Turbulent Fluctuation Analysis using Information Geometry in L-H Transitions at KSTAR

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Hidden Variables

- L-H power threshold predictions rely on fitting multi-machine datasets with **global plasma parameters**. (e.g. ITPA 2008 [1])
- Experimental data has a **large scatter**, limiting extrapolation confidence.
- This points to the importance of **hidden variables** for understanding trigger variability.
- **Information Geometry** quantifies non-equilibrium statistical dynamics and turbulence evolution across L-H transitions.

Information Geometry

- Treat time-dependent PDFs as moving points on a statistical manifold [2].
- Quantify the trajectories of variable x with the information rate and length:

$$\Gamma(t) = \sqrt{\int dx p(x,t) \left(\frac{\partial \ln p(x,t)}{\partial t}\right)^2}$$

$$\mathcal{L}(t) = \int_0^t \Gamma(t')dt'$$

- PDFs can be estimated using histograms of sliding time windows.

Diagnostics

- ECEI measures electron **temperature** fluctuations.
- BES measures electron **density** fluctuations.
- Mirnov Coils measure fluctuations in the **rate of change of magnetic field**.
- Information rate is **system agnostic**, allowing comparison between different variables.
- Data is normalised as $x' = \frac{x}{\langle x \rangle} - 1$ due to non-absolute diagnostics.

Density and Magnetic Topology

- 35645/46/47 are lower single null, **tungsten divertor** shots.
- Toroidal magnetic field strength B_T=1.9T.
- Primary differences are **plasma density**:
  35645: $\bar{n}_e$ ≈ 1.6×10^{19} m^{-3},
  35646: $\bar{n}_e$ ≈ 3.17×10^{19} m^{-3},
  35647: $\bar{n}_e$ ≈ 3.56×10^{19} m^{-3},
  and **increased NBI power** for 35647.
- 35646 exhibits a **strong n=2 coherent magnetic mode**.
- Data and initial analysis were presented in [3].

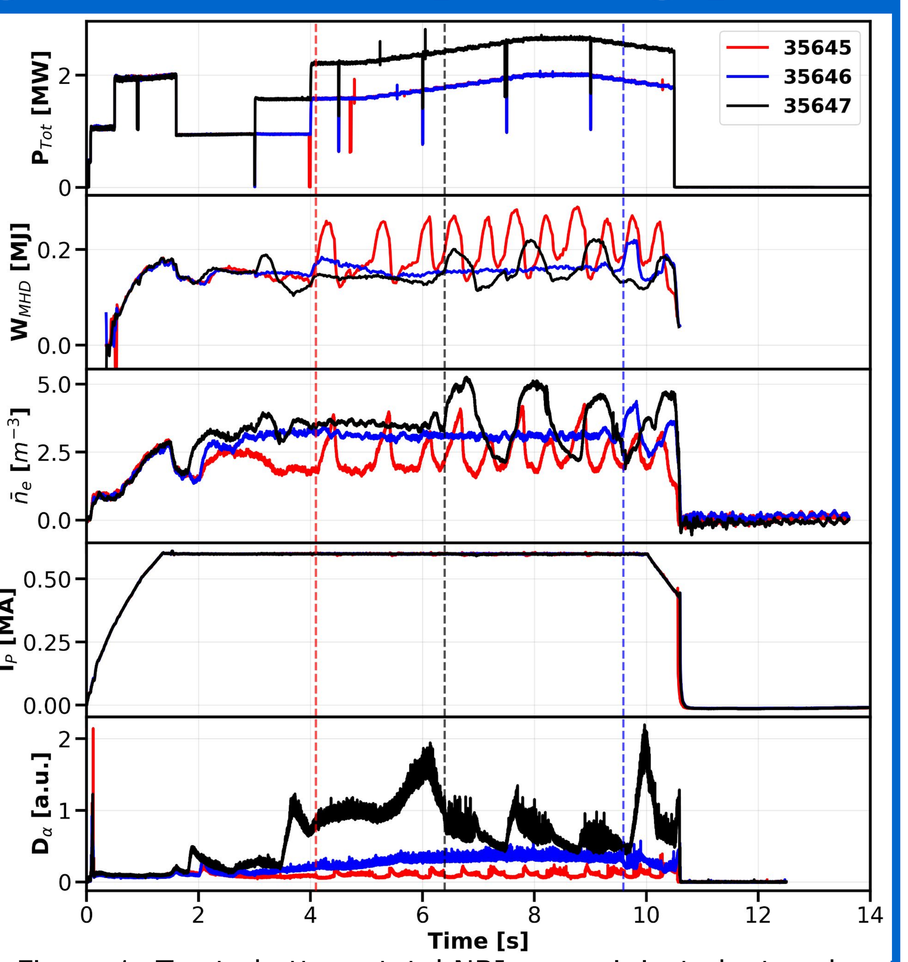

Figure 1: Top to bottom: total NBI power injected, stored energy, line-integrated electron density, plasma current, and emission for shots 35645/46/47. Dashed lines show the first L-H transition.

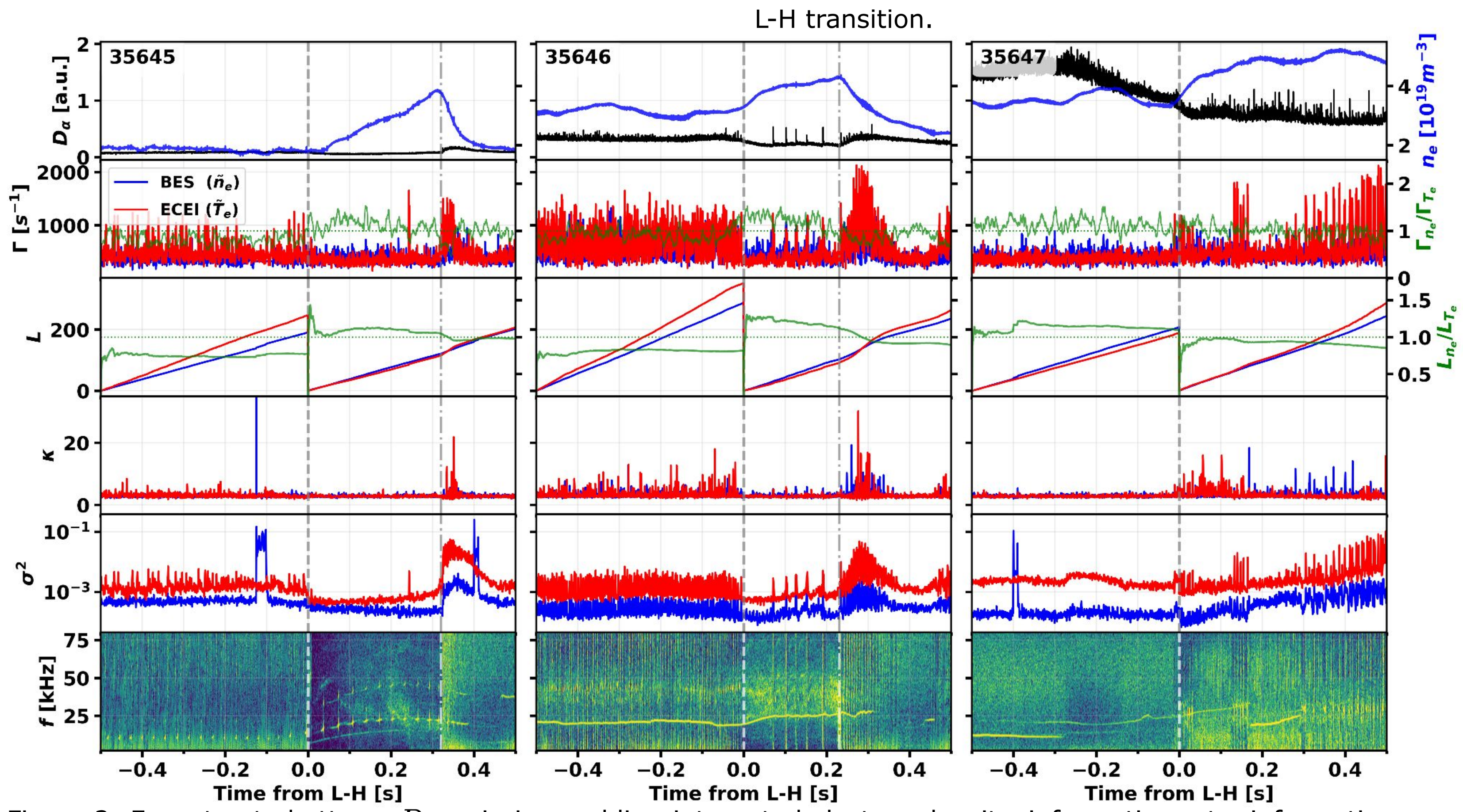

Figure 2: From top to bottom: D_α emission and line-integrated electron density, information rate, information length, kurtosis of PDFs, variance of PDFs, and outboard Mirnov Coil spectrograms for 35645/46/47 (left to right) using BES and ECEI channels at R~2.19m. Time is shown relative to the first L-H transition.

- In L-mode, information lengths are more similar for 35647 than 35645, implying greater correlation between temperature and density fluctuations.
- Presence of coherent mode in 35646 leads to larger L-mode information lengths and greater divergence between them, despite comparable density to 35647.

Preemptive ERMPs

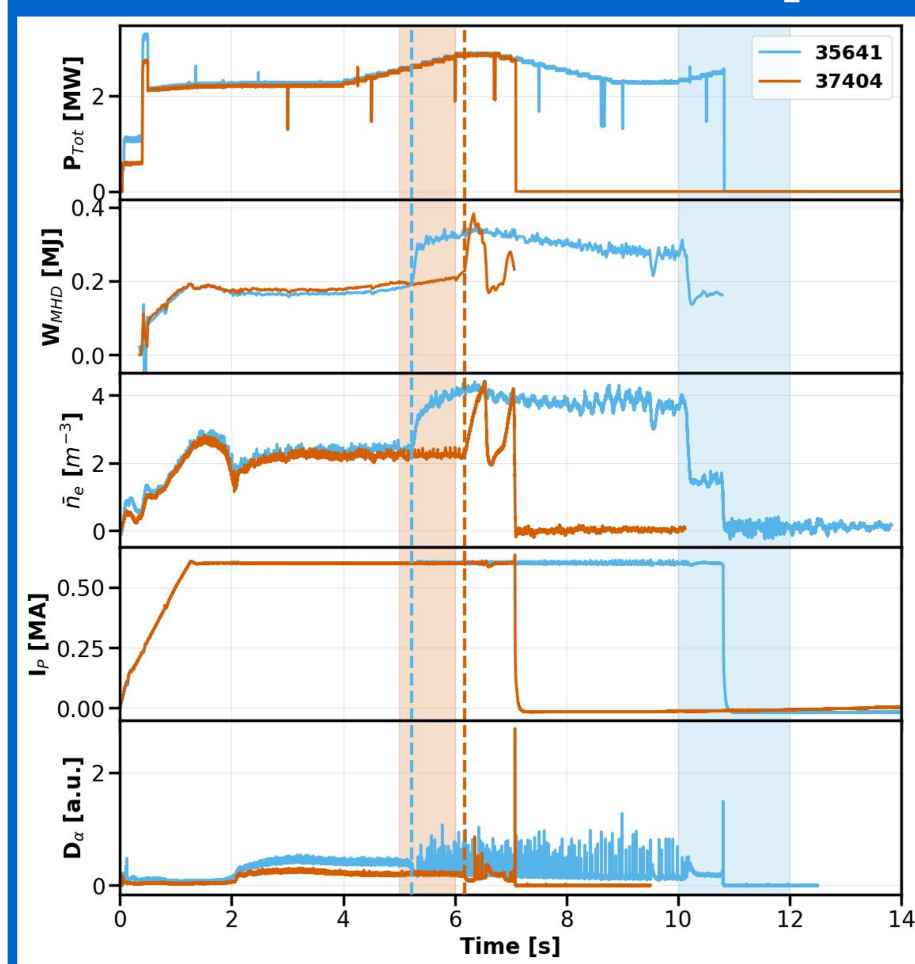

Figure 3: Top to bottom: total NBI power injected, stored energy, line-integrated electron density, plasma current, and D_α emission for shots 35641 and 37404. Dashed lines show the first L-H transition, and coloured windows show when ERMPs were applied.

- 35641 and 37404 are upper single null, **carbon divertor** shots performed ~1 year apart [3].
- Toroidal magnetic field strength B_T=1.9T.
- **Edge-localised Resonant Magnetic Perturbations** (ERMPs) are applied in both shots. These are n=1 perturbations.
- 35641 has conventional ERMPs applied in H-mode [10,12]s.
- 37404 has preemptive ERMPs applied in L-mode [5,6]s.
- Pre-emptive ERMPs appear to **increase the power threshold, delaying the L-H transition**.

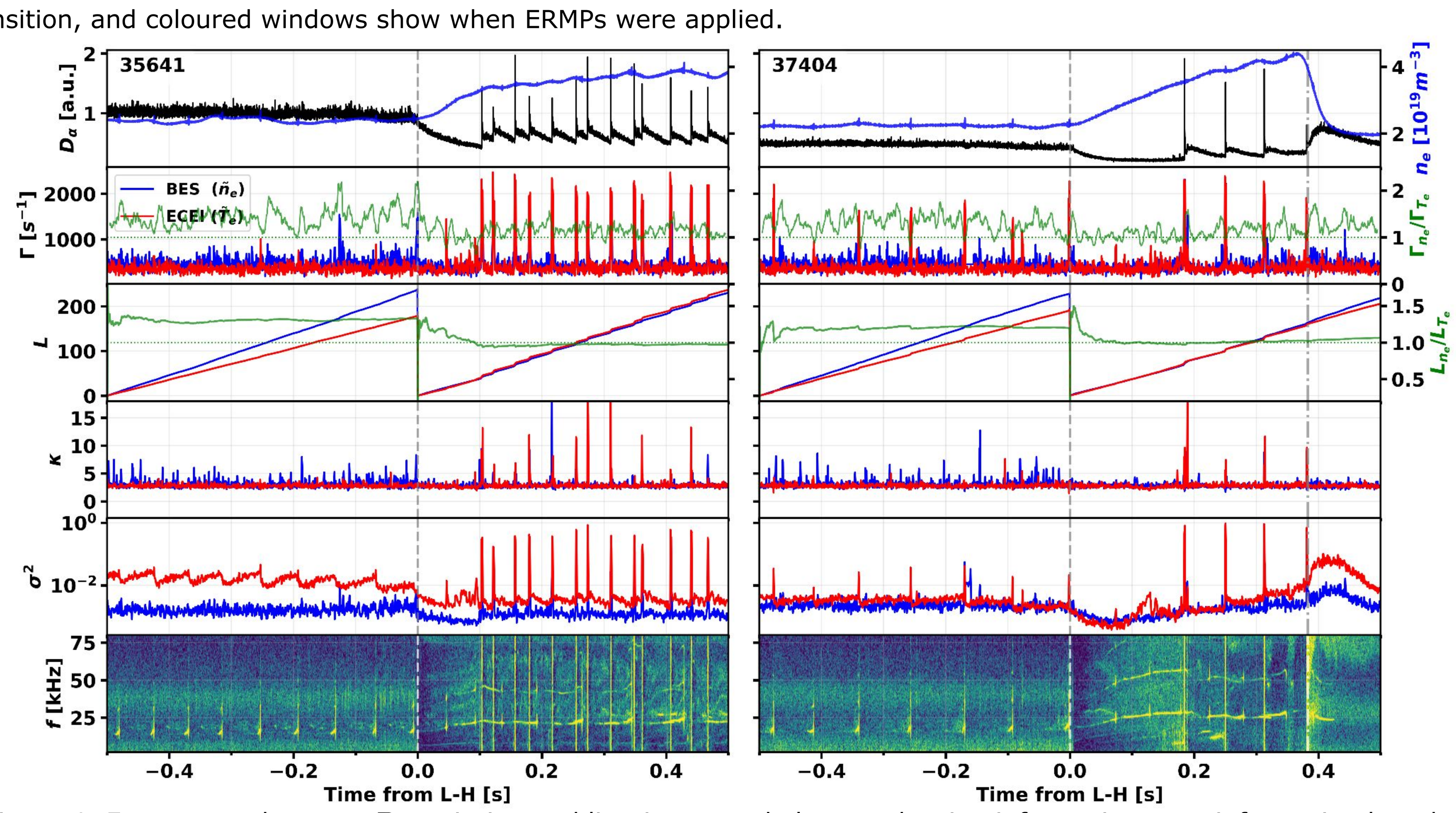

Figure 4: From top to bottom: D_α emission and line-integrated electron density, information rate, information length, kurtosis of PDFs, variance of PDFs, and outboard Mirnov Coil spectrograms for 35641 (left) and 37404 (right) using BES and ECEI channels at R~2.21m. Time is shown relative to the first L-H transition.

- In L-mode information lengths are similar between shots but in H-mode fluctuations evolve more slowly with preemptive ERMPs due to delayed ELM onset and lower ELM crash frequency.
- This suggests imprinting of history dependence by ERMPs, and highlights the sensitivity to the machine condition.

Conclusions

- Information geometry successfully **captures rapid transients** such as ELMs, and tracks the **statistical reorganisation** around L-H transitions.
- Density and magnetic topology affect the coupling and evolution of temperature and density fluctuations, which is reflected in information geometric quantities.
- ERMPs restructure the background L-mode turbulence evolution, **increasing correlation between temperature and density fluctuations**, and **imprint persistent statistical memory**.
- Global parameter scalings **lack the local edge physics** required for predicting H-mode access requirements. Information geometry can help probe differences in access regimes.
- Further results to be reported in Plasma Phys. Control. Fusion [4].

References and Acknowledgement

[1] Y. R. Martin, et al. (2008) J. Phys.: Conf. Ser. 123, 012033 **[2]** E. Kim (2021) Entropy **23**(11), 1393 **[3]** E. Kim et al. (2025) *Novel Effects of Edge-Localised RMPs and Plasma Density on the L-H Transitions and Transport*. Pre-print presented at IAEA FEC 2025, Paper No. EX-P6-3227. **[4]** E. Kim, S. Han, M. Parker et al. (2026) *Variability of the L–H transition in KSTAR: density dependence and electromagnetic pathways*. To be submitted to Plasma Phys. Control. Fusion.

This work is funded by EPSRC Fusion Power Centre for Doctoral Training and Coventry University. I would like to acknowledge and thank the KSTAR team for their help in acquiring the data shown in the figures of this poster.