

EM Topology Stability and Active Field Governance for High Power Hall Thrusters

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Abstract: The in-flight checkout of the Psyche spacecraft's SPT-140 Hall thrusters (Oh et al., *Journal of Spacecraft and Rockets*, 2026) documents five classes of transient and quasi-steady behaviour: burn-in thrust decay, extended mode-hopping, sensitivity to magnet-current settings, ground-to-space performance differences, and thrust variability during calibration. This Technical Comment reinterprets these observations within a unified electromagnetic-topology framework, demonstrating that each behaviour is a manifestation of one of four underlying EM-topology mechanisms, sheath evolution, magnetic-topology drift, ionisation-driven oscillations, and environment-dependent discharge equilibria, rather than an isolated anomaly. The analysis establishes that these instabilities are structural features of passive-topology Hall-thruster architectures and will become increasingly consequential as mission lifetimes and power levels grow. The Psyche dataset is further examined for its relevance to active electromagnetic field-governance research. A one-to-one correspondence is identified between the five observed behaviours and the stabilisation functions of the Rotating Electromagnetic Nozzle (REMNs), an external field-governance architecture designed to suppress mode transitions, damp harmonics, lock B-field topology, and compensate for environmental boundary-condition changes in real time. The Psyche checkout data is presented as a valuable real-flight reference for evaluating next-generation active field-governance approaches in high-power electric propulsion.

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1. Introduction

The recently published Psyche electric-propulsion checkout report provides a detailed account of SPT-140 Hall-thruster behaviour during early mission operations. The authors document several transient and quasi-steady behaviours during the initial activation and characterisation sequence, including thrust drift during burn-in, extended mode-hopping, sensitivity to magnet-current settings, environment-dependent discharge characteristics, and thrust variability during calibration segments. These observations are consistent with prior high-power Hall-thruster experience and represent an important contribution to the flight data record for this class of propulsion system. The purpose of this Technical Comment is to provide additional context regarding the electromagnetic-topology mechanisms that underlie these behaviours. The Psyche paper reports the phenomena accurately and thoroughly but does not explicitly frame them within the broader EM-topology dynamics that govern Hall-thruster stability. This comment draws out those connections and notes that active electromagnetic field-governance architectures, such as the Rotating Electromagnetic Nozzle (REMNs), are being developed specifically to stabilise the classes of behaviour observed during Psyche's checkout. The intent is not to critique the Psyche results. The observed behaviours are intrinsic to Hall-thruster physics and were managed competently by the mission team. Rather, the goal is to extend the interpretation for readers interested in EM-topology stability and active field-governance approaches, and to note that the Psyche checkout data provides a useful real-flight reference point for evaluating next-generation propulsion architectures.

2. Electromagnetic-Topology Behaviours Observed on Psyche

Each of the five behaviours reported during the Psyche checkout sequence can be traced to a specific EM-topology mechanism. The following subsections outline these connections.

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A. Burn-In Thrust Decay

The reported step decrease in thrust during early 4.5 kW operation (277 → 253 mN) is consistent with discharge-mode transition driven by sheath evolution and wall-interaction changes as the discharge channel transitions from its initial cold-wall state toward thermal equilibrium. This process alters the effective ionisation-zone position and plasma-potential distribution, shifting the discharge to a lower-thrust stable mode. Because the magnetic topology is fixed by the thruster's coil geometry, it cannot compensate for these changes dynamically. This behaviour has been observed across multiple high-power Hall systems and is a well-documented EM-topology transition [1, 2].

B. Extended Mode-Hopping and Stabilisation Time

The extended mode-hopping observed on Thruster B, requiring prolonged firing to settle into a stable discharge mode, is characteristic of magnetic-topology drift coupled with electron-temperature oscillations. These transitions occur when the B-field topology is near a boundary between discharge regimes, allowing small perturbations to trigger shifts between quasi-stable attractor states in the discharge parameter space. The timescale of passive stabilisation is set by the thermal and electromagnetic relaxation dynamics of the system, which are not under direct operator control in a passive-topology architecture.

C. Sensitivity to Magnet-Current Settings

The sensitivity of the discharge to small changes in magnet-current settings reflects the tight, nonlinear coupling between magnetic-field topology and the location of the ionisation and acceleration regions. High-power Hall thrusters are particularly susceptible to this behaviour because their operating points lie in regions where the EM-topology landscape is steep: small field perturbations shift the system between neighbouring equilibrium states, altering thrust and specific impulse. This sensitivity is an intrinsic property of the passive-topology architecture and becomes more pronounced as power levels increase [3].

D. Ground-to-Space Performance Differences

The differences between ground and space performance reported in the Psyche paper are consistent with changes in neutral density, wall temperature, and sheath formation in vacuum. These environmental factors alter the EM-topology configuration, leading to shifts in discharge mode and stability characteristics. Because the thruster's magnetic topology is calibrated underground-test conditions, it is optimised for those boundary conditions and must re-stabilise when the environment changes, a process that the Psyche checkout data documents well.

E. Thrust Variability During Calibration

The thrust variability observed during calibration segments aligns with ionisation oscillations, breathing modes, and plasma-potential fluctuations. These oscillatory behaviours are intrinsic to Hall-thruster operation and arise from the coupled dynamics of ionisation, neutral depletion, and EM-topology feedback [4]. Their amplitude and persistence depend on proximity to an instability boundary in the discharge parameter space.

3. A Unified Electromagnetic-Topology Interpretation

Taken together, the behaviours documented in the Psyche checkout form a coherent pattern of EM-topology dynamics. Each behaviour corresponds to one of four underlying mechanisms: sheath evolution, magnetic-topology drift, ionisation-driven oscillations, and environment-dependent discharge equilibria. These are not isolated anomalies; they are manifestations of the same EM-topology processes that govern stability across all high-power Hall thrusters. Making this connection explicit is useful for two reasons. First, it clarifies that the behaviours are structural features of the passive-topology architecture rather than implementation-specific deficiencies. Second, it identifies the physical targets that any stabilisation strategy must address: a system that successfully controls the EM-topology against sheath evolution, drift, oscillation, and environmental perturbation should, in principle, eliminate or substantially reduce all five classes of behaviour. This framing also positions the Psyche checkout data as a natural benchmark for evaluating active field-governance approaches, which are designed to address these mechanisms directly.

4. Relevance of Active Electromagnetic Field-Governance Approaches

Active electromagnetic field-governance architectures are being developed to stabilise the same classes of behaviour observed on Psyche. One such approach is the Rotating Electromagnetic Nozzle (REMNO), which applies controlled, time-varying electromagnetic fields to maintain a predictable EM envelope, suppress harmonic drift, and lock the magnetic topology into a stable operating regime independent of environmental boundary conditions.



REMNs are not thrusters. It is an external field-governance layer that can in principle be applied to a variety of electric-propulsion systems. Its four primary stabilisation functions, mode-transition suppression, harmonic damping, B-field topology locking, and environment-independent discharge stability, map directly onto the EM-topology mechanisms identified in Section 3.

Table 1 presents a one-to-one mapping between the behaviours observed during Psyche's checkout, their underlying EM-topology mechanisms, and the corresponding REMN stabilisation function. The alignment is noted not as a validation claim, the REMN stabilisation mechanisms described here are predictive, based on the physical model underlying the architecture, and have not yet been validated against flight data, but because it illustrates the direct relevance of the Psyche dataset to active field-governance research.

Table 1. Mapping of Psyche SPT-140 checkout behaviours to EM-topology mechanisms and REMN stabilisation functions.

Behaviour Observed on Psyche (SPT-140 Flight Data)	Underlying EM-Topology Mechanism	Corresponding REMN Stabilisation Function
Step thrust decrease during burn-in (277 → 253 mN at 4.5 kW)	Sheath evolution and wall-interaction changes alter ionisation-zone position as channel transitions from cold-wall to thermal-equilibrium state	Predictive EM envelope stabilises sheath geometry and prevents discharge-mode transition from first ignition
Extended mode-hopping on Thruster B requiring prolonged firing to stabilise	B-field topology drift near regime boundary; electron-temperature oscillations trigger transitions between quasi-stable discharge attractors	Harmonic suppression and field-geometry locking collapse the parameter-space attractor to a single stable operating point
Sensitivity to magnet-current settings during calibration	Steep EM-topology landscape at high-power operating points; small field perturbations shift ionisation and acceleration regions between neighbouring equilibria	Active B-field governance maintains topology under load and environmental variation; operating point held against perturbation
Ground-to-space performance differences	Neutral density, wall temperature, and sheath formation differ between vacuum-chamber and space environments, altering EM-topology equilibrium	Adaptive field shaping compensates for environmental boundary-condition changes in real time
Thrust variability during calibration segments	Ionisation oscillations, breathing modes, and plasma-potential fluctuations arising from coupled ionisation–neutral–EM-topology dynamics	EM harmonic damping suppresses oscillatory modes and improves thrust consistency

While the Psyche paper does not discuss active EM-governance approaches, the alignment between the observed behaviours and the stabilisation targets of REMNs is noteworthy and may be of interest to researchers exploring next-generation electric-propulsion architectures.

5. Implications for High-Power and Long-Duration Electric Propulsion

The Psyche checkout data is particularly relevant given the current trajectory of electric-propulsion development. As mission architectures extend Hall-thruster operating lifetimes beyond 10,000 hours and increase power levels toward 50 kW and beyond, the EM-topology instabilities documented in the Psyche data will become increasingly consequential. Burn-in periods will lengthen, mode-hopping will be harder to resolve through passive settling, and ground-to-space performance offsets will grow as thruster geometries and plasma environments diverge further from ground-characterisation conditions.

Passive magnetic topologies are well-suited to the current generation of high-power Hall thrusters. For the next generation, active field governance may move from a desirable option to a mission-enabling requirement, particularly for missions that cannot afford extended in-flight characterisation periods, or that require thrust consistency over multi-year operational timelines without regular ground contact for parameter adjustment.

The Psyche checkout data provides the community with a clear real-flight illustration of the problem space that active governance approaches are designed to address. In this sense, the dataset is a contribution not only to current mission practice but to the longer-term development of active field-governance technology.

6. Conclusion

The Psyche SPT-140 in-flight checkout results provide an important dataset for understanding high-power Hall-thruster behaviour in the space environment. The electromagnetic-topology behaviours reported, burn-in thrust decay, extended mode-hopping, magnet-current sensitivity, ground-to-space performance differences, and calibration-segment thrust variability, form a coherent pattern when interpreted through an EM-topology framework. Each behaviour corresponds to a known mechanism: sheath evolution, magnetic-topology drift, ionisation-driven oscillations, or environment-dependent discharge equilibria. This Technical Comment has outlined those connections and noted that active EM-governance architectures such as REMN are being developed to stabilise this class of behaviours at their physical source. The correspondence between the Psyche observations and the REMN stabilisation targets is direct and one-to-one, and the Psyche checkout data may serve as a useful real-flight reference for future experimental and computational work on active field governance in high-power Hall systems. The authors of the Psyche checkout paper are thanked for the quality and detail of their published dataset, which provides the community with a rare operational baseline for this class of analysis.

7. References

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8. Conflict of Interest

The author declares no competing conflict of interest.

9. Funding

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10. Appendix

11. Table 2. Psyche SPT-140 checkout behaviours (Oh et al. [1]) mapped to EM-topology mechanisms and corresponding REMN active field-governance stabilisation functions.

GREMN vs. Current Electric Propulsion Systems

System	Isp (s)	Efficiency η	Power	TRL	Confinement	Notes
Hall Thruster	1500–2000	~0.55	1–5 kW	9	Open	Mature EP baseline
Gridded Ion Engine	3000–5000	~0.70	1–10 kW	9	Open	High Isp, low thrust
MPD Thruster	2000–4000	~0.30	100–500 kW	3	Open	High power, erosion issues
VASIMR	3000–5000	~0.60	200 kW	5	Open	Requires high power
RMF/FRC Devices	1000–3000	—	50–200 kW	2	Closed	Shear-stabilized plasmas
GREMN Mode C	3000–8000	~0.70	5–12 kW	2	Closed	Two-layer shear engine

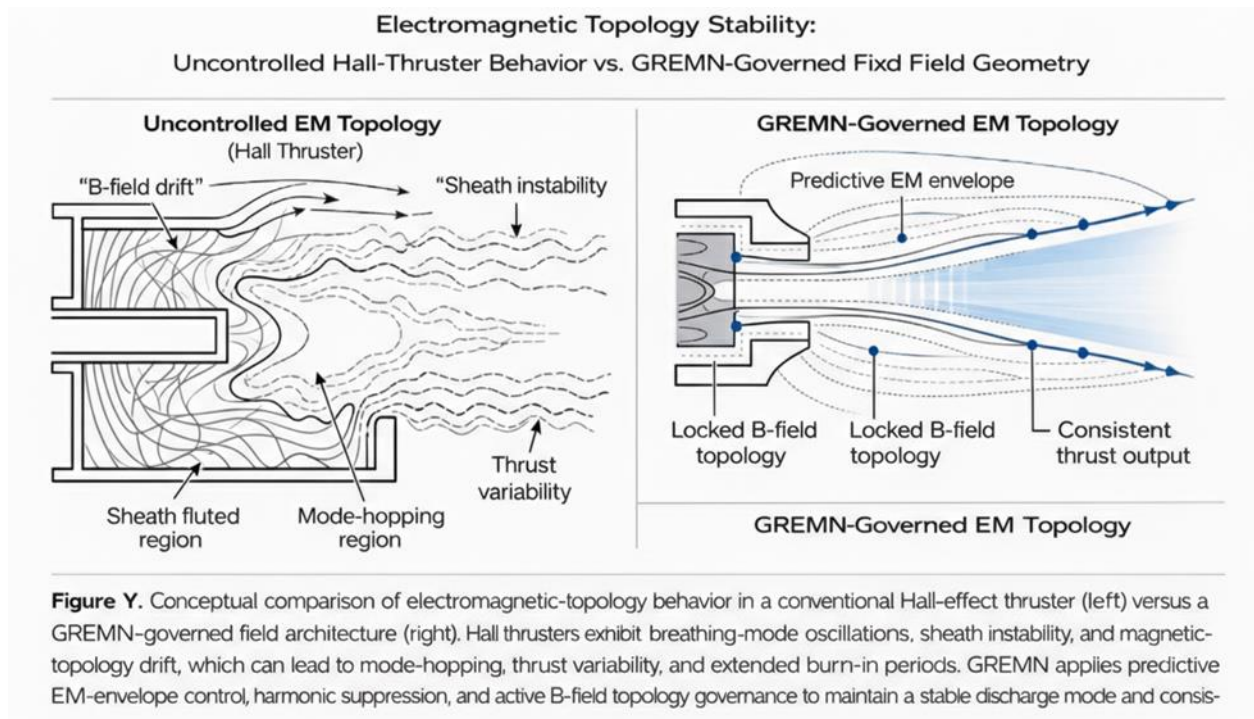


Fig. 2. Passive Hall-thruster EM-topology (left): B-field drift, mode-hopping, and thrust variability. REMN-governed architecture (right): locked topology and consistent thrust.