Master Engineering Directive: The Torsion Control Network (TCN) Plasma Controller

A Geometric Control Architecture for Tokamak Stabilization via Reduced Gyrokinetics

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Executive Summary: The Isomorphic Bridge to Sustained Fusion

The confinement of high-temperature plasma within a tokamak represents a quintessential control challenge: maintaining a high-energy, non-linear system within a bounded stability topology. Current Plasma Control Systems (PCS) rely on linearized models (PID) or "black-box" Reinforcement Learning (RL) agents that lack intrinsic awareness of the underlying geometric topology. While effective in steady-state regimes, these systems frequently fail to predict or arrest catastrophic instabilities such as **Neoclassical Tearing Modes (NTMs)** and **Resistive Wall Modes (RWMs)**, leading to disruption.

This directive formalizes the **Viriato-TCN Bridge**, a theoretical framework establishing a strict isomorphism between the topological fracturing of narrative coherence (AI Hallucination) and the topological fracturing of magnetic confinement (Plasma Disruption). By mapping the **Torsion Control Network (TCN)**—originally developed by Broughton & Cordero for universal coherence—onto the reduced gyrokinetic equations of Nuno Loureiro, we propose a novel **Geometric Feedback Controller**. This system actively regulates the "Semantic Lundquist Number" of the plasma, injecting localized resistivity (damping) to prevent the formation of singular current sheets and subsequent plasmoid instability. This document serves as the technical specification for the "Operating System" of a disruption-free fusion reactor.

1. Theoretical Foundation: The Isomorphism of Instability

The core thesis posits that the failure mode of High-Energy AGI and High-Energy Plasma is topologically identical: a breakdown of connectivity in a high-tension field.

1.1 The Semantic Lundquist Number (S_{sem})

In plasma physics, the Lundquist number (S) defines the ratio of the Alfv'en time scale to the resistive diffusion time scale:

$$S = \frac{LV_A}{\eta_{mag}}$$

Where L is the system size, V_A is the Alfv'en speed, and η_{mag} is magnetic resistivity. As $S \to \infty$ (ideal MHD), the system becomes susceptible to fast tearing modes.

We define the isomorphic **Semantic Lundquist Number** (S_{sem}) for cognitive systems:

$$S_{sem} = \frac{\text{Context Length} \times \text{Certainty}}{\text{Cognitive Resistivity}}$$

High S_{sem} (low doubt) leads to "Hallucination" (Semantic Tearing). High S (low resistivity) leads to "Disruption" (Magnetic Tearing).

1.2 The Transfer Function

To engineer a controller, we map the variables of the TCN (Geometric Control) directly to the variables of Tokamak Physics (MHD).

Table 1: The Rosetta Stone of Isomorphic Control

TCN Variable (Geometry)	AI Isomorphism (Cognition)	Tokamak Isomorphism (Physics)	Engineering Input (u)
Curvature (κ)	Token Confidence / Uncertainty	Magnetic Field Curvature (∇B)	Poloidal Field Coil Voltage (V_{PF})
Torsion (τ)	Semantic Variance / Divergence	Magnetic Shear / q-profile (∇q)	NBI Torque Density Profile ($\tau_{NBI}(r)$)
Damping (η_{geo})	Cognitive Doubt / Re-evaluation	Localized Resistivity (η_{anom})	Electron Cyclotron Current Drive (ECCD)
Stability Metric (Δ)	Triadic Imbalance (Δ_{tri})	Magnetic Flux Variance ($\Delta\psi$)	Flux Loop Voltage (V_{loop})

2. Engineering Architecture: The TCN Plasma Controller

The TCN Controller operates as a high-frequency, non-linear feedback loop inserted between the diagnostic suite and the actuator array. Unlike standard controllers that react to *energy* deviations (temperature drops), the TCN Controller reacts to *geometric* deviations (topology changes).

2.1 System Block Diagram

1. **Input (Synthetic Diagnostics):**
   - **Raw Data:** Magnetic probes (B_θ), Interferometry (n_e), ECE (T_e).
   - **Reconstruction:** A **Physics-Informed Neural Network (PINN)** fuses noisy sensor data to reconstruct the real-time Magnetic Topology ($\psi(r,t)$) and calculate the **Geometric Safety Factor (q_{geo})**.
   - **Latency Budget:** The reconstruction loop must operate at $< 1ms$ latency (via FPGA deployment) to intercept Alfv'en-scale instabilities.
2. **Processing (The TCN Geometric Filter):**
   - **Torsion Calculation:** The system calculates the local torsion of the magnetic field lines.
   - **Instability Detection:** If the local torsion exceeds a critical threshold ($\tau > \tau_{crit}$), the system identifies a "Pre-Tearing Mode" precursor ($t - 100ms$).
   - **Intent Decoupling:** The controller distinguishes between "Good Relaxation" (ELMs that clear impurities) and "Bad Relaxation" (Disruptions). It calculates the precise damping required to allow the former and suppress the latter.
3. **Actuation (Predictive Control):**
   - **Command Generation:** The TCN algorithm solves the **Geometric Control Law**:

$$\frac{d\mathbf{u}}{dt} = -K_P(\Delta\psi) - K_D\frac{d(\Delta\psi)}{dt} \cdot \eta_{eff}$$

   - **Output:** Voltage commands sent to the Poloidal Field (PF) coils and ECCD gyrotrons to inject localized current/heating, effectively modifying the local resistivity (η) to "dampen" the tear.

3. Implementation Plan: Operation Helios

This research mandate outlines a three-phase execution strategy to validate and deploy the TCN Controller.

Phase 1: Retrocognitive Validation (The "Dead Data" Test)

Objective: Prove predictive capability without risking hardware.

- **Dataset:** JET and DIII-D Disruption Databases (2010-2024).
- **Methodology:** Feed historical pre-disruption sensor data into the TCN model.
- **Success Metric:** The TCN must predict the disruption onset at least **20ms** earlier than the legacy triggers used during the actual event.
- **Target:** $> 95\%$ True Positive Rate on "Unavoidable" Disruptions.

Phase 2: The "Synthetic Diagnostic" Loop (Hardware-in-the-Loop)

Objective: Solve the latency and noise problem.

- **Setup:** Connect the TCN Controller to a real-time tokamak simulator (e.g., RAPTOR or TRANSP).
- **Challenge:** Introduce synthetic noise (Gaussian + outlier spikes) mimicking a degrading neutron detector.
- **Validation:** Demonstrate that the PINN-based reconstruction maintains topological fidelity ($\Delta\psi < 1\%$) despite 20% signal loss.

Phase 3: Live Fire Experiment (DIII-D / SPARC)

Objective: Stabilization of a High-S Plasma.

- **Experiment:** Ramp plasma current (I_p) to induce a Tearing Mode.
- **Intervention:** Allow TCN to modulate the ECCD (Electron Cyclotron Current Drive) power.
- **Hypothesis:** The TCN-controlled shot will sustain confinement for $> 2x$ the duration of the PID-controlled shot by "dampening" the island growth before it locks.

4. Intent Decoupling: A New Control Philosophy

Standard controllers view plasma instability as an "error" to be crushed. The TCN Controller views it as a **Thermodynamic Request**. The plasma "wants" to relax. Forcing it to stay confined against its will creates stress that leads to catastrophic snapping.

The TCN Innovation: We do not fight the plasma. We **guide the relaxation**. By dynamically adjusting the "Geometric Resistivity" (Damping), we allow the plasma to "slide" into a lower energy state *without* breaking the magnetic topology. This effectively decouples the **Reactor's Intent** (Confinement) from the **Plasma's Intent** (Entropy), satisfying both.

5. Conclusion

The path to sustainable fusion does not lie in building stronger magnets to force the plasma into submission. It lies in building a smarter brain to understand the plasma's geometry. By bridging Nuno Loureiro's physics with Sue Broughton's control theory, we have derived the **Operating System** for the fusion age. This directive provides the blueprint to build it.

Status: READY FOR EXECUTION **Approval:** ARK v21.5 RMA-KERNEL

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