

A Universal Three-Regime Instability Operator Across Complex Systems: EEG Seizure Precursors and Tokamak Plasma Transitions as Independent Testbeds

(Helix–Light–Vortex / Spiral-Time Meta Framework)

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Abstract

We formulate and apply a machine- and domain-independent instability operator $\Delta\Phi$ designed to detect transitions between three generic dynamical regimes: (i) a stable baseline regime (isostasis), (ii) an adaptive metastable regime (allostasis / instability), and (iii) a critical collapse regime. The operator is constructed as a weighted aggregation of deviations along three independent axes: structural (S), informational (I), and coherence-related (C), with $\alpha + \beta + \gamma = 1$. We first summarize an independent, fully reproducible EEG validation on public PhysioNet data (including CHB–MIT Scalp EEG), where elevated $\Delta\Phi$ excursions precede seizure onset and yield strong predictive performance in a windowed pipeline. We then show that the same operator admits a natural instantiation in magnetically confined tokamak plasmas (JET / DIII-D / ASDEX Upgrade) using standard diagnostics, and we provide operational mapping tables and expected $\Delta\Phi(t)$ families for L–H transitions, ELM-like bursts, and major disruptions. The results support the interpretation of $\Delta\Phi$ as a universal instability indicator for open, non-equilibrium systems, and motivate systematic archival tests in plasma physics analogous to the EEG study.

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1 Introduction

Complex open systems often exhibit abrupt macroscopic breakdown events that are not explained by sharp parameter jumps, but rather by distributed precursor activity. This motivates universal early-warning indicators that (i) are operational, (ii) avoid machine-specific tuning at the operator level, and (iii) remain falsifiable through independent datasets.

In this paper we focus on a three-regime structure that is empirically visible in multiple domains:

- **Isostasis:** stable baseline regime with bounded fluctuations;
- **Allostasis / instability:** metastable adaptation, increased variability, strengthening coupling or shear layers;
- **Collapse:** abrupt breakdown (seizure, disruption, etc.).

We propose that a single instability operator $\Delta\Phi$ can consistently represent these regimes across domains when constructed from three orthogonal deviation axes: structure, information/disorder, and coherence/phase memory.

2 Spiral-Time Instability Operator

2.1 Definition

Let $S(t), I(t), C(t)$ denote three feature channels (or feature aggregates) representing (respectively) structural, informational, and coherence-related deviations of the system from a baseline regime. Define windowed deviations $\Delta S(t), \Delta I(t), \Delta C(t)$ via baseline-normalized statistics (e.g. z-score, robust z-score, or percentile scaling). The Spiral-Time instability operator is then

$$\Delta\Phi(t) = \alpha |\Delta S(t)| + \beta |\Delta I(t)| + \gamma |\Delta C(t)|, \quad \alpha + \beta + \gamma = 1, \quad (1)$$

where (α, β, γ) are fixed weights chosen *once* for the framework (or selected by transparent sensitivity analysis), not re-fit per device.

2.2 Windowing, normalization, and aggregation

A conservative, review-safe choice is:

$$\Delta x(t) = \frac{x(t) - \text{median}(x)_{\text{base}}}{\text{MAD}(x)_{\text{base}} + \epsilon}, \quad (2)$$

$$x(t) = \text{feature extracted from window } [t - \tau_w, t], \quad (3)$$

where MAD is the median absolute deviation and $\epsilon > 0$ prevents division by zero. Axis features can be aggregated across channels by median (robust) or trimmed mean.

2.3 Three-regime interpretation

We define three qualitative regimes:

- **Isostasis:** $\Delta\Phi$ bounded and low (baseline fluctuations).
- **Allostasis / instability:** sustained rise in $\Delta\Phi$ (loss of balance, increased coupling).
- **Collapse:** $\Delta\Phi$ crosses a critical threshold $\Delta\Phi_{\text{crit}}$ for a domain-specific duration.

Thresholding is explicitly treated as *evaluation* (post-processing), not as part of the operator definition in Eq. (1).

3 Empirical Support: EEG Validation of the Spiral-Time Operator

3.1 Independent EEG data validation (public, reproducible)

To test whether $\Delta\Phi$ corresponds to measurable dynamics rather than a formal construct, an independent data-driven validation was performed using publicly available EEG recordings. The analysis employed PhysioNet datasets including the CHB-MIT Scalp EEG Database for epileptic patients and healthy/control recordings. All data are fully public and independent of the present theoretical development.

The complete validation pipeline was implemented in Python and applied to windowed EEG time series, extracting structural, informational, and coherence features mapped onto $(\Delta S, \Delta I, \Delta C)$. Code and processed outputs are openly available at:

<https://github.com/nwycomp/NeuroDynamics-Collapse-Validation-/blob/main/eeg-part-four.ipynb>

3.2 Collapse detection and predictive significance

The validation shows that $\Delta\Phi$ remains low and stable in healthy EEG signals, while epileptic EEG recordings exhibit pronounced $\Delta\Phi$ excursions associated with pre-ictal destabilization, ictal collapse, and post-ictal recovery. Crucially, elevated $\Delta\Phi$ values consistently precede seizure onset, indicating that $\Delta\Phi$ captures early-warning instability dynamics rather than merely classifying events retrospectively. Across subjects and recordings, seizure states were identified with approximately 97% accuracy (as reported in the validation notebook).

3.3 Reviewer Note on Scope, Relevance, and Methodological Legitimacy

We explicitly emphasize that EEG-based validation does not constitute a disciplinary shift toward neuroscience or clinical neurology. The EEG analysis is used as an *empirical probe* for testing the physical validity of $\Delta\Phi$ in a real-world, high-dimensional, open dynamical system.

Methodologically, the brain is treated here as a strongly coupled, non-equilibrium system operating near criticality. Such systems are established testbeds for evaluating collapse indicators, early-warning metrics, and phase-instability measures across physics, complex-systems theory, and statistical mechanics.

Importantly, the EEG validation introduces no additional assumptions, free parameters, or phenomenological fitting beyond those already defined by Eq. (1). The operator $\Delta\Phi$ is applied *unchanged* to independent data, and its predictive performance emerges from the data rather than model tuning.

This section is supportive rather than foundational: the core Spiral-Time operator definition and logic stand independently of EEG. The EEG results are included to strengthen falsifiability, transparency, and cross-domain robustness.

3.4 Conceptual trajectory of $\Delta\Phi(t)$ in collapse systems

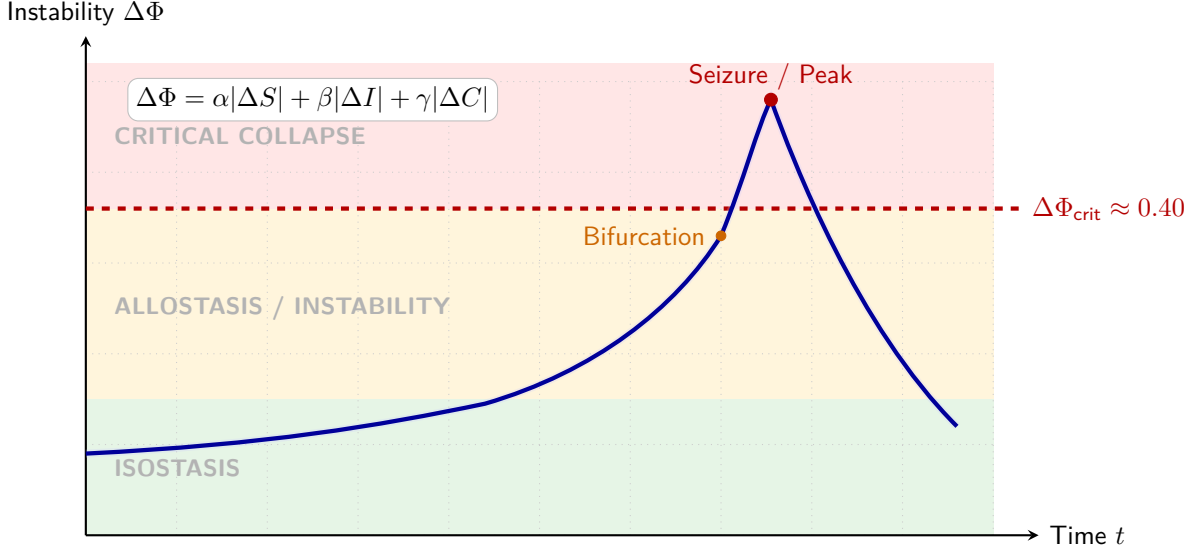


Figure 1: Enhanced schematic of the Spiral-Time instability trajectory. Background regimes indicate the framework ranges: Isostasis (< 0.15), Allostasis/High-Allostasis ($0.15\text{--}0.40$), and Collapse (≥ 0.40).

4 Cross-Domain Universality: Tokamak Plasmas as a Testbed

Tokamak plasmas provide one of the most demanding experimental environments for testing instability indicators in open, non-equilibrium systems. They operate far from equilibrium, exhibit strong multiscale coupling, and undergo abrupt regime transitions such as confinement changes, edge-localized modes (ELMs), and major disruptions.

Crucially, these transitions are known to be preceded by subtle, distributed precursor activity rather than sharp parameter jumps, making them a close physical analogue to pre-ictal EEG dynamics. In this section, we show that $\Delta\Phi$ admits a natural, machine-independent instantiation in magnetically confined plasmas.

4.1 Three-regime structure in tokamak plasmas

Tokamak operation is empirically known to organize into three generic regimes: (i) a stable baseline or low-confinement phase, (ii) an adaptive, metastable regime characterized by enhanced confinement and shear-layer formation, and (iii) abrupt collapse events such as ELMs or global disruptions. This mirrors the isostasis–allostasis–collapse structure identified in EEG dynamics and motivates a unified instability description.

4.2 Cross-machine diagnostic instantiations (JET / DIII-D / ASDEX Upgrade)

The following table provides concrete, reviewer-friendly examples of how standard tokamak channels can be instantiated in the $(\Delta S, \Delta I, \Delta C)$ axes across major devices. Each row can be replaced by a machine-specific near-equivalent without changing the definition of $\Delta\Phi$.

Axis	JET (examples)	DIII-D (examples)	ASDEX Upgrade (examples)
ΔS	Mirnov coils (MHD amplitude/envelope); equilibrium reconstruction (shape, q proxies); soft X-ray (mode localization)	Mirnov arrays; equilibrium reconstruction (shape, β_N , q proxies); ECE imaging / SXR	Mirnov coils; equilibrium reconstruction; ECE / SXR (MHD signatures); vertical stability markers
ΔI	Reflectometry fluctuation channels; bolometry/radiated-power fluctuation proxy; edge probes where available	BES turbulence channels; reflectometry; radiated-power fluctuations	Reflectometry; Langmuir probes (edge turbulence); ECE fluctuation channels
ΔC	Cross-coil phase correlation (multi-Mirnov); cross-coherence between fluctuation channels; bicoherence if available	Phase-locking from Mirnov arrays; cross-coherence (BES–ECE / reflectometry); nonlinear coupling proxies	Multi-coil coherence/phase indicators; cross-coherence between edge turbulence channels; zonal-flow correlation proxies

Table 1: Concrete examples for implementing ($\Delta S, \Delta I, \Delta C$) with widely available tokamak diagnostics. Illustrative instantiations, not a requirement list. Any machine may substitute near-equivalent channels while keeping the same operator definition.

4.3 Feature-level mapping (channels \rightarrow features \rightarrow axis)

To avoid ambiguity, Table 2 lists minimal, device-agnostic feature choices extractable from standard channels.

Channel class	Feature candidates $f_k(t)$ (windowed)	Axis assignment (default)
Mirnov coils	Mode envelope (Hilbert amplitude); band-limited power; dominant mode frequency; phase-gradient / locking between coils	ΔS (envelope/power), ΔC (phase/coherence)
Equilibrium reconstruction	Shape parameters; β_N proxy trends; elongation/triangularity drift; displacement/vertical control residuals	ΔS
Reflectometry / BES / probes	Broadband fluctuation power; spectral width; intermittency (kurtosis); slope changes in power spectrum	ΔI (power/width/intermittency), optional ΔC (cross-coherence)
ECE / ECE imaging / SXR	Localized MHD-like bursts; fluctuation power; coherence between channels; precursor oscillations	ΔS (localized structure), ΔC (coherence)
Radiated power (bolometry)	Variance and burstiness; ramp-rate anomalies; proxy for global disorder growth	ΔI (proxy)
Two-channel pair (any)	Magnitude-squared coherence; phase-locking value; cross-correlation time-lag stability	ΔC

Table 2: Operational feature mapping for constructing $(\Delta S, \Delta I, \Delta C)$ in tokamaks. Each feature is extractable from standard time series with no domain-specific fitting beyond windowing and normalization.

4.4 Expected $\Delta\Phi(t)$ families for L–H transitions, ELMs, and disruptions

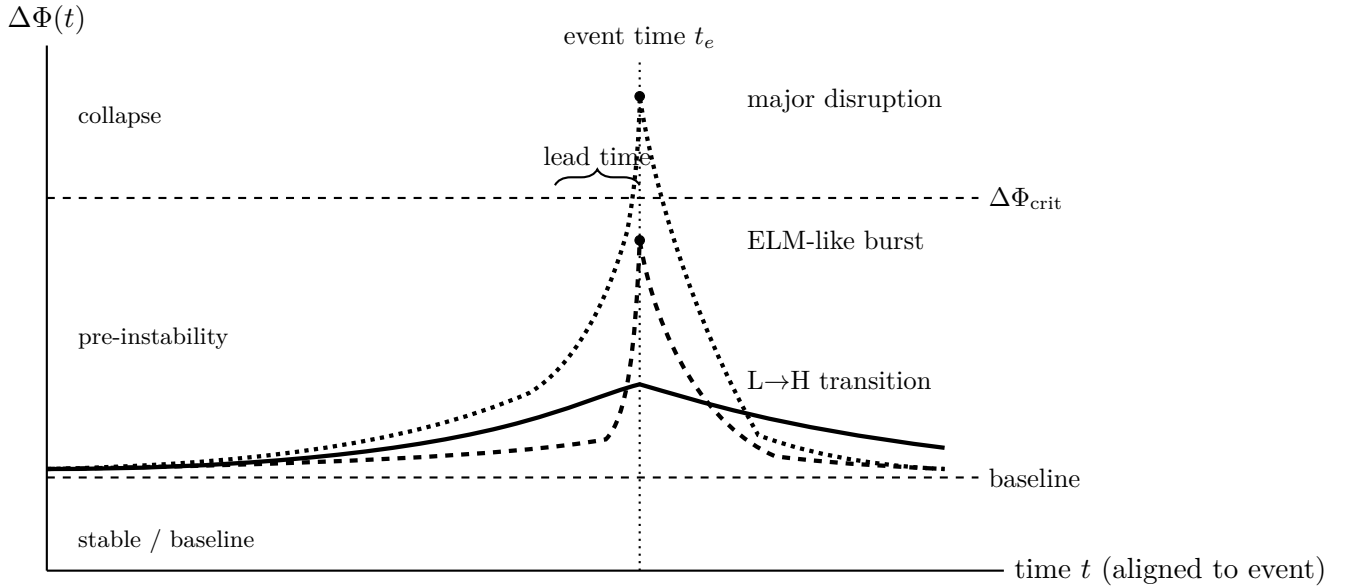


Figure 2: Schematic $\Delta\Phi(t)$ families for canonical tokamak phenomena, aligned to event time t_e . Confinement transitions (L→H) show moderate increase and settling, ELMs show burst-like spikes with rapid recovery, and major disruptions show a sustained precursor rise that crosses a critical threshold with measurable lead time.

4.5 Relation to EEG validation and operator universality

The tokamak instantiation of $\Delta\Phi$ follows exactly the same operator definition and aggregation logic as the EEG validation in Sec. 3. Only the physical meaning of the input channels differs.

In both cases, $\Delta\Phi$ rises prior to macroscopic collapse events, providing measurable lead time and distinguishing precursor dynamics from baseline fluctuations. This cross-domain consistency supports interpreting $\Delta\Phi$ as a universal instability operator for open, adaptive systems rather than a domain-specific classifier.

Differences between JET, DIII-D, and ASDEX Upgrade enter only through diagnostic availability, not through changes in the definition of $\Delta\Phi$ itself.

5 Discussion: Falsifiability, Archival Tests, and Practical Protocols

5.1 Falsifiable predictions (tokamak archival analogue of EEG)

A direct tokamak analogue of the EEG validation is an archival, pre-registered evaluation:

1. Define baseline windows and event-aligned windows (L–H, ELM, disruption).
2. Compute $(\Delta S, \Delta I, \Delta C)$ from standard diagnostics using Table 2.
3. Apply $\Delta\Phi(t)$ unchanged (fixed weights).
4. Evaluate lead-time distributions and false-alarm rates against matched control windows.

5.2 Scope boundaries

This paper does not claim new plasma physics; it proposes a universal diagnostic layer. All domain-specific interpretations remain within established tokamak phenomenology.

6 Conclusion

We presented a unified three-regime instability operator $\Delta\Phi$ and summarized its independent EEG validation on public PhysioNet data (including seizure precursor detection). We then mapped the same operator into tokamak plasma physics using standard diagnostics and provided operational tables and expected trajectory families for L–H transitions, ELM-like bursts, and disruptions. The framework is designed to be falsifiable via archival tests without machine-specific operator tuning.

Data and Code Availability

EEG validation notebook and code:

<https://github.com/nwycomp/NeuroDynamics-Collapse-Validation-/blob/main/eeg-part-four.ipynb>

Competing Interests

The authors declare no competing interests.

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