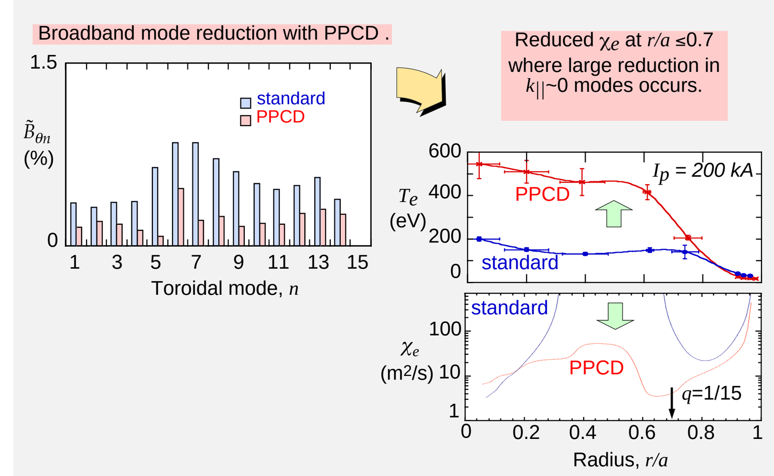




Magnetic diffusivity in the RFP varies strongly in space.



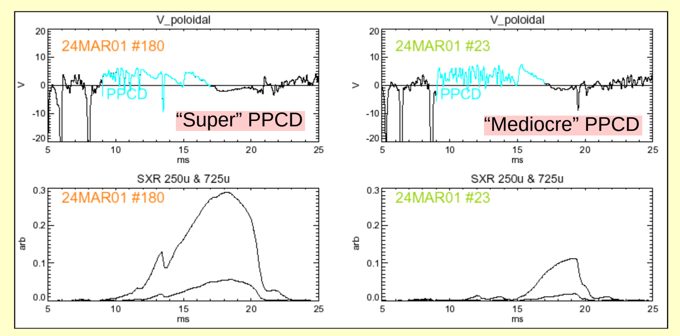
Transport reduction greatest just inside reversal surface where many high-n, m=1 modes packed closely together.



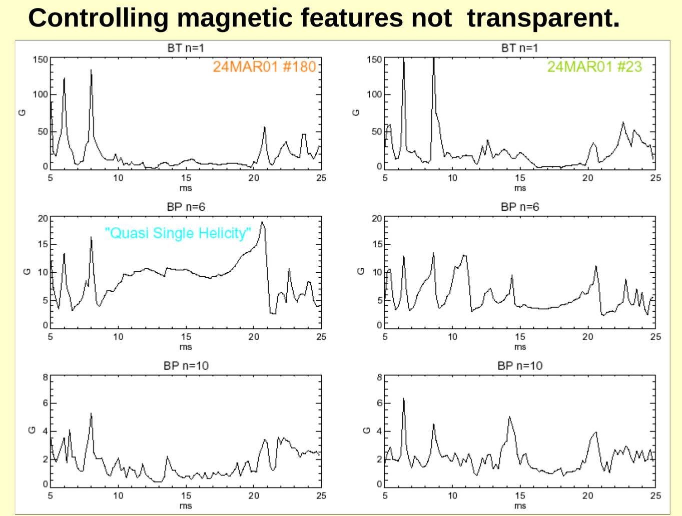
Question: What magnetic features control PPCD confinement and shot-to-shot variation?

Approach: Correlate core electron temperature with magnetic spectral dynamics.

Example shot-to-shot PPCD variation.



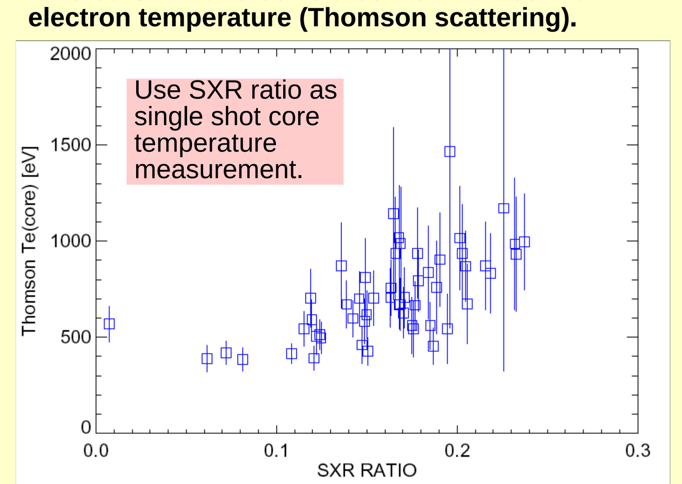
Controlling magnetic features not transparent.



Central electron temperature should be a good global confinement indicator:

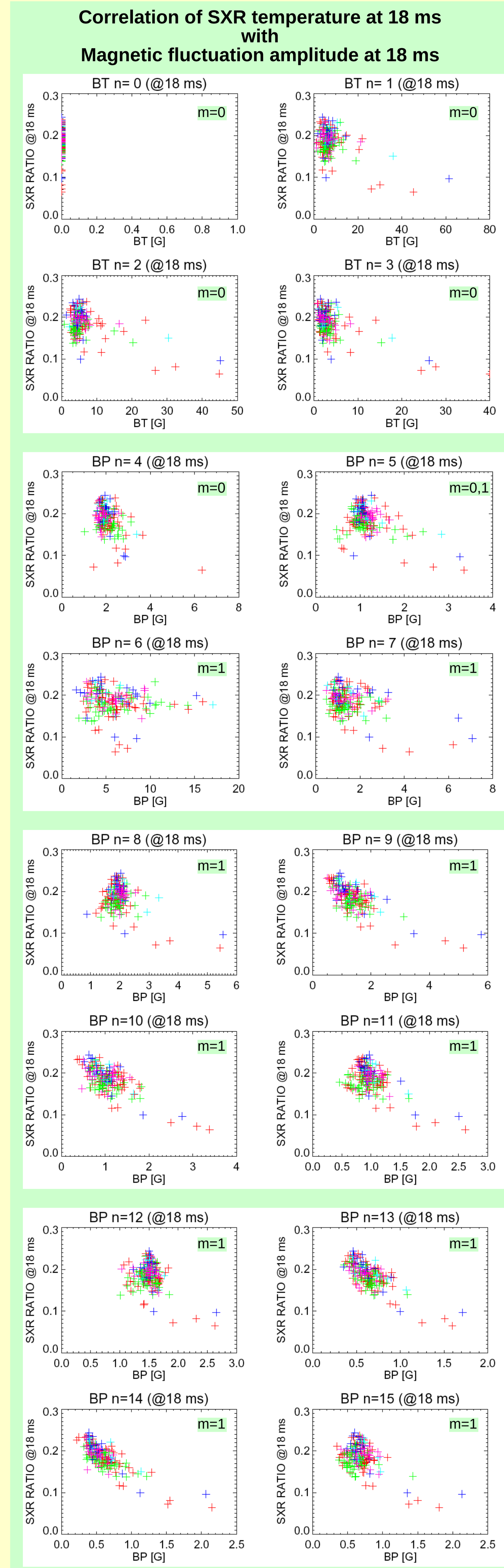
- tracks increase in beta
- determines magnitude of Ohmic input power

Filtered SXR ratio correlates well with central electron temperature (Thomson scattering).

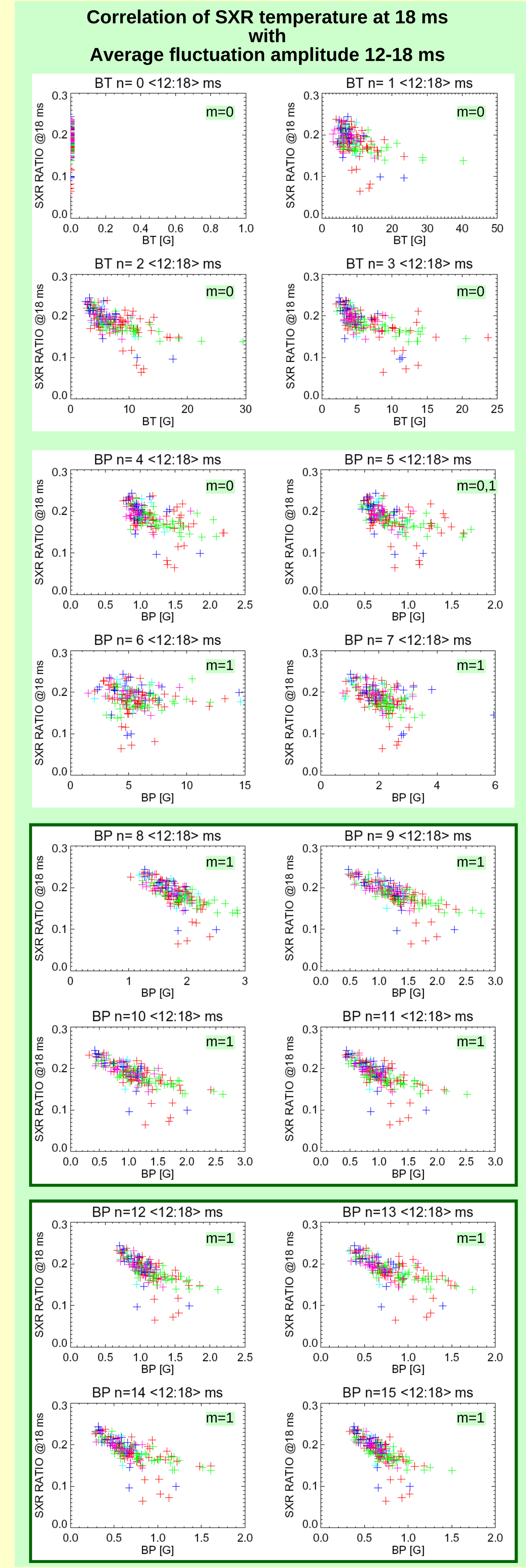


Correlation data shown below:
- four consecutive days of PPCD (each day's data plotted as a separate color)
- plasma current 390±15 kA
- plasma density 1.0±0.1x10¹³ cm⁻³
- mode rotation throughout PPCD

Correlation of SXR temperature at 18 ms with Magnetic fluctuation amplitude at 18 ms



Correlation of SXR temperature at 18 ms with Average fluctuation amplitude 12-18 ms



Answer:

- Temperature at end of PPCD period correlates best with time-average amplitude of m=1, high-n modes.
- These modes are resonant exactly where the temperature gradient increases with PPCD.
- The time-average amplitude of m=0 modes is also typically smaller in the hottest PPCD plasmas, but the correlation isn't as strong as for high-n modes.
- The temperature correlates weakly with the amplitude of the innermost resonant modes m=1, n=6,7.

⇒ "Quasi-single-helicity" spectra do not appear to be a determinant of high temperature.