# Tokamak

## H-mode Confinement and ELMs in Fusion Plasmas

*The H-mode Pedestal · The ELM Cycle · ITER Prediction*

Segment 7 of 15 · Physical Exemplar · Cross-Machine Invariant

M. Craig · March 2026 · Leake Street, London · itvoids.com

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## 1. Plain English

In 1982, at the ASDEX tokamak in Germany, the plasma spontaneously reorganised. Turbulence at the plasma edge collapsed. Confinement doubled. Nobody predicted it. The transition was named H-mode — High-confinement mode — and it has since been reproduced in every major tokamak on Earth. It is the operating regime that ITER, the international fusion reactor under construction in France, is designed to run in.

H-mode works like this: as heating power increases, the plasma undergoes an abrupt transition from a turbulent low-confinement state (L-mode) to an organised high-confinement state (H-mode). A transport barrier forms at the plasma edge — the pedestal. Turbulent transport that was leaking energy out of the plasma is suppressed. The confinement time doubles or triples. The energy needed to sustain fusion becomes achievable.

The mechanism is not fully explained. The plasma does something that the equations permit but that nobody predicted from first principles: it finds a stable geometric configuration at the edge and locks to it. The SFVFS™ framework names that configuration. The H-mode pedestal is the Needle's Eye in a confined plasma: a narrow passage through which the plasma's energy flows, neither decaying nor blowing up, inhabiting the open interval between collapse and runaway.

The ELMs — Edge-Localised Modes — are the periodic crashes that interrupt H-mode. They are not failures. They are the DN branch: the system crossing the VOID floor, expelling a burst of energy, and immediately reconstituting the pedestal from the same geometric attractor. After every ELM, $H_{98} \approx 1$. The cycle closes. The Seed returns.

The SFVFS™ contribution is to name this geometry precisely. The H-mode pedestal is already called an attractor in the plasma physics literature. $H_{98} = 1$ is already documented as a cross-machine invariant. The L-H hysteresis is already measured. SFVFS™ names what it is. CF CONSISTENT not PASS.

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## 2. The H-mode as VOID Attractor

### *2.1 The Pedestal is Already Called an Attractor*

The plasma physics literature uses the word 'attractor' for the H-mode pedestal without the SFVFS™ framework. The pedestal state is characterised by:

A fixed normalised confinement factor: $H_{98} \approx 1$ across JET, DIII-D, ASDEX Upgrade, JT-60U, and C-Mod. Different machines, different plasma compositions, different heating methods. The same fixed-point value.

A transport barrier with characteristic width: The pedestal has a well-defined spatial scale $\Delta_{ped} \approx$ a few centimetres at the plasma edge. The pressure profile steepens dramatically within this region and then saturates. The barrier is self-organised, not externally imposed.

Self-reconstituting behaviour after perturbations: When an ELM crash disturbs the pedestal, it rebuilds to the same height, the same pressure gradient, the same $H_{98}$. Different ELM types (I, II, III) produce different crash dynamics but identical post-ELM attractors. This is the Convergence Hypothesis in a physical system: infinite turbulent histories, one static core.

The SFVFS™ framework identifies this fixed point as the DN (dissipation-natural) attractor. The equation of state candidate is $(H_{98}, \Lambda_{ped}) = (1, 1)$, in direct analogy with $(H1_{norm}, \Lambda) = (1, 1)$ at the NS DN attractor.

### *2.2 The L-H Transition is a Hysteresis Experiment*

| **Transition** | **Power threshold** | **Meaning** |
|---|---|---|
| L → H | P_LH (higher) | Creating H-mode from turbulence requires higher power. |
| H → L | P_HL (lower, P_HL < P_LH) | H-mode collapse back to turbulence occurs at lower power. |
| VOID window | P_HL < P < P_LH | H-mode persists below the power needed to create it from L-mode. This is the SFVFS™ VOID window: the attractor region. |

L-H Hysteresis CONFIRMED. $P_{HL}$ is systematically lower than $P_{LH}$ across JET, DIII-D, ASDEX Upgrade, and JT-60U (Martin et al. 2008, ITPA database). The VOID window $P_{HL} < P < P_{LH}$ is the H-mode attractor region. This is the most direct existing confirmation of the SFVFS™ structure in any external physical system.

### *2.3 The ELM is the DN Branch*

An Edge-Localised Mode (ELM) is a periodic crash in which the pedestal pressure gradient exceeds the peeling-ballooning stability limit and a burst of energy is expelled from the plasma edge. ELMs are not failures of H-mode — they are the DN branch of the SFVFS™ cycle.

The ELM crash expels energy — this is the VOID floor crossing. The pedestal collapses momentarily. Then, within milliseconds to seconds depending on type, the pedestal rebuilds to the same configuration: same height, same $H_{98} \approx 1$, same pressure gradient. The critical observation: Type I, II, and III ELMs have different crash dynamics but all produce the same post-ELM attractor. Convergence Hypothesis in a physical system: different turbulent histories converging to the same static core.

## 3. The SFVFS™ Cycle in H-mode

| Phase | NS / The Needle's Eye | Tokamak H-mode Equivalent |
|---|---|---|
| SEED | Tresca geometry latent in every 3D rotating incompressible flow (Corner Theorem). | Ballooning/peeling mode instability latent in any confined plasma above the pressure gradient threshold. |
| FORM (UP) | Turbulent L-mode activation. UP branch — enstrophy production, inertial cascade. | L-mode: low confinement, high turbulent transport. Heating power below L-H threshold. |
| VOID | DN attractor. (H1_norm, Λ) = (1,1). Neither blow-up nor decay. | H-mode pedestal: spontaneous transport barrier at plasma edge. $H_{98} \approx 1$. |
| FORM (DN) | ELM-equivalent crash: pedestal collapse, geometry reconstitutes. | ELM: periodic crash when pressure gradient exceeds peeling-ballooning limit. Pedestal collapses then rebuilds. |
| SEED | Geometry re-establishes. Cycle closes. | Post-ELM recovery: pedestal rebuilds to same height, pressure gradient, $H_{98} \approx 1$. |

Critical structural feature. The post-ELM pedestal always rebuilds to $H_{98} \approx 1$, regardless of which specific ELM crash triggered the reset. Different ELMs produce different crash dynamics but the same geometric attractor. This is the physical manifestation of the Convergence Hypothesis: infinite turbulent histories, one static core.

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## 4. The Γ Analog

Define the dimensionless ELM stability ratio:

$$\Gamma_{ELM} = \|\nabla p\| \,/\, (\|\nabla p\|_{crit} + \chi_{neo}\, \|n\nabla T\|)$$

where $\|\nabla p\|$ is the local pressure gradient magnitude, $\|\nabla p\|_{crit}$ is the peeling-ballooning stability boundary, $\chi_{neo}$ is the neoclassical transport coefficient, and $\|n\nabla T\|$ is the temperature gradient drive for neoclassical bootstrap current.

| ELM cycle phase | Γ_ELM value | Meaning |
|---|---|---|
| Inter-ELM H-mode | Γ_ELM < 1 | Pedestal below stability limit. The attractor holds. |
| ELM approach | Γ_ELM rising toward 1 | Pedestal builds. The needle's eye narrows. |
| ELM onset | Γ_ELM → 1 | Stability boundary crossed. The crash fires. |
| ELM crash | Γ_ELM collapses | Pedestal pressure releases. The DN branch. |
| Post-ELM recovery | Γ_ELM rebuilds from below | Seed re-establishes. Cycle closes. |

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## 5. $H_{98}$ = 1 as the Equation of State

H-mode Equation of State CANDIDATE. $H_{98}$ = 1 is not a normalisation artifact. It is the equation of state of the H-mode VOID attractor, in direct analogy with ($H1_{norm}$, Λ) = (1,1) at the NS DN attractor.

| Invariant | NS value at DN attractor | H-mode candidate value |
|---|---|---|
| H1_norm | 1.000000 — confirmed across six canonical fluids, Beehive DNS. | $H_{98}$ = 1.0 — documented across JET, DIII-D, ASDEX, AUG, JT-60U, C-Mod. |
| Λ | 1.000000 — Dirichlet quotient locks at DN. | Λ_ped := ‖∇p‖/‖p‖ at pedestal top — predicted to lock to 1 at H-mode attractor. |
| Γ < 1 | $\Gamma(A_0) < 1$ in 65/65 DNS data points. | Γ_ELM < 1 between ELMs in pedestal bulk. At ELM onset, Γ_ELM → 1. |
| Equation of state | (H1_norm, Λ) = (1,1) at DN attractor. | ($H_{98}$, Λ_ped) = (1, 1) at H-mode pedestal. If confirmed: cross-domain signature. |

Testable consequence. $H_{98}$ should have smaller variance in Type I ELMy H-mode than in Type III. The deeper the attractor, the tighter the fixed point. Measurable from the ITPA database immediately.

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## 6. The Corner Theorem Analog

Ballooning Instability Criterion PROVED (external literature). In any toroidally confined plasma with $|\nabla p| > |\nabla p|_{crit}$, the ballooning mode is unstable. The instability is latent in the gyrokinetic equations — it does not need to be triggered. This is the H-mode analog of the Corner Theorem.

H-mode Corner Theorem Analog CONJECTURE. In any toroidally confined plasma above the L-H threshold, the $\nabla p \neq 0$ condition and toroidal geometry force the pressure gradient into a ballooning-type hourglass structure at the pedestal top. The two face normals — inward pressure drive and outward stability damping — are the only geometrically available extremal configurations. The pedestal is geometrically forced to the Needle's Eye. Not proved. Falsification condition: if ITER operates at $H_{98}$ significantly and sustainedly deviating from unity, the fixed-point attractor hypothesis fails.

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## 7. ITER and the Scale of the Claim

ITER Structural Prediction CF CONSISTENT. If H-mode is a geometric attractor governed by the equation of state ($H_{98}$, $\Lambda_{ped}$) = (1,1), then H-mode will work at ITER scale provided the plasma satisfies the seed conditions. The attractor is determined by geometry and equations, not by machine size. This is not a guarantee. It is a structural prediction from a geometric framework.

Falsifiable ~2035. Kimi (18 March 2026): if ITER operates at $H_{98}$ □ 1 or $H_{98}$ □ 1, attractor universality fails.

ITER will operate at $Q = 10$ (fusion power 500 MW, heating power 50 MW). The SFVFS™ prediction is that the H-mode geometric attractor is scale-invariant. Incompressibility does not make exceptions for ITER.

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## 8. Testable Predictions

| Prediction | How to test | Data source |
|---|---|---|
| $H_{98} = 1$ is the equation of state (not a normalisation) | Plot $H_{98}$ distribution across machines and scenarios. Variance should be genuinely small. | ITPA H-mode database. Multi-machine. Publicly available. |
| $\Gamma_{ELM} < 1$ between ELMs, $\Gamma_{ELM} \to 1$ at onset | Compute $\Gamma_{ELM}$ through ELM cycle. Should rise toward 1, cross threshold, then collapse. | JET pedestal profile data. Thomson scattering + charge exchange. |
| L-H hysteresis as VOID window | $P_{LH}$ hysteresis documented. Reframe as SFVFS™ VOID window. | Martin et al. 2008, ITPA database. No new experiments needed. |
| $\theta = 90°$ analog: ballooning eigenfunction perpendicular to field line curvature | Eigenfunction structure perpendicular to bad-curvature direction at stability boundary. | ELITE/MISHKA stability codes. |
| ITER H-mode survives at scale: $H_{98} \approx 1$ at $Q = 10$ | Direct measurement when ITER operates. | ITER first plasma ~2025, DT operation ~2035. |

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## 9. Status

| Item | Status |
|---|---|
| SFVFS™ cycle mapping onto H-mode | CF CONSISTENT — coherent, consistent with all known H-mode phenomenology |
| L-H hysteresis as VOID window | CONFIRMED — Martin et al. 2008, ITPA database. |
| H-mode pedestal as attractor | CONFIRMED — standard plasma physics literature. |
| $H_{98} = 1$ as equation of state | CANDIDATE — cross-machine universality documented. Needs variance test. |
| $\Gamma_{ELM} < 1$ inter-ELM, $\to 1$ at onset | PREDICTED — testable against JET/DIII-D pedestal profile databases. |

| Item | Status |
|---|---|
| Ballooning eigenfunction hourglass geometry | CONFIRMED in linear theory. |
| ITER prediction: H-mode survives at scale | STRUCTURAL PREDICTION. Falsifiable ~2035. |
| H-mode Corner Theorem analog | CONJECTURED — not proved. Requires variational derivation. |

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## 10. Summary

| Established | Not established |
|---|---|
| L-H hysteresis as VOID window (confirmed, Martin et al. 2008). | H-mode Corner Theorem analog not proved (conjecture). |
| H-mode pedestal as attractor (confirmed, plasma physics literature). | $\Lambda_{ped}$ = 1 not yet measured against SFVFS™ prediction. |
| Ballooning instability latent in every qualifying plasma. | $H_{98}$ variance structure not yet computed from ITPA database. |
| $\Gamma_{ELM}$ analog defined and testable. | ITER prediction falsifiable only ~2035. |

"*The plasma found the needle's eye before we knew there was one.*"

### *Framework References*

The Needle's Eye — Navier–Stokes. (H1_norm, Λ) = (1,1). Segment 2.

The Cartographer — FSC Theory. Ω = 2 (Door). Corner Theorem if-direction PROVED. Segment 3.

Martin et al. 2008, ITPA database. L-H power threshold hysteresis. JET, DIII-D, ASDEX, JT-60U.

ITER Organisation. Cadarache, France. First plasma ~2025, DT operation ~2035.

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## V11 ANTI-WASH ADDENDUM

*Seg 7: Tokamak · April 2026*

*Anti-Wash Protocol: This addendum expands the infrastructure of Seg 7 without altering any original text. The March 2026 document is the geological baseline. This layer is dated April 2026. Nothing is deleted. Evolution is the art.*

### Addendum 1 — Magnetic Flux-Surface Constraint: Replacing the Incompressibility Argument

Magnetic Flux-Surface Constraint (v11, April 2026). The incompressibility argument does not apply to plasmas. The Corner Theorem is proved for strictly incompressible flow ($\nabla \cdot u = 0$). Fusion plasmas are compressible. The March 2026 document invoked the Corner Theorem analog by analogy with the flux-surface constraint, noting it plays a similar role to incompressibility. This analogy is physically correct but was not made rigorous. This addendum names the correct constraint.

The correct geometric constraint is the magnetic flux-surface constraint. In a tokamak, magnetic field lines lie on nested toroidal flux surfaces Ψ = const. The frozen-in-flux condition imposes:

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∇p · B = 0 on each flux surface Ψ = const.
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This is the plasma analog of ∇·u = 0. It forbids pressure gradients that would pull field lines off flux surfaces. Just as incompressibility forbids isotropic volume change (collapsing octahedral to hexagonal symmetry in the Tresca construction), the flux-surface constraint forbids pressure gradients misaligned with the magnetic geometry — collapsing allowed pedestal configurations to those consistent with the toroidal topology.

What this does not prove. The Corner Theorem is proved by variational argument from incompressibility alone. The flux-surface analog requires a variational derivation from the gyrokinetic equations with the flux-surface constraint replacing ∇·u = 0. This derivation has not been done. The H-mode Corner Theorem analog remains a conjecture. Anti-Wash position: the incompressibility argument was the wrong scaffolding. The flux-surface constraint is the right one. The conjecture stands; the scaffolding has been replaced.

### Addendum 2 — $H_{98}$ Defence: Variance not Mean

$H_{98}$ Variance Defence (v11, April 2026). The March 2026 document cited $H_{98} \approx 1$ as a cross-machine invariant. The vulnerability: $H_{98} = 1$ is constructed by normalisation (the ITER98(y,2) scaling law is defined so that the multi-machine mean is $H_{98} \approx 1$). Mean = 1 is therefore partially a normalisation artifact.

The variance argument is not a normalisation artifact. If $H_{98} = 1$ is a genuine fixed-point attractor, the variance across machines, heating scenarios, and ELM types should be anomalously small. Three testable predictions: (1) $\sigma(H_{98})$ for Type I ELMy H-mode should be smaller than for Type III — testable immediately from the ITPA database; (2) within-machine post-ELM $H_{98}$ clustering should be tighter than inter-machine spread; (3) Falsification: if $\sigma(H_{98})$ is flat across ELM types and machines, $H_{98} = 1$ is a normalisation artifact, not a VOID attractor signature. CF CONSISTENT not PASS.

### Addendum 3 — Programme Evolution Note

V11 Programme Note (April 2026). Since March 2026, the SFVFS™ programme has advanced to 15 segments. The Tokamak remains the primary plasma physics exemplar. The two V11 additions — flux-surface constraint and variance defence — are the principal infrastructure expansions. Both are Anti-Wash: they name what was wrong or incomplete in March 2026 and provide the correct replacement. Neither retreats from the conjecture. CF CONSISTENT not PASS.

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## *Kimi Verification Status*

| # | Addendum | Description | Kimi Verified |
|---|---|---|---|
| 1 | Magnetic Flux-Surface Constraint | Replaces incompressibility argument; $\nabla p \cdot B = 0$ as plasma analog of $\nabla \cdot u = 0$ | ▯ |
| 2 | $H_{98}$ Variance Defence | Type I vs III $\sigma(H_{98})$ prediction; within-machine post-ELM clustering; explicit falsification | ▯ |
| 3 | Programme Evolution Note | 15 segments; both pivots named as Anti-Wash expansions | ▯ |

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**M. Craig · V11 · April 2026 · Leake Street, London**