Fast characterization of plasma states in W7-X with permutation entropy

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Today: introduce *permutation entropy (PE)*\(^1\) and report on application case

PE: measure for complexity of time series from information theory. In practice, a single number.

Benefit of PE: **fast** and **robust** method (sorting algorithms) for the detection of plasma state changes: potential $\rightarrow$ in-situ monitoring of plasma parameters.

**Main result:** PE detected changes in the plasma state unraveled in large-scale data mining in ECE and soft-X ray data.

Quantifying disorder with permutation entropy

How is PE defined and calculated?

Basis: Shannon Entropy: \( H(X) = -\sum_x p_x \log(p_x) \) → PE: permutation probabilities \( (p_x) \) of \( m \)-th order

Example: PE of order \( m = 3 \)

- \((3,2,1)\)
- \((2,3,1)\)
- \((1,3,2)\)
- \((3,1,2)\)
- \((2,1,3)\)
- \((1,2,3)\)

✓ Fast: based on sorting algorithms
✓ Robust: ordinal method (invariance for order preserving mappings)

PE: tool to detect irregularities based on Shannon Entropy that describes degree of randomness (disorder)

Plasma state characterization through permutation entropy

PE detects transient mode activity (seemingly linked to plasma state change – see $T_e$)
Localization of spontaneous $T_e$ increase and mode activity

Do all ECE channels measure a $T_e$ increase?

$T_e$ profile

![Graph showing $T_e$ profile with LFS and HFS regions marked]

- MHD activity observed
- Fluctuation analysis possible but no MHD activity observed
- No fluctuation analysis possible (low S/N)

PE/spectral analysis: identify channels with low response for fluctuations (‘blind’ channels)

Mode activity localized at: $-0.35 < \rho < 0.3$
Can spontaneous $T_e$ increase and mode activity be detected from SXR data through PE?

SXR data fluctuates when $T_e$ suddenly rises → indication for plasma state change detection

Local characteristics: both increasing and decreasing emissivity time series found.
2-D localization of $T_e$ increase and MHD activity

Lines of sight that detected MHD activity

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region of MHD activity (Poor-man’s tomography)

Cam 4A los-#8

Spectrogram: two ‘mode activities‘ one ~ 3 kHz (all times), one ~2 kHz (up to transition)

PE analysis: clear detection of transition
Plasma state characterization through permutation entropy

Before $T_e$ transition ($\text{PE}_{\text{ECE}} = 0.94$)

After $T_e$ transition ($\text{PE}_{\text{ECE}} = 0.99$)

Decay in PE goes along with previously unrevealed change in plasma profiles
Summary

- PE analysis is a method for calculating complexity in time series
- Use case: detection of spatio-temporal bifurcation of $T_e$ data
- Fast and robust detection of previously unrecognized mode activity seemingly linked to plasma state changes: potential applicability in machine learning to analyze bulk data
- Transport investigations underway

$\rightarrow$ PE is a suitable tool to detect plasma state changes and novelty detection in plasma data
Appendix
High-iota plasma with ECCD driven MHD activity: strong "event" led to plasma termination

PE analysis detects structures apparently linked to plasma termination (see $W_{\text{dia}}$)
Additional use case: detecting precursors of plasma termination events

What is PE detecting?

Down-chirp (2 kHz → 0.2 kHz) observed

PE analysis: suitable for the detection of activity preceding changes in the plasma state